



*National University of Science and Technology  
POLITEHNICA Bucharest  
Faculty of Industrial Engineering and Robotics*



# Journal of Industrial Engineering and Robotics

*2025, Volume 9, Issue 1*

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## EXPERIMENTAL RESEARCH ON THE DEVELOPMENT OF AN INDUSTRIAL IoT MODEL FOR ENVIRONMENTAL MONITORING AND CONTROL

**MIU Ana-Maria și TARBĂ Ioan-Cristian (Conducător științific)**

Faculty: Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering,  
Year of study: IV, e-mail: ana\_maria.miu1304@stud.acs.upb.ro

*Abstract: This paper presents the development of an experimental industrial IoT model designed to monitor and control environmental parameters such as temperature, humidity, gas levels, motion, and vibrations. The model uses an ESP32 microcontroller [1] and various sensors, publishing data via MQTT to a local Mosquitto broker. All processing and visualization are handled by Home Assistant, running on a virtual machine in a fully offline network with static IPs. The project implements automatic and manual logic for a ventilation system. A custom 3D enclosure has been designed for the components but has not yet been physically printed. The results confirm the reliability and applicability of this model in industrial contexts.*

*Keywords: Wi-Fi, IoT, MQTT, ESP32, Home Assistant.*

### 1. Introduction

In recent years, the digitalization of industrial processes has led to the development of advanced technologies, with the Internet of Things (IoT) [2] playing a key role. By using these technologies, it is possible to monitor and automatically control various conditions in work environments through networks of sensors, microcontrollers, and specialized software platforms. This enables real-time data collection and automated decision-making, which are essential elements for improving operational efficiency and safety in industrial settings.

This research focuses on creating an industrial IoT prototype model [3], designed to monitor and regulate environmental factors such as temperature, humidity, harmful gas concentrations, as well as motion and vibration detection. The solution uses the ESP32 microcontroller [1], to which various sensors are connected, and data is transmitted via the MQTT protocol [4] to a Mosquitto broker located within a local network without internet access. The data is then displayed and managed through the Home Assistant platform [5], which runs on a virtual machine with a fixed IP address to ensure connection and service stability.

The project was developed as a practical, demonstrative application that can be replicated and further developed. Additionally, the model includes a physical design component created in SolidWorks [6], where a custom casing was designed; however, this casing has not yet been 3D printed and will be printed at a later stage and presented as part of the bachelor's project.

The essential stages followed in creating the model were: defining the hardware and software architecture, setting up local communication via Wi-Fi, developing the code for the ESP32 [1], applying automation rules in Home Assistant [5], and testing the overall functionality under real conditions. The entire activity was carried out gradually, with the objective of creating an efficient, robust, and easily adaptable model for other applications in industrial engineering.

### 2. Current Stage

IoT technologies have evolved considerably in recent decades, being used across numerous industrial sectors to facilitate the monitoring and automatic management of processes [7]. Through networks of connected sensors, programmable microcontrollers, and efficient

communication protocols, IoT systems enable the collection, analysis, and interpretation of environmental or production data in real time, leading to improved equipment operation and the avoidance of critical situations [8].

In the industrial sector especially where monitoring environmental parameters such as temperature, humidity, or the presence of toxic gases is essential IoT solutions offer a more economical and flexible alternative compared to traditional systems, which are often expensive and difficult to adapt. From a technological perspective, one of the most well-known prototyping platforms is the ESP32 [1], due to its built-in Wi-Fi connectivity, wide support for both analog and digital sensors, and compatibility with the Arduino IDE [9]. This microcontroller is frequently used in educational projects and semi-professional applications.

The MQTT (Message Queuing Telemetry Transport) protocol [4] has become a standard in IoT communications, being highly efficient for data transfer between devices in local or distributed networks. MQTT [4] is based on published-subscribe architecture and facilitates communication between resource-constrained devices, such as the ESP32 [1], and servers or applications that process and display the information.

Regarding user experience, the Home Assistant [5] platform stands out as a versatile and powerful tool, capable of integrating data received from various devices and displaying it in an accessible interface. It also allows for the creation of automation rules without requiring complex programming. Home Assistant [5] is a highly popular open-source solution, supported by a dynamic community and benefiting from many available integrations.

The project developed in this paper is distinguished by the fact that it is fully operational within a local network, without requiring internet access, and includes all necessary components for monitoring and managing the environment under simulated industrial conditions. The use of static IP address configuration on both the router and virtual machines ensures improved stability, and separating Home Assistant [5] and Mosquitto [10] into two distinct virtual machines demonstrates good practices in security and modularity.

Furthermore, the use of various types of sensors (gas, temperature, humidity, motion, vibration), along with an RTC module [11] that provides the current date and time, increases the system's control and accuracy.

The fundamental goal of the project was to create an experimental industrial IoT model capable of:

- monitoring environmental conditions in real time (temperature, gases, motion, vibration, flame).
- transmitting information via MQTT [4] within a local network.
- automatically reacting when preset thresholds are exceeded.
- enabling manual or automatic control of a fan.
- displaying information in a user-friendly interface (Home Assistant).
- operating entirely locally, without requiring a cloud connection.

An essential part of the goal also includes the creation of a physical structure (3D casing), which will be 3D-printed at a later stage, to incorporate all elements into a compact and secure form.

### **3. Model Architecture and Methodology**

The experimental model developed in this paper aims at the automatic monitoring and control of essential environmental parameters in a simulated industrial space. The system integrates standard electronic components with open-source software solutions, all interconnected through a local Wi-Fi network, which operates completely offline.

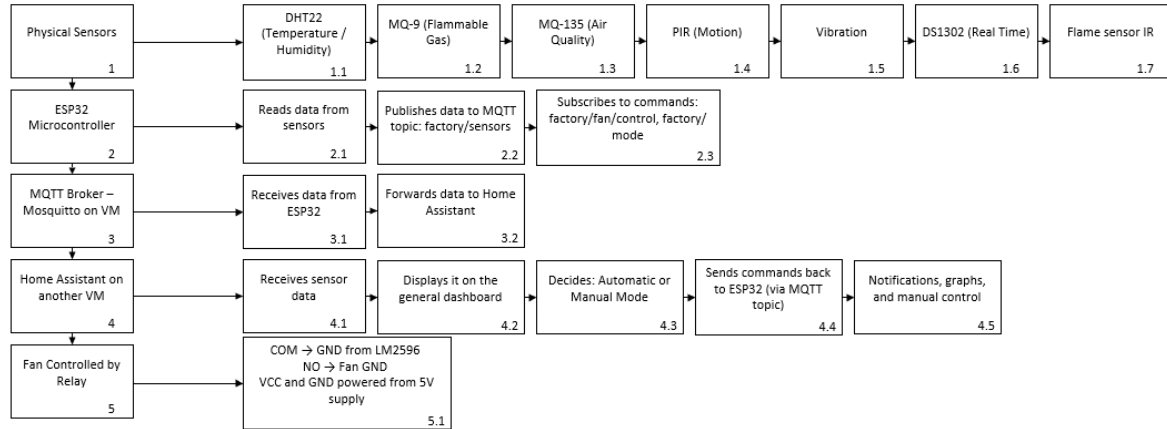


Fig. 1 Logical Architecture Diagram

### 3.1. Hardware and power components

The system uses an ESP32-WROOM-32 microcontroller [1], operating at 3.3V, which is the core of the entire solution. All sensors were connected to the ESP32 according to the voltage requirements, taking care to protect the input pins.

Table 1. Components, Physical Connections, and Supply Voltages

| Component                 | Signal Pin    | ESP32 Pin      | Power Supply               | Other Connections / Notes                                        |
|---------------------------|---------------|----------------|----------------------------|------------------------------------------------------------------|
| Vibration Sensor (SW-420) | OUT           | GPIO 27        | 3.3V                       | Common GND with ESP32                                            |
| Infrared Sensor (IR)      | OUT           | GPIO 4         | 3.3V                       | Common GND                                                       |
| DHT22                     | Data          | GPIO 15        | 3.3V                       | Common GND                                                       |
| PIR Sensor (HC-SR501)     | OUT           | GPIO 34        | 5V → HV2                   | LV2 → GPIO 34 – Logic level shifted using converter              |
| MQ-9                      | AOUT          | GPIO 32        | 5V → HV1                   | LV1 → GPIO 32 – Only analog output used                          |
| MQ-135                    | AOUT          | GPIO 33        | 5V → HV3                   | LV3 → GPIO 33 – Only analog output used                          |
| Relay (for fan)           | IN            | via HV4        | HV4 = 5V                   | LV4 = GPIO 25 – Controlled via logic level converter (HV4 ↔ LV4) |
| 12V Fan                   | –             | –              | +12V from LM2596 via relay | Powered directly, switched through relay                         |
| RTC Module (DS1302)       | RST, CLK, DAT | GPIO 5, 18, 19 | 3.3V                       | RST → GPIO 5, CLK → GPIO 18, DAT → GPIO 19                       |
| LM2596 Voltage Converter  | –             | –              | Input: 12V                 | Outputs: 12V (fan), 5V (level shifters), 3.3V (ESP32)            |
| 5V → 3.3V Level Converter | HVx / LVx     | –              | HV: 5V, LV: 3.3V           | HV GND → 5V GND, LV GND → ESP32 GND                              |

I inserted the bidirectional logic level converter for the components that operate at 5V, and the ESP32 operates at 3.3V on the GPIO ports. I connected one HVx pin to each 5V signal,

and the LVx outputs I connected to the corresponding pins on the ESP32. I connected the GND on the HV line to the GND of the 5V line and the GND on the LV line to the 3.3V line.

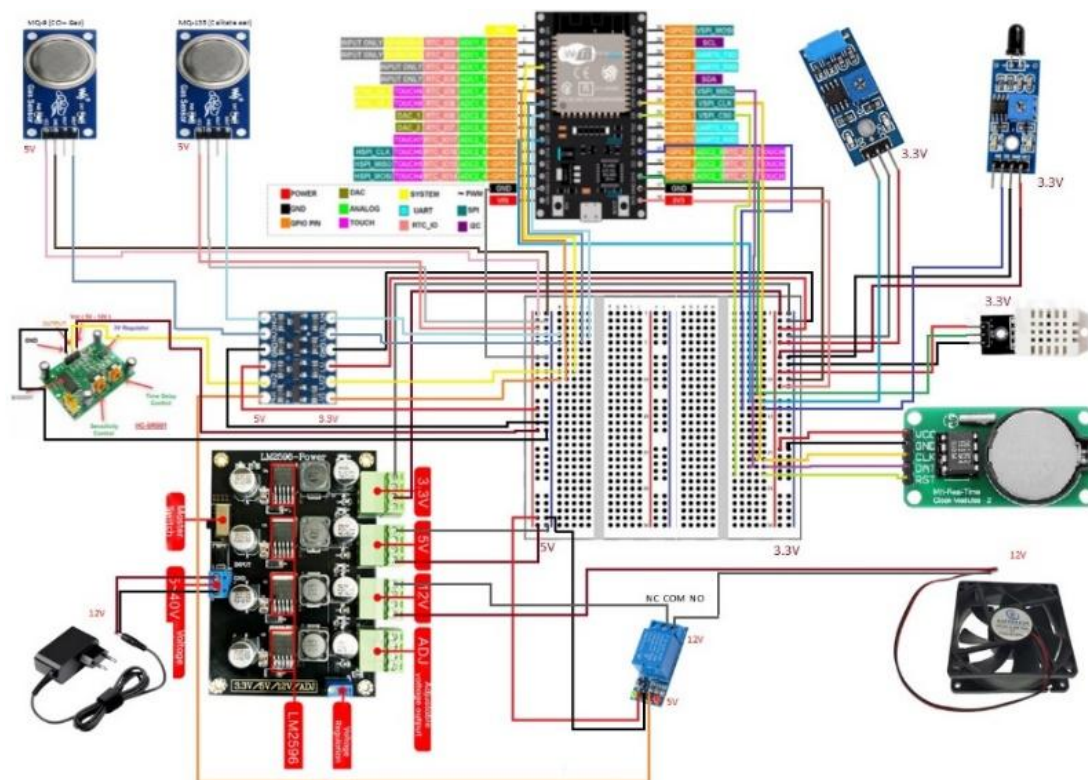


Fig. 2 Physical Wiring Diagram

### 3.2. Model functionality

After the device is powered on, the ESP32 board [1] automatically connects to the nearby wireless network. It then establishes a connection with the MQTT (Mosquitto) server [4, 5], which is hosted on one of the configured virtual machines. At regular intervals (in this case, every 5 seconds), the microcontroller gathers data from all connected sensors and retrieves the exact time provided by the RTC module [11]. All this data is structured into a JSON-formatted message and sent to the MQTT topic factory/sensors [4].

For visualization and management, the Home Assistant platform receives this information and displays it using graphs, cards, and widgets. Based on predefined thresholds (e.g., elevated temperature or the presence of hazardous gas concentrations), automatic actions can be triggered—such as turning on the fan. If manual mode is enabled, the user can directly control the fan from the graphical interface, by passing sensor input.

The code running on the ESP32 continuously listens to messages on the `factory/fan/control` topic and, depending on the current mode (automatic or manual), determines how the relay controlling the fan should respond. After each action, the device sends an update with the current fan status to the `factory/fan/state` topic, allowing Home Assistant to reflect changes in real time.

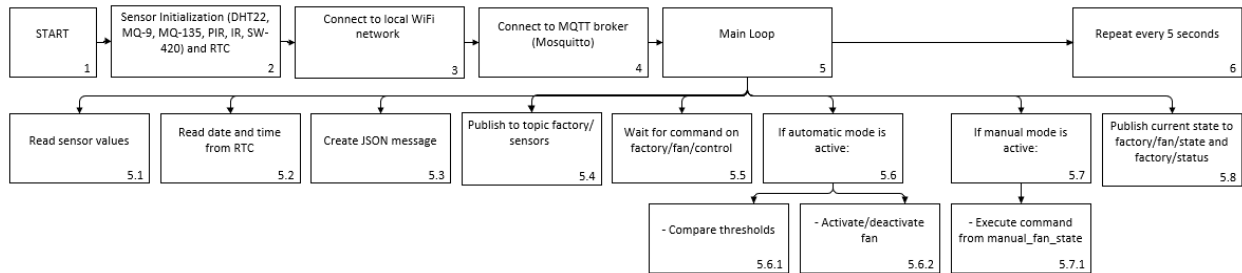


Fig. 3 ESP32 Flow Diagram

## 4. Model testing

After connecting all the components, I continued with the testing phase to determine if the model operates as expected. I wanted to check if the ESP32 correctly receives the information from the sensors, transmits it via MQTT [4] and that the Home Assistant presents it and reacts appropriately, especially in relation to the fan control.

I performed the tests in a simple environment, without internet access. I configured the router to use static IPs for all devices: the ESP32 board, the Mosquitto server and the Home Assistant. This way I prevented connection difficulties.

### 4.1. MQTT connection check

As soon as the ESP32 [1] is activated, it connects to the local network and then to the Mosquitto server [10] running on a virtual machine. I checked in MQTT Explorer [16] whether messages are being sent and noticed that every few seconds, a new message appears in the factory/sensor's topic. Inside it, all the sensor values are included: temperature, humidity, gas level, motion, vibration and the current time. The JSON format is clear and easy to understand.

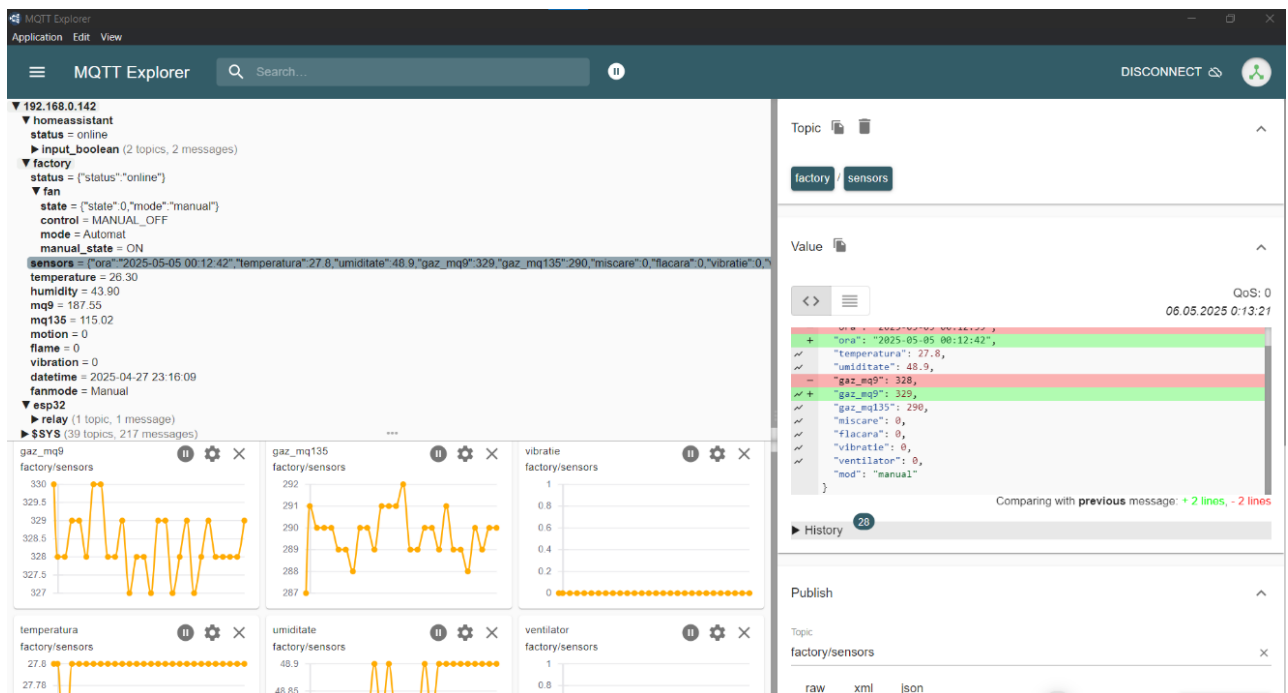


Fig. 4 Data Transmitted via MQTT Explorer

## 4.2. Sensor operation check

I tested each sensor separately:

- The DHT22 was brought close to a hair dryer, and the temperature increased significantly in Home Assistant [5].
- On the MQ-9 [14] and MQ-135 [15], we used a lighter to simulate smoke or gas, and the values increased rapidly.
- On the PIR sensor, we waved our hand in front of it, and it responded instantly.
- The vibration sensor was activated when I touched the worktop.
- The RTC module [11] transmitted the correct time in the message emitted by ESP32 [1].

All sensors reacted appropriately to the evaluated stimuli, without delays or failures.

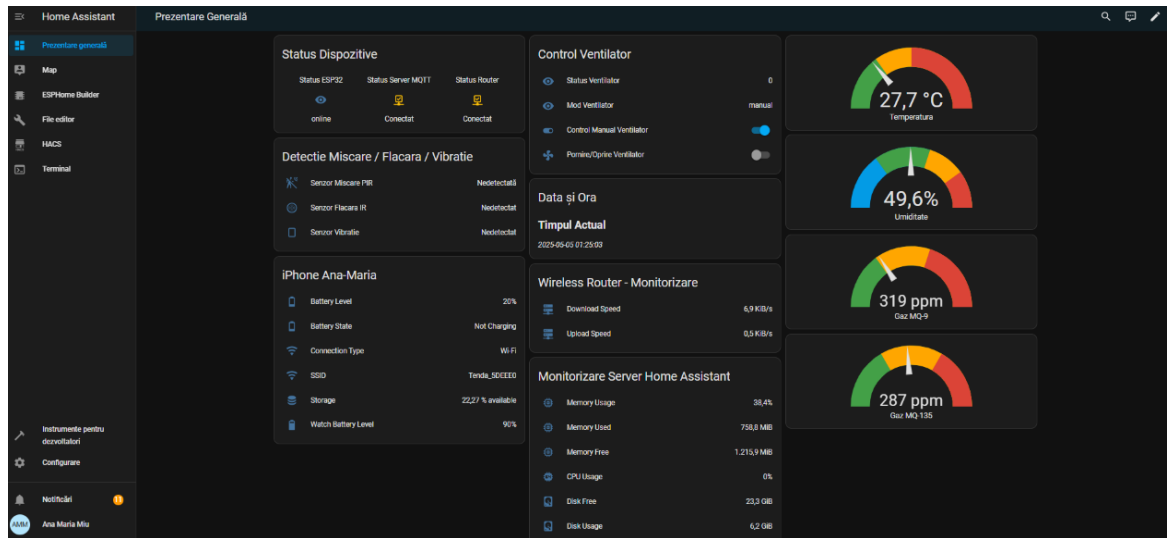


Fig. 5 Home Assistant Control Panel Visualization

## 4.3. Logical verification of fan control in the stages: automatic and manual

In Home Assistant [5] we configured a few simple rules: if the temperature exceeds 30°C, the fan is automatically activated. Also, if the gas concentration is increased. We recreated these conditions, and the system responded correctly – the fan turned on and the interface indicated its status.

I also tried the manual option. I pressed the `manual_override` button in the interface, and the automatic logic was disabled. Then we were able to turn the fan on and off manually, regardless of what the sensors indicated. ESP32 [1] correctly identified the commands and returned to Home Assistant with the status (ON or OFF).

## 4.4. Current limitations and improvements for the future

The local network, created with a Tenda router and without internet access, facilitated efficient communication between all devices. Fixed IPs were beneficial to prevent conflicts and maintain order.

The only component that is not yet complete is the 3D housing. I designed it in SolidWorks [6], and I plan to do this in a future stage, to obtain an integrated model, easy to transport and well physically protected.

In the current version of the project, the MQTT broker is established with user authentication and password, thus providing an unprecedented level of security against access [16]. This simple but effective operation ensures that only authorized and recognized devices can send or receive network messages.

In the future, I plan to investigate more deeply the security testing of the created IoT network. I plan to use Wireshark to monitor MQTT traffic and analyze the types of data circulating on the network, how exposed they are without TLS, and whether the authentication method used provides real protection. I will also use MQTT Explorer to study the system's reaction in case of a connection attempt with wrong or inappropriate data.

I planned to perform a simulation of a controlled mini-network attack, sending unauthorized messages to MQTT topics from an unregistered client, to check whether the broker rejects them and how the system reacts. This experiment will give me the opportunity to highlight in practice the level of isolation and defense of my local IoT network.

I want to include external notifications (email or phone), so that the system notifies users, even if it is not connected to the home assistant. To this end, I will implement support for logging data in InfluxDB and display it in Grafana, which will facilitate historical analysis and identify certain patterns.

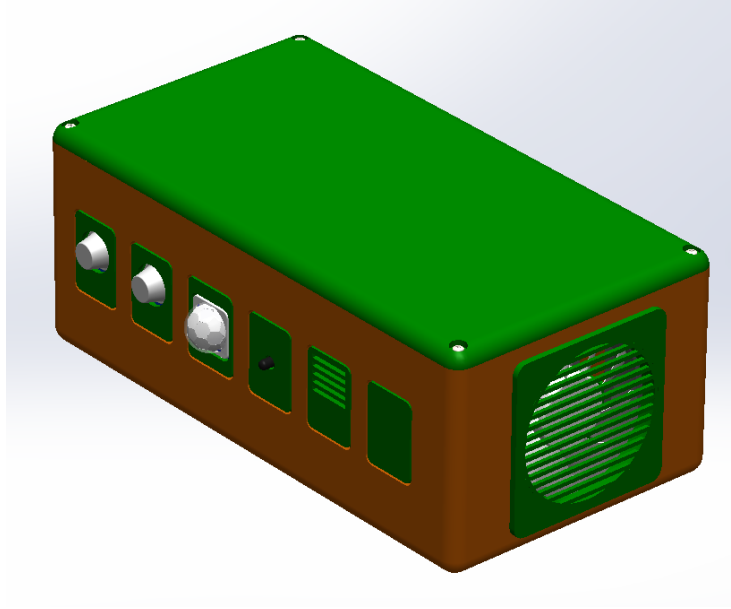


Fig. 6 3D View – 3D-Designed and Assembled Enclosure

## 5. Conclusions

The completed project demonstrated that it is feasible to create a functional industrial IoT model using accessible resources and without requiring an internet connection. By using the ESP32 microcontroller, appropriate sensors, and a communication system based on MQTT [4], I was able to monitor and manage environmental parameters in real time within an experimental space.

Home Assistant [5], installed on a dedicated virtual server, enabled clear visualization of the data and efficient configuration of automations, such as the automatic activation of the fan at critical temperatures. The RTC module [11] ensured stable time readings, and the automatic/manual logic allowed the testing of various scenarios, with accurate results in both modes.

From a hardware perspective, the system was safely powered through voltage converters, with a common GND, which protected the components from overvoltage. All the

tests performed confirmed consistent and reliable operation. In addition, the 3D model of the casing was created and is scheduled to be printed to complete the physical assembly.

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## 7. Notations

The following notations were used in the preparation of the presented work:

T – Temperature [°C]

H – Relative Humidity [%]

MQ-9 – Flammable Gas [0–1023 ADC]

MQ-135 – Air Quality [0–1023 ADC]

PIR – Motion Detection [0/1]

RTC – Real-Time Clock [hh:mm:ss]

VCC – Positive Power Supply Voltage [V]

GND – Ground (Common)

NO – Normally Open Contact (relay)

COM – Common Terminal (relay)

JSON – Structured Message Format (JavaScript Object Notation)

MQTT – Publish-Subscribe Communication Protocol

ESP32 – Microcontroller with Integrated Wi-Fi

3D – Three-Dimensional Modeling (casing designed in SolidWorks)

IoT – Internet of Things (interconnection of smart devices)

IP – Internet Protocol

## EXPERIMENTAL RESEARCH ON THE DESIGN AND IMPLEMENTATION OF A MOBILE ROAD SAFETY BARRIER

**CHIRVASIU Cosmin-Mihai și TARBĂ Ioan – Cristian(Conducător științific)**

Faculty of Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering,  
Year of study: IV, e-mail: cosmin.chirvasiu@stud.fiir.upb.ro

*Abstract: The thesis is based on an intelligent method of restructuring parts of traffic flow depending on the incidents encountered. It works as a movable wall that can shift in different directions and it can be used flexibly, creating a safe working area through quick and simple operation. This automated traffic wall offers a better and safer method of separating traffic from the road work area compared to traditional open barriers like traffic cones or additional signs. Moreover, it is a more efficient solution that saves plenty of time being easy to assemble, transport and use due to its ability of being controlled by a joystick tablet. It is clearly a fast way to finish an incident, because the wall can move during the operations.*

*Keywords: movable wall, traffic flow, safe working area, joystick tablet, automated traffic wall.*

### 1. Introduction

In recent years, road traffic has become a major problem in terms of congestion and interventions for road maintenance or repair must be resolved quickly, efficiently and safely, both for workers and for traffic participants. For this reason, the need for modern solutions that allow the temporary delimitation of work areas, without completely blocking the traffic. The mobile road barrier represents a temporary traffic wall whose main purpose is to separate traffic from the worker's operational area and to restructure traffic flow based on the incidents of the roads.

The aim of this project is to design and develop an experimental model of a mobile road barrier, capable of being quickly assembled and controlled by a remote method such as a mobile application. Each barrier segment includes a robot capable of supporting the entire structure and being operated by a worker to move according to traffic incidents, offering a highly flexible and fast method of restructuring traffic.



Fig 1. Interior of the mobile barrier

The concept idea started from the desire to create a functional experimental model inspired by the few existing models, such as the one developed by Mobile Barriers, which is based more on a “wall trailer” transported by a truck. This system is very equipped for roadwork, even using a crane for situations that require moving large objects. However, it is quite bulky and difficult to maneuver compared to the initial idea envisioned for a more compact and flexible solution.

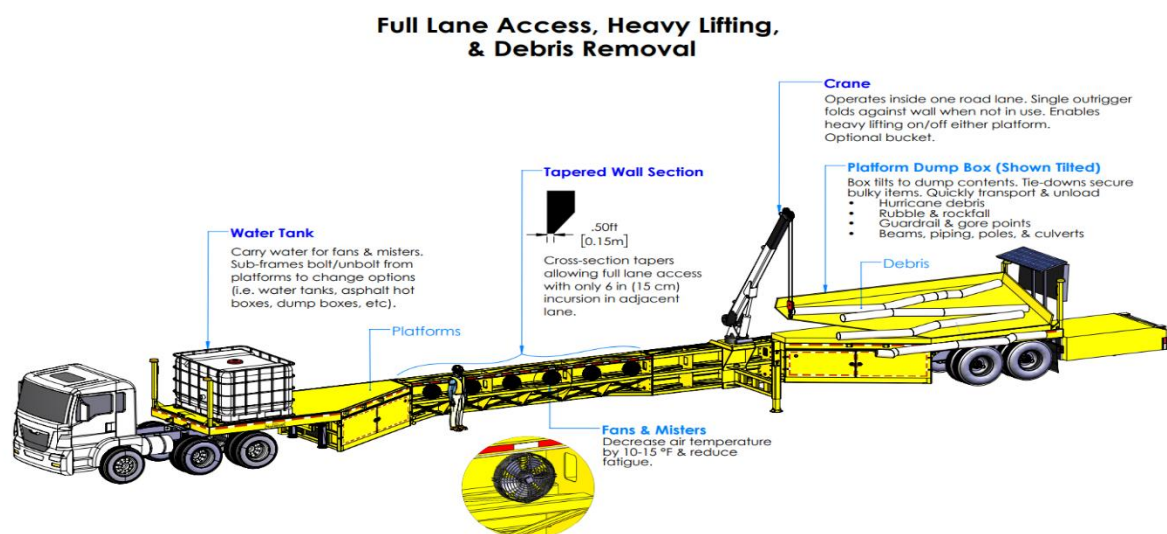


Fig 2. Traffic barrier concept [1]

### Presentation of a Barrier Concept

Another slightly more advanced method is the mobile barrier developed by Schneider, which is more of a movable mobile barrier, operated via a control panel by an operator. However, it is limited to a set of predefined movements.

The most advanced and efficient version of a mobile barrier is, without a doubt, GoBarry, an intelligent, safe and effective traffic barrier that can be easily operated using a remote control. [2]

“Using GoBarry means that work zones are shorter and less time is wasted on moving barriers. The greatest advantage is, of course, the significant increase in safety for both road

workers and traffic participants. This is because GoBarry enables work operations that previously had to be carried out behind open barriers (cones/beacons).” [3]

## 2. State of the art

This project focuses on the development of an experimental model of a mobile road barrier, designed to be safety and flexibility in traffic management. The project highlights the replication of the modern “GoBarry” traffic barrier solution.

### Main Components:

- **Mechanical Subsystem:** Each segment of the barrier is mounted on a 2WD robotic chassis, which ensures its movement. The barrier’s housing is manufactured using 3D printing and is divided into segments.
- **Electrical Subsystem:** Each segment includes an ESP32 WROOM kit with a TB6612FNG motor driver, allowing individual motor control. Power is supplied via 3.7V 18650 batteries.
- **Control Subsystem:** Segment synchronization is achieved through ESP-NOW wireless communication, enabling automatic coordination and alignment. The entire system can be controlled using a mobile application or a remote control.

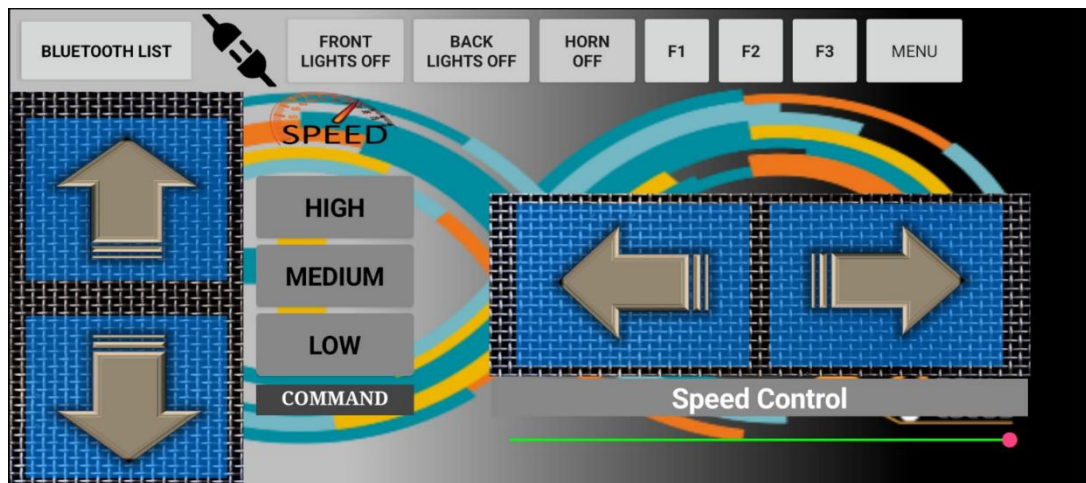


Fig 3. Example of control application interface

### Operating Mode:

The project will consist of three segments in total. Each segment moves independently but remains synchronized with the others, maintaining proper alignment through a dedicated control algorithm.

HC-SR04 ultrasonic sensors detect obstacles and adjust each segment’s trajectory to prevent collisions.

Synchronization between segments is achieved through a wireless network, either via Bluetooth with ESP-NOW, ensuring fast response and efficient control of the entire system. For now, the experimental model is approximately 70% complete, excluding the full testing phase of the entire system. The main elements achieved so far include the design of several components and the partial assembly of the robots that will support the barrier.

**Next Steps:**

1. To assemble the electrical systems on all robots
2. To develop the customized robot control application
3. Perform minor adjustments to the casing for more efficient 3D printing
4. Make small modifications related to assembly constraints

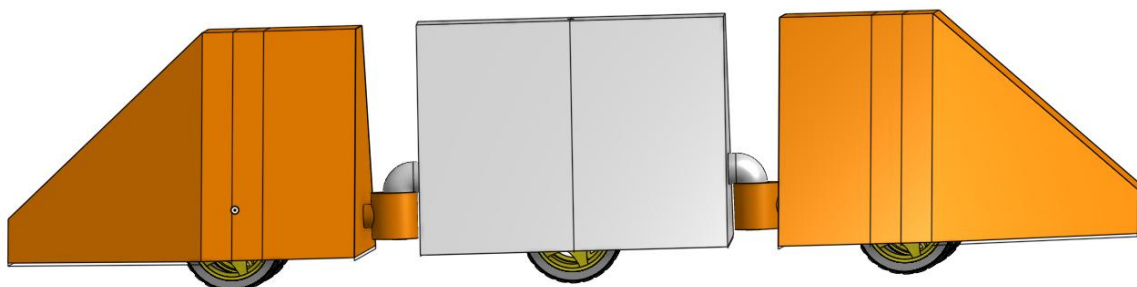


Fig. 4. Mobile road barrier design

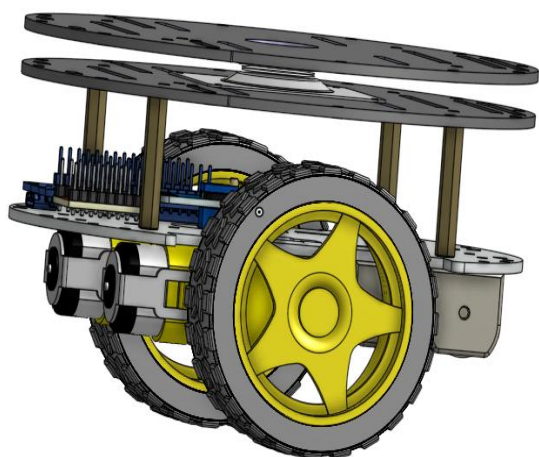


Fig. 5.1. 2WD car chassis robot

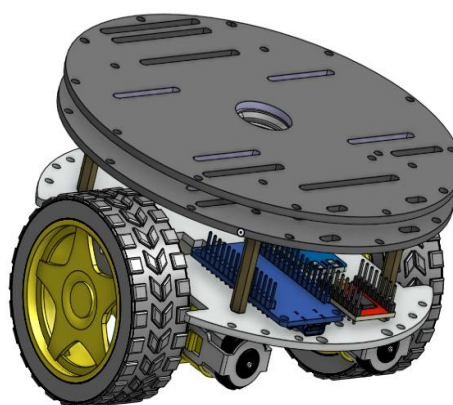


Fig. 5.2. 2WD car chassis robot

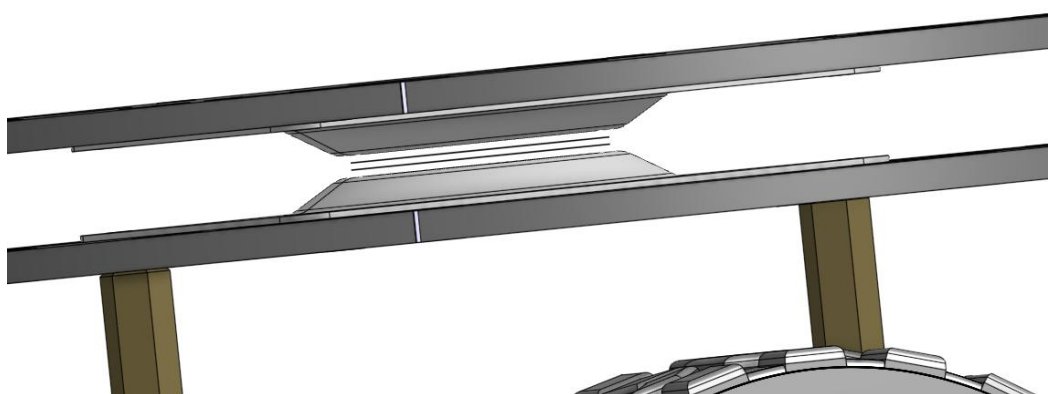


Fig. 6. The bearing between the robot and the barrier case

To connect the barrier case to the chassis robot in a way that allows it to turn in different directions, a bearing will be used. This bearing will be attached to the robot's circular plates, which are perforated at 30-degree intervals along their edges so we can use screws into these holes to act as stoppers, limiting the turning angle based on specific needs and the physical constraints of the barrier structure.

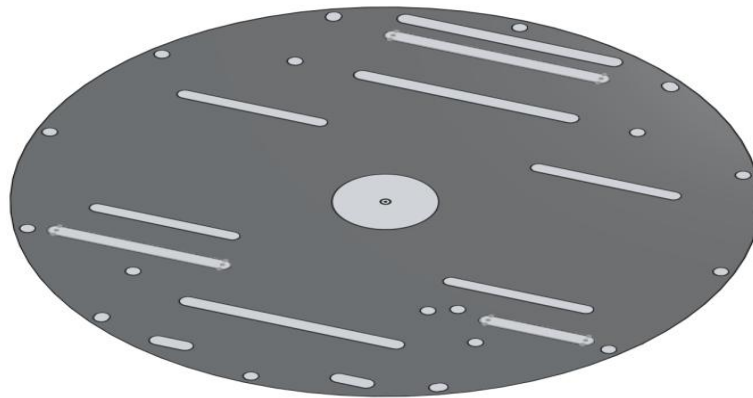


Fig. 7. Connector-disc between the housing and the robot

### 3. Conclusions

The project has proven to be not only feasible but also practical in terms of the need for modernization and intervention in road infrastructure, through the construction of an experimental model of a mobile road barrier. By integrating accessible and efficient components such as the 2WD car chassis, ESP32 board, and HC-SR04 ultrasonic sensors we successfully created a functional experimental model capable of controlled movement and replicating the behavior of a real mobile barrier system.

This system presents a viable alternative to traditional work zone delimitation methods, offering a safer, faster and more user-friendly solution. The barrier can easily adapt for various field scenarios, including closed spaces such as bridges or tunnels.

The project also identified a number of challenges, particularly related to movement stability, power autonomy and the efficient design of the housing and electrical assembly. These aspects can be improved in the future by using higher-quality electrical components.

In conclusion, the system makes people's lives easier by saving time thanks to the viable mobile barrier system that can adapt to different traffic incidents.

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## RESEARCH ON AN EXPERIMENTAL MODEL FOR MONITORING AND CONTROLLING FARM ENVIRONMENTAL PARAMETERS

**BATALAN Andreea-Beatrice și TARBĂ Ioan-Cristian (Conducător științific)**

Faculty: Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering,  
Year of Study: 4, e-mail: andreea.batalan@stud.fiir.upb.ro

*Abstract: This paper explores the design of an experimental model for monitoring and controlling environmental parameters in an automated farm using an ESP32 microcontroller. The system integrates sensors (temperature and humidity, water level, air quality) and actuators (water pump, relay, LED, buzzer, DC fan, servomotor) for dynamic management. A web-based application enables real-time data visualization and remote control. Custom 3D-printed supports enhance system stability. Results highlight the potential of IoT in smart farming, improving efficiency and sustainability.*

*Keywords: IoT, smart farming, ESP32, sensors, actuators, automation, environmental monitoring, web application.*

### 1. Introduction

Modern agriculture faces significant challenges, such as global population growth, climate change, and the need to produce more resources with a reduced environmental impact. In this context, automation and IoT (Internet of Things) technologies play a critical role in transforming traditional agricultural practices into intelligent, efficient, and sustainable systems [1]. Livestock farms, particularly those for cattle, require constant monitoring of environmental parameters such as temperature, air quality, and water availability to ensure animal welfare and maximize productivity.

This paper proposes the development of an IoT system for automating a cattle farm by integrating sensors for monitoring environmental parameters, actuators for controlling devices, and a web application for data management and remote control. The system uses an ESP32 microcontroller, which enables Wi-Fi communication and real-time data processing [2]. Additionally, the system includes mechanical components designed in CAD software for optimal sensor positioning, a database for user authentication and data storage, and feedback mechanisms (LED, buzzer, LCD display) to signal anomalies.

This system addresses the current needs of precision agriculture and contributes to reducing resource consumption by automating manual processes. By integrating modern technologies, the proposed model has the potential to improve animal living conditions, reduce operational costs, and facilitate data-driven decision-making in real time.

### 2. Current State

The current state of cattle farm automation reflects a gradual transition toward modern technology-based solutions, driven by the need to improve efficiency and sustainability in agriculture. According to recent studies, manual monitoring of environmental parameters remains predominant in many traditional farms, leading to human errors and inefficient resource use [1]. However, the adoption of IoT technologies has begun to gain traction, offering systems capable of collecting real-time data and automatically controlling actuators such as pumps, fans, and windows [4].

Specialized literature [1] indicates that existing systems frequently use microcontrollers like the ESP32 for data processing and wireless communication, integrated with sensors such as the DHT11 for temperature and the MQ-135 for air quality [4]. However, practical implementations are limited by high costs, lack of Wi-Fi infrastructure in rural areas, and the need for precise sensor calibration.

Globally, precision agriculture has advanced through the integration of databases for data storage and web applications for remote monitoring, but adapting these technologies to the specific conditions of cattle farms in Romania remains a challenge due to climatic variations and limited resources [2]. Thus, the current state highlights significant potential for automation but also a series of obstacles requiring innovative and tailored solutions to meet local needs.

### **3. Objectives and Purpose of the Experimental Model**

Establishing the project's objectives is a critical step in defining a clear direction for developing an IoT system dedicated to farm automation. This chapter outlines the main goals of the system, explaining how each objective contributes to creating an integrated solution capable of addressing the specific needs of modern agriculture.

The system's development was focused on ensuring accurate monitoring of environmental parameters essential for maintaining animal health and optimizing productivity. The system integrates specialized sensors for temperature, water level, and air quality, each selected to provide precise, real-time data. The temperature sensor monitors thermal variations, preventing the risks of heat stress that can reduce milk production or affect animal health. The water level sensor oversees reservoirs to ensure a continuous supply, necessary for proper hydration. The air quality sensor detects ammonia and carbon dioxide concentrations, critical values for assessing ventilation and maintaining a safe environment. Together, these components create an interconnected monitoring network that provides essential data for the automated and efficient operation of the farm.

Another key objective is the implementation of automated control of farm equipment to reduce manual interventions and optimize resources. The system uses a relay to control the water pump, a servomotor to adjust window openings, and a DC motor to operate a fan. Actuators are activated based on sensor data, enabling rapid responses to environmental changes. For example, exceeding the 20 ppm ammonia threshold automatically triggers the opening of a window and the activation of a fan, helping to restore air quality.

A current project objective is the development of a web application that will enable real-time parameter monitoring and remote device control via wireless connection. The application will include a secure authentication system based on a database and provide an intuitive interface for displaying sensor values and manually controlling actuators, enhancing system flexibility and accessibility.

The project also aims to implement a real-time feedback system. An LCD display will show sensor values, while an LED and buzzer will signal when critical thresholds are exceeded (e.g., temperature above 25°C or ammonia above 20 ppm), enabling rapid interventions.

For operational flexibility, the system includes manual intervention options via dedicated buttons, allowing direct control of the pump, fan, or window in case of sensor malfunctions or special situations.

The mechanical design of sensor supports complements the system's architecture, ensuring component protection and optimal positioning. The 3D models, created in CAD software, are designed to shield electronic components from moisture and dust, tailored to farm operating conditions. This aspect underscores the importance of integrating mechanical engineering into IoT system development, where all components must function harmoniously.

By combining these objectives—precise monitoring, automated control, ongoing web application development, real-time feedback, manual intervention, and mechanical design—the project aims to deliver a complete IoT solution for optimizing agricultural processes and improving animal rearing conditions.

#### 4. Technologies Used and System Description

Selecting appropriate technologies is a critical step in developing a functional and efficient IoT system. This chapter details the hardware and software components used to create the farm automation system, highlighting the role of each in the overall architecture. Each component was chosen to meet reliability and efficiency requirements in farm-specific conditions.

##### 4.1. Hardware Components

Hardware components are essential for data collection, device control, and real-time feedback in an IoT system designed for farm automation. These include a microcontroller for processing, sensors for monitoring environmental parameters, actuators for automated control, and auxiliary components for user interaction [2].

- **ESP32 Board:** A microcontroller with Wi-Fi and Bluetooth capabilities, used as the central processing unit. It processes sensor data, controls actuators, and provides wireless connectivity for communication with the web application [2].



Fig. 1. – ESP32 Microcontroller

- **Sensors:**
  - **Temperature Sensor (DHT11):** Measures temperature and humidity, essential for monitoring thermal conditions and preventing heat stress in cattle [4].
  - **Water Level Sensor (T1592):** Detects water depth in reservoirs, ensuring a constant supply for animal hydration [4].

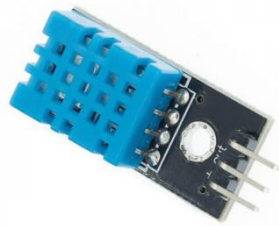


Fig. 2 - Temperature and Humidity Sensor



Fig. 3 - Water Level Sensor

- Air Quality Sensor (MQ-135): Measures ammonia and CO<sub>2</sub> concentrations, critical parameters for maintaining proper ventilation in the farm [4].



Fig. 4 - Air Quality Sensor

- Actuators:

- 5V Relay: Controls the water pump, enabling automatic or manual activation of water supply based on detected levels [2].
- Servomotor: Adjusts window opening and closing for ventilation, contributing to air quality maintenance [2].

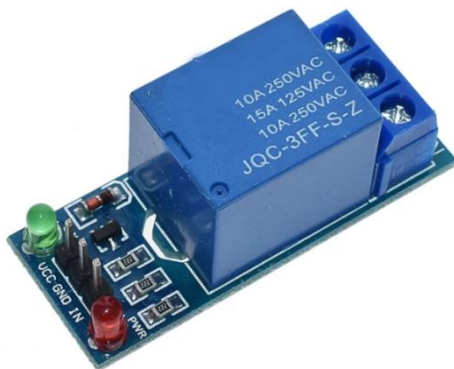


Fig. 5 - 5V Relay Module



Fig. 6 – Servomotor

- DC Motor: Operates the fan to ensure air circulation, essential when high ammonia or CO<sub>2</sub> levels are detected [2].
- Submersible Water Pump: Fills water reservoirs, activated by the relay when water levels fall below the optimal threshold [2].



Fig. 7 – DC Motor



Fig. 8 - Submersible Water Pump

- Auxiliary components:

- LCD Display (1602): Displays sensor values in real time, providing direct feedback to the user [4].
- Button: Enables manual control of actuators, offering flexibility in system management [4].



Fig. 9 – LCD Display



Fig. 10 – Button Module

- LED Module and Passive Buzzer: Signals visual and audible alerts when parameters exceed critical thresholds, enhancing system safety [4].



Fig. 11 - LED Module



Fig. 12 - Passive Buzzer

## 4.2. Software Components

The software used plays a crucial role in programming, managing, and monitoring the IoT system, facilitating communication between hardware and the user. These include development environments for the microcontroller, user interface platforms, database systems, and CAD tools for mechanical design [3].

- Arduino IDE: Used for programming the ESP32 microcontroller, providing an accessible environment for developing code to read sensors and control actuators [2].
- Visio: Used to create system diagrams, facilitating the visual representation of the architecture and hardware connections [5].
- SolidWorks: CAD software used for designing sensor supports, offering advanced tools for 3D modeling and component strength simulation [3].
- Microsoft Project: Used for planning and detailing the production of mechanical supports, providing efficient resource and stage management [6].
- Z-Suite: Software dedicated to 3D printing, used for generating and optimizing G-code files needed to produce the designed mechanical supports [7].
- Grafana: A data visualization and analysis platform, evaluated for real-time display of monitored parameters, with its use still under consideration [8].

## 5. Project Development Process

To ensure the project's success, the research was structured into clear stages, combining theoretical analysis with practical implementation. This chapter describes the methodological approach, from literature review to planning the web application development.

The research began with an analysis of specialized literature on agricultural automation and IoT technologies. Scientific articles and similar projects were studied to identify the most effective monitoring and control solutions [1].

The system design was carried out in several stages, each contributing to the development of an integrated solution:

- a) Connection Diagram Development: Creating an electrical schematic for connecting sensors, actuators, and auxiliary components to the ESP32 microcontroller, using Visio software.

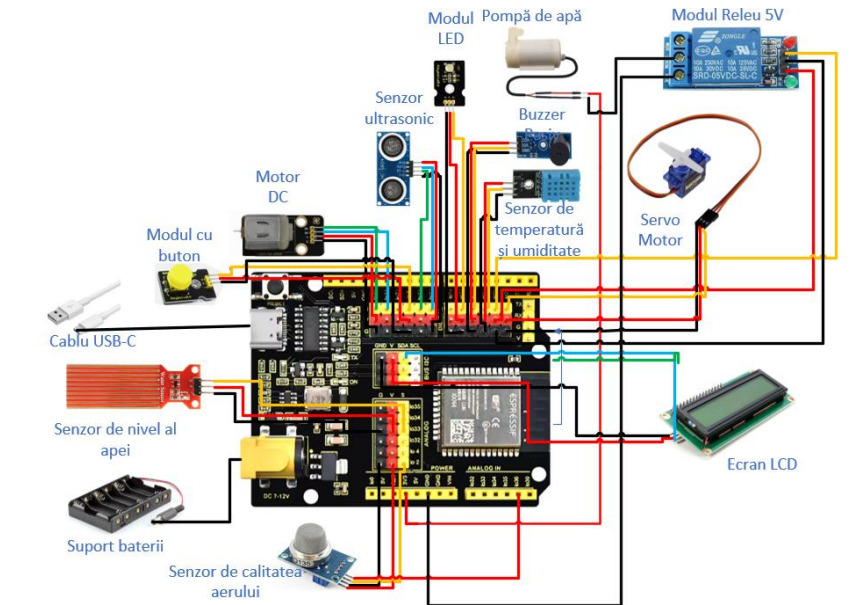


Fig. 13 – System Connection Diagram

- b) Mechanical Support Design: Creating 3D models for sensor supports using SolidWorks CAD software. These were designed to protect electronic components from moisture and dust, optimized for farm conditions.
- c) Software Development: Programming the ESP32 microcontroller in Arduino IDE to read sensor data, control actuators, and ensure communication with the web application.
- d) Preliminary Testing: Verifying the functionality of each module (sensors, actuators, application) through preliminary tests. Sensor accuracy and actuator responses to basic commands were tested, including simulating environmental conditions (e.g., high temperatures, low water levels) to observe system reactions.

Web Application Development Planning: Creating a simple interface using the microcontroller's web server is planned for a future project stage. The application will include secure authentication and real-time data display, enabling remote farm parameter monitoring.

## 6. Preliminary Results

Testing the components and integrated system is a crucial step in validating functionality. This chapter summarizes the results obtained from preliminary tests, comparing measured values with optimal ranges established through research.

To date, component testing has been completed. The temperature, humidity, water level, and air quality sensors function correctly, providing accurate data. The table below presents the optimal values established through research and the sensors' measurement ranges.

Table 1. Optimal Environmental Parameter Values

| Measured Parameter | Measurement Range | Optimal Values |
|--------------------|-------------------|----------------|
| Temperature        | -20°C - 50°C      | 5°C - 25°C     |
| Humidity (THI)     | 20-90 THI         | <68 THI        |
| Ammonia Level      | 0-20 ppm          | <10 ppm        |
| Carbon Dioxide     | 0 ppm - 5000 ppm  | <3000 ppm      |

|             |         |        |
|-------------|---------|--------|
| Water Level | 0-30 cm | 0-5 cm |
|-------------|---------|--------|

## 7. Conclusions

This project aims to develop an IoT system for automating a livestock farm, integrating sensors, actuators, and an ESP32 microcontroller to monitor and control essential environmental parameters. Several critical project stages have been completed, demonstrating the feasibility of the proposed solution.

Hardware integration has been finalized, connecting sensors (DHT11, T1592, MQ-135) and actuators (relay, servomotor, DC motor) to the ESP32 microcontroller, enabling temperature, water level, and air quality monitoring. The connection schematic was developed using Visio, and sensor supports were designed in SolidWorks, prepared for 3D printing. Preliminary tests confirmed system functionality, with sensors recording values within optimal ranges. These stages align with precision agriculture goals, reducing the potential for human error and optimizing environmental conditions for animals.

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## DESIGN AND DEVELOPMENT OF AN EXPERIMENTAL MODEL FOR TESTING FK7A PNEUMATIC SEMI-COUPPLINGS

**SIMUȚ Alexandru și SAVU Tom (Conducător științific)**

Faculty of Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering,  
Year of study: IV, e-mail: alexandru.simut@stud.fiiir.upb.ro

*Abstract: The paper proposes the development of a test stand for an air semi-coupling used in railway pneumatic systems. The stand will integrate an STM32 controller with a graphical display, data saving on a MicroSD card, and real-time graphical display of system pressure. Additional functionalities include RFID authentication and sensor-based monitoring.*

*Keywords: pneumatics, STM32, SPI, RFID*

### 1. Introduction

The work aims to develop a technical solution for testing the tightness of air semi-couplers used in the construction and operation of railway rolling stock (locomotives and wagons). The project aims to evaluate the coupler's performance under controlled conditions, using modern embedded systems for control, acquisition and data storage.

The air coupler is used to connect the pneumatic braking system between the locomotive and the wagons (fig. 1).



**Fig. 1 Coupling attached to locomotive**

### 2. Current status

At the moment, the STM32 controller and modules are soldered, wired on a THT PCB, (air pump, 2 relays, THT screen, pressure sensor, current sensor, temperature sensor for the pump, EEPROM module, SD card module, USB type C board for powering the project.)

On the software side, these components are implemented, and a graph representing the pressure sensor readings is generated on the screen, which are saved on the SD card.

At the moment the current sensor is mounted but not yet incorporated through software.

All parts are mounted on a wooden board, as an educational model.

### 3. Proposed solution

The project consists of creating a stand on which the semi-coupling will be mounted, tested at working pressure, and subsequently decompressed controlled by a solenoid valve. The

**Main components:**

## STM32 controller :

- digital (via the HX710B ADC converter that reads the pressure sensor) buses.

- **TFT display** : allows viewing the pressure in real time and displaying the pressure graph based on the values measured at each reading cycle (approximately every 100ms).

- **MicroSD** : saves test session data in text format (.txt), each line representing a pressure measurement.

- **RFID mode** : operator authentication; data is recorded in an external EEPROM that verifies the card ID.

- **Sensors :**
  - Air pressure (0-2 bar, analog read);
  - Thermocouple temperature;
  - Electric current;

- **Buzzer** : audible warning in case of error, such as rapid pressure drop below the set threshold.

The changes made to the MicroSD card module are presented in the following figures.

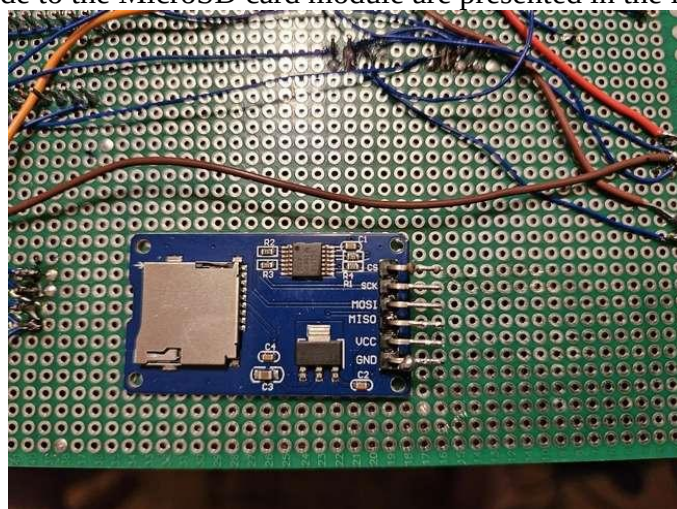


Fig. 2. Original shape of the MicroSD module

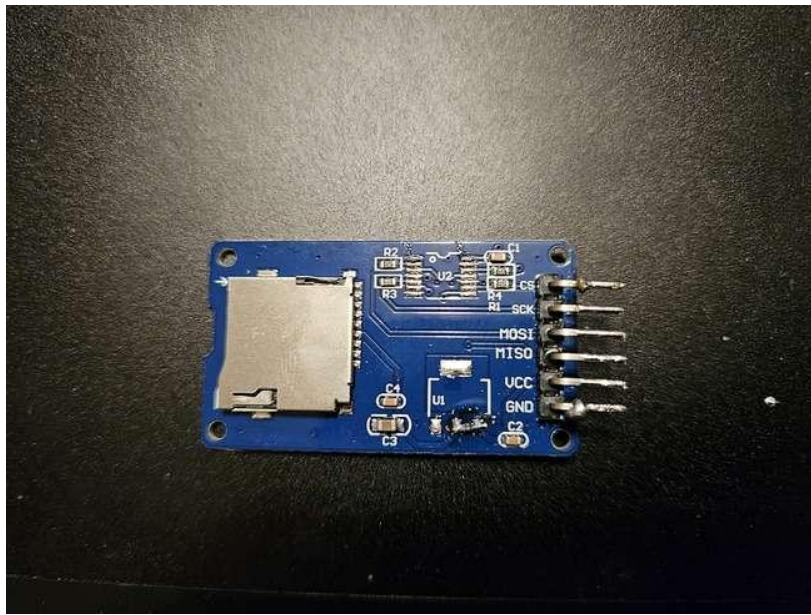


Fig. 3. Removing the voltage regulator and level shifter

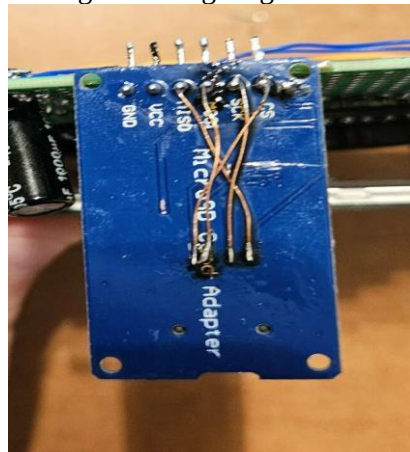


Fig. 4. Wires pulled to the back of the module to bypass the level shifter  
The final assembly of the test board is represented in figures 5-7.

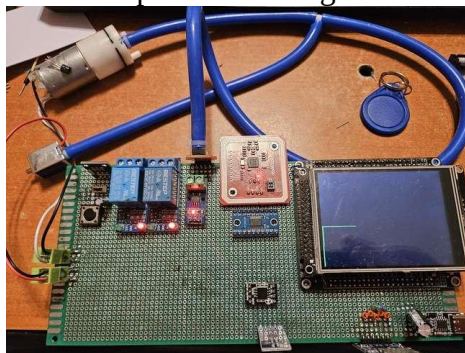


Fig. 5. Motherboard with mounted modules.



Fig. 6. TFT screen connected and functional.

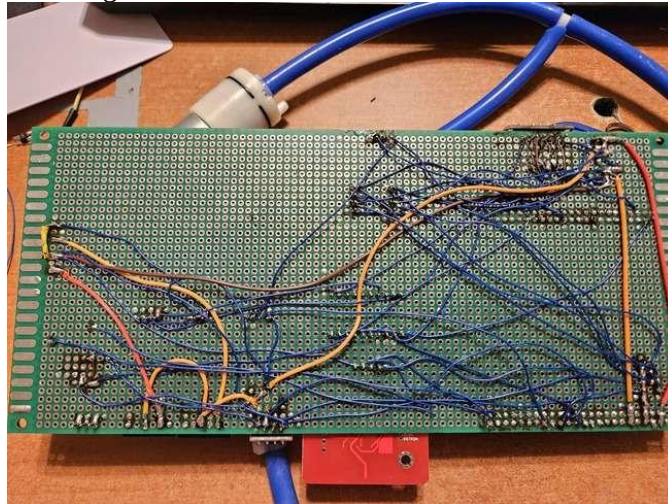


Fig. 7. Rear view of the complete wiring.

#### 4. System implementation

The system architecture is modular:

- **Control:** STM32 takes all inputs and outputs through dedicated protocols and graphically displays the data.
- **Authentication:** The RFID module communicates via UART; upon identification of a valid card, the system allows the initiation of testing procedures.
- **Graph display:** The pressure graph is made by plotting the points collected from the pressure sensor, forming a continuous monitoring curve.
- **Storage:** Data is saved sequentially on MicroSD in a single file, timestamped at test initiation.
- **Security:** The external EEPROM contains the ID of the allowed RFID card, verification being performed before each test session.
- **Pressure sensor calibration:** To establish the reference value (offset), an arithmetic average of 50 successive readings taken by the HX710B converter is used, according to the relationship:

$$baseline = \frac{1}{50} \sum_{i=1}^{50} citire_{HX710B}(i)$$

Where  $citire_{HX710B}(i)$  represents the pressure sensor reading value when taking a reading

Problems encountered: In the initial phase, the simultaneous use of the RFID module and the SD card generated conflicts on the SPI bus, leading to write/read errors. The problem is documented on the Arduino forum [1]. The solution adopted was to eliminate the level shifter that did not comply with the SPI communication protocol specification, eliminate the voltage regulator through the bridge, thus communicating with the SD card at the native level of the STM32 microcontroller.

**Workflow example:**

1. The operator authenticates with an RFID card.
2. The system starts the compressor, monitors the pressure.
3. Real-time display of the pressure graph, updated every 300ms.
4. The solenoid valve releases the pressure after a preset time.
5. Test data is saved on the MicroSD in a .txt file with timestamp.

The data recorded on the MicroSD card is illustrated in Fig. 8.



Fig. 8. Data saved on the MicroSD card - pressure values.

6. The system automatically warns via buzzer in case of abnormal pressure drop.

**5. Expected results**

- Automatic semi-coupled tightness testing.
- View and save pressure graphs.
- Secure data archiving for traceability.
- Automatic warning in case of errors by acoustic signal.
- Controlled and monitored access to the system via RFID.

**6. Conclusions**

The proposed project provides a modern, scalable and efficient embedded solution for testing railway air semi-couplers. Real-time graphical display of pressure and data saving provide traceability and transparency in the validation process. The use of an autonomous system based on STM32 reduces the dependence on external IT infrastructure.

**7. References**

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## RESEARCH REGARDING THE DESIGN AND IMPLEMENTATION OF A DOSING AND BOTTLING SYSTEM FOR COSMETIC PRODUCTS

CIOHODARU Miruna-Andreea și TARBĂ Ioan-Cristian(Conducător științific)

Faculty of Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering,  
Year of study: IV, e-mail: miruna.ciohodaru@gmail.com

**ABSTRACT:** *The proposal involves the development of an automated dosing and bottling system for cosmetic products, designed to reduce working hours and increase productivity. The entire process entails collecting empty, uncapped containers and moving them along a rotary element to be filled and sealed sequentially. To fulfil these functions, a series of electronic components were required, including stepper motors, a pump, a linear actuator, and sensors, all monitored by a microcontroller. The algorithm is developed based on sensor feedback, such as the presence of a container or the remaining material level in the reservoir.*

**KEYWORDS:** *pump, algorithm, sensor, filling.*

### 1. Introduction

This analysis examines the operation of a system designed for cosmetic products (in a liquid-viscous aggregate state), which fills and bottles colorless plastic containers. These containers are introduced and removed from the system using methods that do not involve motorized actuation, relying instead on gravitational force. The material is introduced into the containers via a peristaltic pump, followed by a cap placed on the top of the bottle, which is then assembled using a system featuring a linear actuator and a rotary motor.

### 2. Current State

The industry has evolved remarkably over time, successfully enhancing both the products and the techniques used, while reducing execution time by tens of times. Advanced automation technologies have been implemented to ensure the market release of high-quality products at the lowest possible production cost. Filling stations are designed to be easy to clean and resistant to corrosive substances, with pumps calibrated and programmed to prevent leaks or material losses. Traceability systems for batch and expiration date control have been integrated, along with continuous line monitoring using video cameras and flow sensors. Figure 2 illustrates an automated line for cosmetic products that meets current standards.

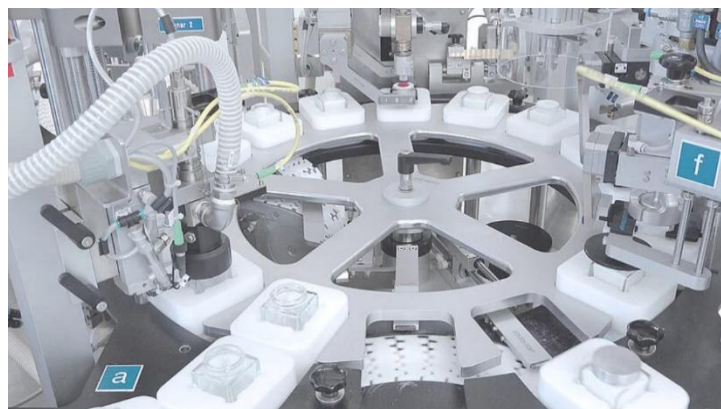


Figure 2. Filling station - Groninger Group

### 3. Prototype Design

The developed system requires stable support structures for each incorporated component, as they may generate vibrations, and the position of each plays a significant role in optimal functioning. In the case of the rotary platter, the decision on its final shape and design was made to ensure that the total mass, including the filled containers, is not excessively high, while the entire subsystem remains sufficiently robust. To transport the containers, the experimental model integrates a rotary table, selected based on specific considerations: the use of a single motor to drive it (unlike other options, such as conveyor belts), which reduces both energy consumption and algorithm complexity; and the compacting of the workspace, a crucial detail for factories. The components will be constructed using additive manufacturing methods (3D printing), except for assembly elements like screws and nuts, which will be made from various metal alloys. For cylindrical surfaces, a keyway joint was chosen to completely prevent accidental disassembly. The 3D model is presented in Figure 1.1.

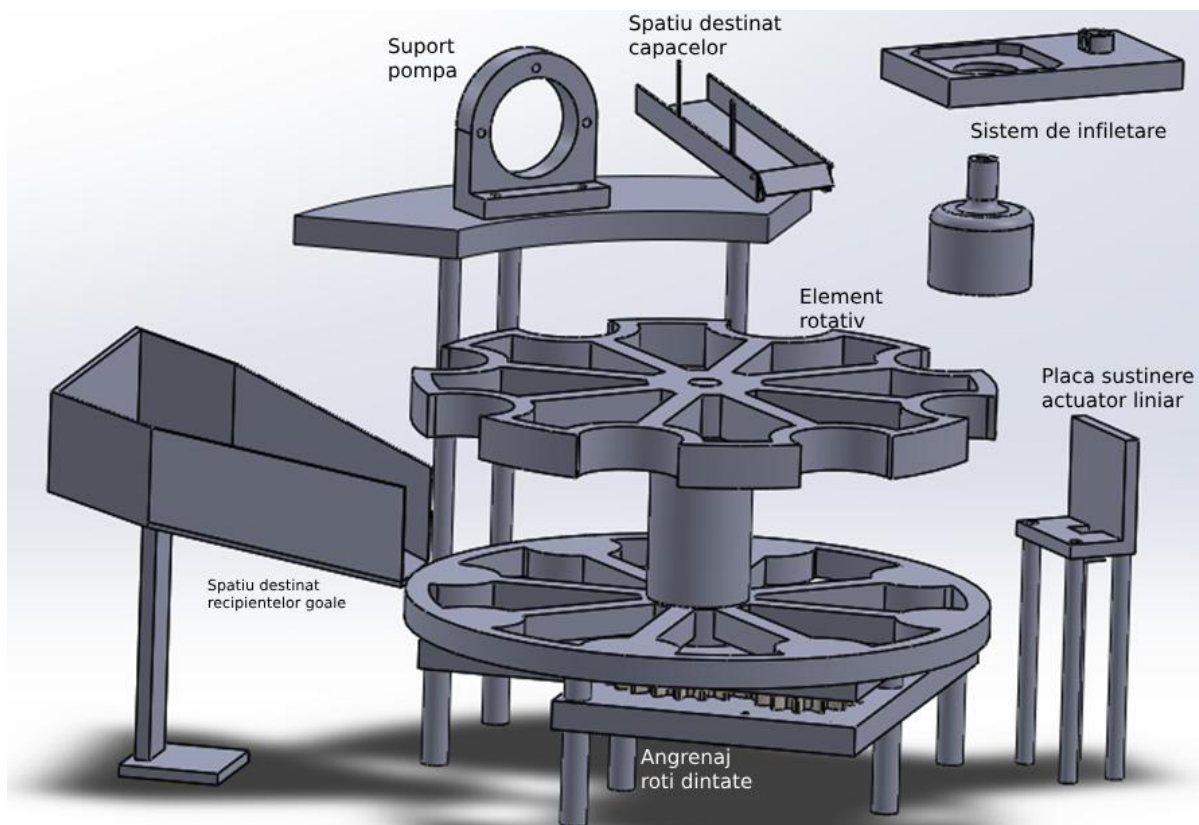


Figure 1.1. 3D Model of the prototype (does not contain electronic components)

The motion executed by the motor within the subassembly with the rotary element is supported by a gear system with two gear wheels. Its purpose is to increase torque, reduce motor vibrations, ensure smoother rotation, and protect the motor shaft from stresses such as the weight of the subassembly. A gear ratio of 1:2 was chosen, where the pinion has 12 teeth and the driven gear has 24 teeth, with a module of 2.5 and a tooth angle of  $14.5^\circ$ , as shown in Figure 1.2.

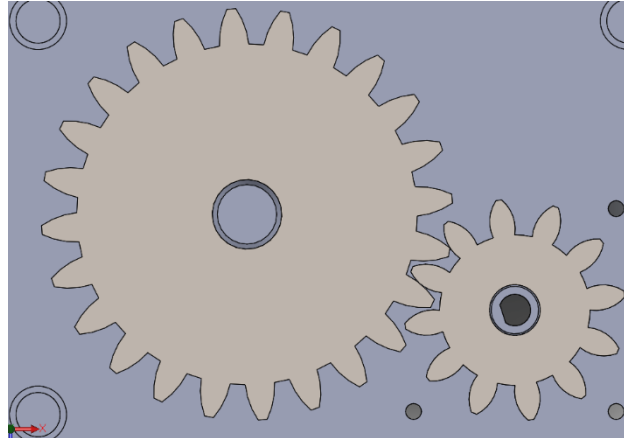


Figure 1.2. Gear system

### 3.1. Stepper Motors

The operating principle of an electric motor is based on converting electrical energy from a power source into mechanical energy. For rotary motors, this is achieved through coils that generate an electromagnetic field, causing the rotor to turn. Stepper motors follow the same principle, but the motion is sequential and very short, allowing the motor shaft to rotate with high precision (typically, one "step" is valued at  $1.8^\circ$ ). [1] The power supply is provided indirectly via a driver connected to a microcontroller and powered by a source, through the motor's four cables. These wires are labeled A+, A-, B+, B-, representing the motor coil poles, which are energized alternately to precisely control the segmented movements. The chosen motor is a NEMA 17, with a holding torque of 0.25 Nm, as shown in Figure 1.2.



Figure 3.1. Stepper Motor NEMA 17

### 3.2. Pumps

The type of material to be introduced into the containers, along with the flow rate and pressure, are the most critical factors in selecting the optimal pump for such a system. The viscosity of the material used in the developed system is approximately 15-20% higher than that of water, necessitating the use of a pump suitable for dense products. In the cosmetic and food industries, peristaltic pumps are the most commonly used due to the enhanced protection they provide to the substance, as it is transported exclusively through a tube, without contact with other surfaces. Another advantage is the low risk of component degradation, as they are

not subject to corrosion, and the only element that requires cleaning is the tube. All these factors extend the pump's lifespan, ensure trouble-free operation with minimal breakdowns, and significantly reduce equipment maintenance costs. The only drawback of this pump is its low flow rate, specifically a maximum of 150 ml/min for a small-sized pump suitable for the presented system. Considering the material's viscosity, this rate may decrease further. Based on (3), the approximate time required to fill a container with material was calculated. [2] Given the presented advantages and disadvantages of using a peristaltic pump, it was decided to incorporate such a component into the developed system, as it meets all the imposed requirements. Regarding the low flow rate, in a similar but larger-scale system, an appropriate industrial peristaltic pump can be used. For the current case, the filling time of a container is approximately equal to the time required for cap tightening, with both activities being performed in parallel. The operating principle of a peristaltic pump is illustrated in Figure 1.3.

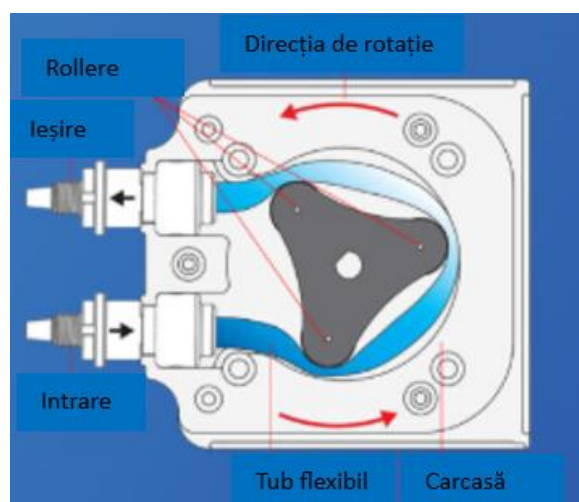


Figure 3.2. Peristaltic pump

### 3.3. Linear actuators

To facilitate the cap tightening process, it was observed that a combination of rotational and translational motion is required, synchronized to some extent, while ensuring that excessive pressure is not applied to the cap to prevent damage. To achieve this operation, the action of a stepper motor—for rotation—and a linear actuator—for translation—was combined. A linear actuator is a device that converts rotary motion into linear motion using various mechanical subsystems, such as a rack-and-pinion system, gears, or ball or trapezoidal screws. A motor inside the actuator rotates one of the subsystem components, which then transmits linear motion to an actuating rod. In the developed system, the linear actuator's role involves moving a support plate on which the stepper motor and its attached components are mounted, designed to precisely fit the shape and contour of the container's cap.

The selection of an actuator to perform this function correctly and fully was based on several criteria, including stroke - the maximum length the actuating rod can travel - force, and speed. Given the prototype's small dimensions, the selected actuator has a length of 157.5 mm, with an additional stroke of 100 mm, and a maximum load capacity of 96 N. According to (4) in Chapter 3, the actuator can safely lift and lower a maximum weight of 9.8 kg, which significantly exceeds the total mass of the subassembly that needs to be handled.

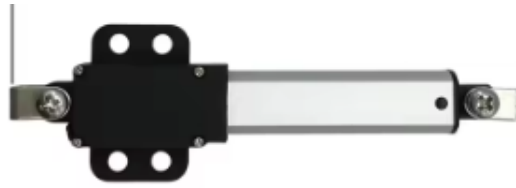


Figure 3.3. Linear actuator

### 3.4. Control and command of components

A dosing and bottling system for cosmetic products requires high precision and enhanced control of components, achieved through sensors, a microcontroller, and drivers. These checks are performed by sensors, whose signals are received and interpreted by a microcontroller, which then sends commands to motors, actuators, and pumps. Sensors are devices that process data from the external environment to be interpreted by the microcontroller, depending on the observed physical quantity. In a dosing and bottling system for cosmetic products, the position of the container and the remaining quantity (liquid, caps, containers) are of major importance. For both cases, proximity sensors were used—devices that utilize sound waves or light beams to detect the presence of an object in close proximity. The liquid level remaining in the tank was intended to be measured using a level sensor, but the increased viscosity hindered the functionality of such a sensor. Consequently, a proximity sensor was chosen instead, positioned above the tank, perpendicular to the liquid level line, with the remaining quantity calculated based on the measured distance.

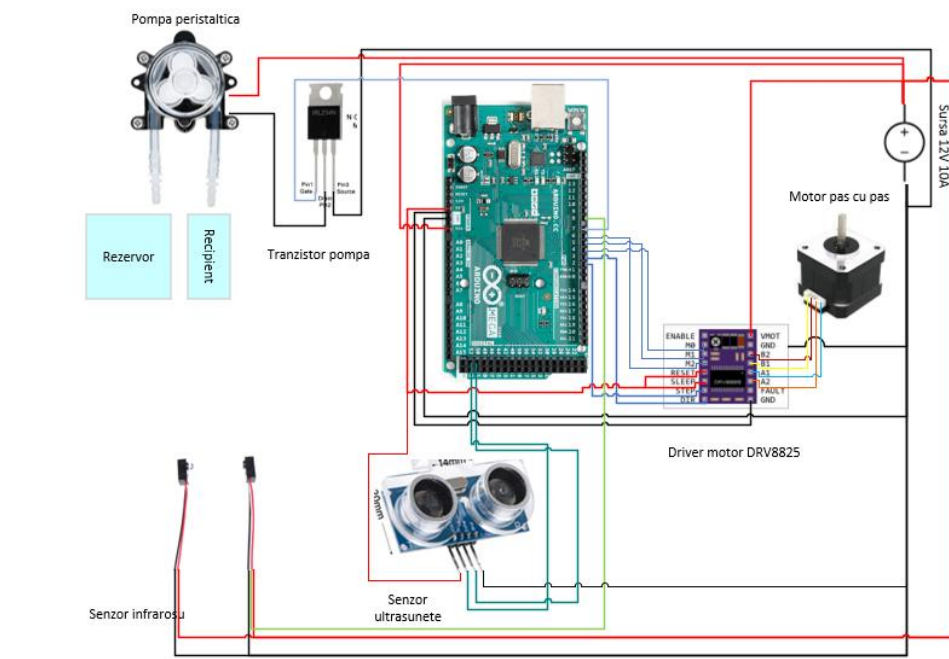


Figure 3.4. Wiring diagram for one subassembly

The motor, pump, and actuator were connected to the microcontroller through a series of drivers, which serve to convert the control signal and provide the appropriate voltage from the power source, while also protecting the component from potential short circuits or overheating. [3]

### 4. Formulas used

To select a suitable stepper motor for the developed system, a series of equations and formulas were utilized:

Determination of the Required Torque:

$$J = \frac{1}{4}mr^2 = \frac{1}{4} \times 0.641kg \times (0.1)^2 = 0.0016 kg \times m^2, J - \text{moment of inertia (1)}$$

$$T_{total} = J \times \frac{2 \times \theta}{t^2_{acc}} \times 2 = 0.0016 \times 6.28 \times 2 = 0.202 N \times m \quad (2)$$

Determination of the Container Filling Time

$$t = \frac{V}{Q} = \frac{2.5}{50} = 20s, Q - \text{flow rate (3)}$$

Determination of the Linear Actuator's Maximum Load

$$m = \frac{F}{g} = \frac{96N}{9.81m/s^2} = 9.785kg \approx 9.8kg \quad (4)$$

## 5. Conclusions

The development of a dosing and bottling system for cosmetic products placed significant importance on verifying the technical specifications of each component used, ensuring smooth process operation and compliance with requirements. Several options were considered, identifying needs and potential issues, as well as existing technologies. Initially, the containers, pump, actuator, and control devices were selected, as the dimensions and positioning of these components shape the overall assembly. Following the design of the subassembly including the rotary element, the motor was chosen. Tests, simulations, and potential adjustments were necessary to ensure the developed system met the initially specified requirements.

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## DEVELOPING AN AI-BASED WEB APP FOR ASSISTING ENGINEERS IN MECHANICAL DESIGN AND MANUFACTURING PROCESSES

**STAICU Andrei-Alexandru, TUNSOIU Nicolae,  
GHEORGHITĂ Vlad (Conducători științifici)**

Faculty: Industrial Engineering and Robotics, Specialization: Applied Computer Science in Industrial Engineering,

Year of study: III, e-mail: andyalexandru20045@gmail.com

***ABSTRACT:** This paper proposes an interactive platform based on artificial intelligence that revolutionizes the support provided to engineers in the design and manufacturing of mechanical parts. The system integrates advanced functionalities for calculating dimensional tolerances, generating optimal cutting parameters, simulating manufacturing costs, planning technological processes and configuring clamping devices. With an intuitive chatbot-based interface, the platform provides personalized answers, interactive diagrams and technical recommendations adapted to the context. By integrating precise engineering calculations with the capabilities of modern LLMs, the application facilitates decision-making, reducing design time and technological errors. This innovative approach transforms the way engineers interact with digital tools, providing complete support for the entire product development cycle, from conceptual design to manufacturing.*

**KEYWORDS:** Tolerances, Production, Efficiency, Industry, Optimizations.

### 1. Introduction

"The manufacturing industry is evolving rapidly, driven by artificial intelligence (AI). AI agents are redefining automation by enabling real-time decision-making, reducing operational costs, and increasing production efficiency. Unlike traditional automation, AI agents learn and adapt over time, making them indispensable for modern factories" [1].

"AI agents optimize production scheduling and resource allocation, significantly increasing output while reducing waste. For example, manufacturers using AI-based scheduling can dynamically adjust production deadlines based on real-time demand forecasts, leading to improved production processes and resource utilization" [2].

In the context of the evolution towards Industry 5.0, this paper presents an innovative application that uses advanced technologies for the digitalization of manufacturing and mechanical design processes. The application integrates a specialized AI agent solution capable of automating complex workflows and providing contextual assistance to engineers, thus contributing to the efficiency of industrial operations. Through this approach, the potential of AI agents to transform how engineering processes are conceived and implemented is highlighted, marking a significant step towards a smarter and more adaptable industry.

Currently, the market is dominated by multiple solutions based on large language models (LLMs), such as ChatGPT developed by OpenAI, Claude by Anthropic, Gemini by Google, and others. Although these models can provide useful answers to engineering questions, whether related to calculations or technical aspects, they operate predominantly based on probabilities, without guaranteeing compliance with engineering standards. Thus, even if the answers are sometimes correct, errors can also occur, which is problematic in a field where precision and adherence to standards are essential.

In this context, AI agents come into play, leveraging the power of LLMs to create specialized, standardized applications strictly focused on engineering needs. These agents not only reduce the risk of errors but also increase the efficiency, safety, and performance of engineering processes, transforming the way engineers approach technical tasks.

## 2. Existing Problems with LLMs

"Because the attention mechanism of LLMs has limitations regarding local focus, LLMs tend to concentrate more on nearby words or sentences at each position. This leads to a high risk of instruction forgetting during decoding" [3].

This phenomenon is known as "AI hallucination" and refers to the generation of incorrect or misleading responses by artificial intelligence models [4]. Such errors can become critical when integrated into technical systems that rely on an LLM for decision-making. According to a study conducted by AiMultiple [5], some of the most popular large language models, such as GPT-4o, Gemini 2.0 Flash, DeepSeek V3, and Claude 3.5 Sonnet, exhibit a hallucination rate of approximately 41%.

It is true that, with technological advancements, more advanced versions of these models have been developed, and the hallucination rate has been reduced to around 20%. However, the risk of generating incorrect information persists. Therefore, in critical contexts such as engineering, where precision is fundamental, these limitations cannot be overlooked. Local training of models and the development of specialized AI agents represent viable solutions to reduce errors and ensure reliability in technical applications.

We will now review the divisions of my application to highlight its superiority compared to other similar applications.

## 3. Creation of the AtlasBot Agent

The web application, named "AtlasBot", is developed using Angular, an open-source web application framework created by Google, based on TypeScript. It enables the creation of dynamic, structured, and scalable applications. Through the Angular framework, well-structured web components can be created, which automatically generate the necessary HTML, CSS, and TypeScript files. These components are integrated into a modular architecture that offers dynamic routing, a performant HTTP client, component-based organization, and clearly separated logic through services. This approach allows for the rapid, scalable, and easily maintainable development of modern web applications.

Angular is used for the front-end development, providing a modern, modular, and easy-to-manage interface. For the back-end, the proposed solution integrates multiple technologies, including Ollama, Python, WampServer, and MySQL.

Ollama is an open-source platform that allows large language models (LLMs) to run locally on the user's device. In this application, the model deepseek-r1:14b was used, where deepseek-r1 is the model's name, and 14b indicates the number of parameters it was trained with, namely 14 billion parameters.

According to the DeepSeek team, large models can be distilled into smaller versions without losing reasoning capabilities, thus achieving better performance compared to small models traditionally trained using reinforcement learning methods [6]. This makes DeepSeek models runnable locally, without requiring high-performance hardware infrastructure or access to supercomputers.

However, to ensure a smooth experience and acceptable response times, a dedicated NVIDIA GeForce RTX 3060 graphics card was used to handle the model's processing. One of the major advantages of running a local model is that all data remains on the device, without being transmitted to external servers, which provides increased privacy and allows functionality even without an internet connection. The model is activated directly in PowerShell.

Using the Python programming language, I developed the back-end of the application, implementing specific functionalities and integrating an LLM trained to respond to predefined data sets. Through Flask, a lightweight and flexible web micro-framework, I created a local server that communicates directly with the Angular-based front-end. The server receives HTTP requests, processes them, and returns appropriate responses, thus ensuring smooth interaction between the user interface and the application engine.

The backend functionalities are centralized in a single Python file that completely manages the application logic and coordinates all involved processes. Additionally, to manage persistent data, I used

WampServer, which provides a complete local platform for managing a MySQL database. This database is used for certain application functionalities that will be detailed in the following sections.

#### 4. WEB Interface

Upon entering the application, we are greeted by the main page (see Figure 1):

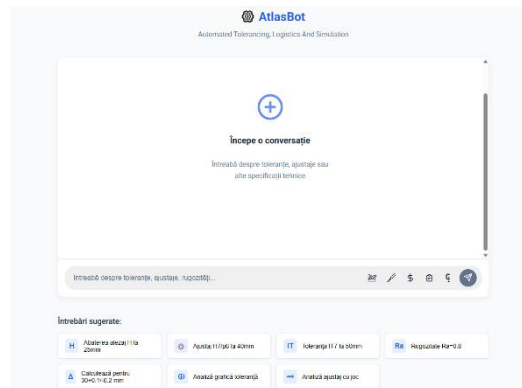


Fig. 1. Home page

The application interface is designed in a minimalist manner, aiming to provide the user with an intuitive and efficient experience. The application's title, “AtlasBot,” is suggestive and stands for Automated Tolerancing, Logistics And Simulation, highlighting its multifunctional nature and its role as a digital assistant in engineering processes.

The application is presented as a text-based chatbot, where the user can input a question into a dedicated text box. The question is sent to the LLM model, processed in real time, and the generated response is returned and displayed to the user in a clear and organized format.

To reduce thinking time and ease repetitive tasks, the interface includes a set of predefined questions, designed to cover common or standardized scenarios. These include questions related to the calculation of deviations for a bore or a shaft, tolerance determination, graphical tolerance analysis, or the evaluation of a clearance fit. Other functionalities of the application include: CNC Code Generator, Cutting Parameters Calculator, Manufacturing Cost Simulator, Technological Process Planner, and Clamping Device Configurator.

#### 5. Standardization of AI Agents

To prevent the occurrence of AI hallucinations, the standardization of the data used plays a crucial role. The AtlasBot agent was specifically designed to work with rigorous, verified information aligned with international standards, ensuring that the responses provided are accurate and reliable.

To demonstrate this principle in practice, I implemented a series of engineering calculations related to tolerances, using exclusively standardized data. For this purpose, I created a database called tolerante, managed using WampServer and MySQL.

This database contains comprehensive tables that include ISO 286-1 standards (equivalent to SR EN ISO 286-1:1997 in Romania) regarding dimensional tolerances, specific character strings (such as the type of fit), values of upper and lower deviations, roughness classes, as well as other relevant technical information (see Figure 2).

| Table                                                                     |
|---------------------------------------------------------------------------|
| <input type="checkbox"/> abateri_limita_unghiulare                        |
| <input type="checkbox"/> abateri_lim_gen_pt_dim liniare_ale_tesiturilor   |
| <input type="checkbox"/> abateri_lim_gen_pt_dim liniare_cu_exceptia_tesit |
| <input type="checkbox"/> categorii_intervale_nominale                     |
| <input type="checkbox"/> clase_rugozitate                                 |
| <input type="checkbox"/> dimensiuni_standard                              |
| <input type="checkbox"/> formule_tolerante_fundamentale                   |
| <input type="checkbox"/> intervale_dimensionale                           |
| <input type="checkbox"/> intervale_intermediare                           |
| <input type="checkbox"/> intervale_principale                             |
| <input type="checkbox"/> recomandari_trepte_precizie                      |
| <input type="checkbox"/> serii_dimensiuni                                 |
| <input type="checkbox"/> tolerante_bataie_frontala                        |
| <input type="checkbox"/> tolerante_bataie_radiala                         |
| <input type="checkbox"/> tolerante_bataii_supraf                          |
| <input type="checkbox"/> tolerante_circularitate_cilindricitate           |
| <input type="checkbox"/> tolerante_generale_rectilinitate                 |
| <input type="checkbox"/> tolerante_individuale_unghiulare                 |
| <input type="checkbox"/> tolerante_ind_parallel_perp_incl                 |
| <input type="checkbox"/> tolerante_perpendicularitate                     |
| <input type="checkbox"/> tolerante_poznom_coax_conc_sim                   |
| <input type="checkbox"/> tolerante_rectilinitate_planitate_forma          |
| <input type="checkbox"/> tolerante_simetrie                               |
| <input type="checkbox"/> trepte_tolerante_fundamentale_gama1              |
| <input type="checkbox"/> trepte_tolerante_fundamentale_gama2              |
| <input type="checkbox"/> unghiuri_prisme_inclinari                        |
| <input type="checkbox"/> unghiuri_prisme_inclinari_speciale               |
| <input type="checkbox"/> valorile_numerice_ale_abaterilor_fund_alezaje    |
| <input type="checkbox"/> valorile_numerice_ale_abaterilor_fund_arbori     |
| <input type="checkbox"/> valorile_rugozitatilor                           |
| <input type="checkbox"/> valori_tolerante_fundamentale                    |

Fig. 2. Tolerances database

Through this approach, AtlasBot becomes not only an intelligent tool but also a predictable and safe one, capable of delivering results that comply with real engineering requirements.

To better understand the capabilities of the application, let us analyze a few examples from the list of suggested questions. AtlasBot is capable of managing and querying the database, but also of automatically identifying certain patterns in the phrasing of the questions. Thanks to prior training, the agent can automatically extract the relevant information necessary for processing. For example, for the question: "What is the fundamental deviation for a hole H at the size of 25 mm?", AtlasBot recognizes that it is a question related to the fundamental deviation. It identifies that it refers to a hole, retrieves the tolerance letter (H) and the nominal size (25 mm), then searches this information directly in the database, providing a precise and standardized answer.

Another example might be: "For the dimension  $30+0.1/-0.2$  mm, determine the limit deviations, the limit sizes, and the tolerance." In this case, in addition to accessing the database, AtlasBot also performs mathematical calculations to determine the maximum and minimum dimensions, as well as the total tolerance.

An additional functionality is the graphical representation of a tolerance. For the command: "Graphical representation tolerance 25H7", AtlasBot extracts the information about the nominal size and the H7 tolerance position from the database, performs the necessary calculations, then generates a graph that places the tolerance on the zero line, facilitating the visual understanding of the position and deviations.

Finally, the application also allows the solving of more complex fit-related problems. For example: "In a fit, the following are known: for the hole,  $D_{nom} = 100$  mm,  $ES = 45$   $\mu$ m,  $EI = 20$   $\mu$ m; for the shaft,  $d_{nom} = 100$  mm,  $es = 10$   $\mu$ m,  $ei = -10$   $\mu$ m." AtlasBot can calculate the tolerance of the hole and the shaft, the limit sizes, the maximum, minimum, and average clearances, the total clearance tolerance and, additionally, it can estimate whether the fit is suitable for mass production or single-item production.

To give an overview of the results, the application generates two explanatory graphs: the Clearance Distribution Diagram and the Simplified Fit Representation (see Figure 3). These visualizations help the user make quick and technically grounded decisions based on precise and visual data.

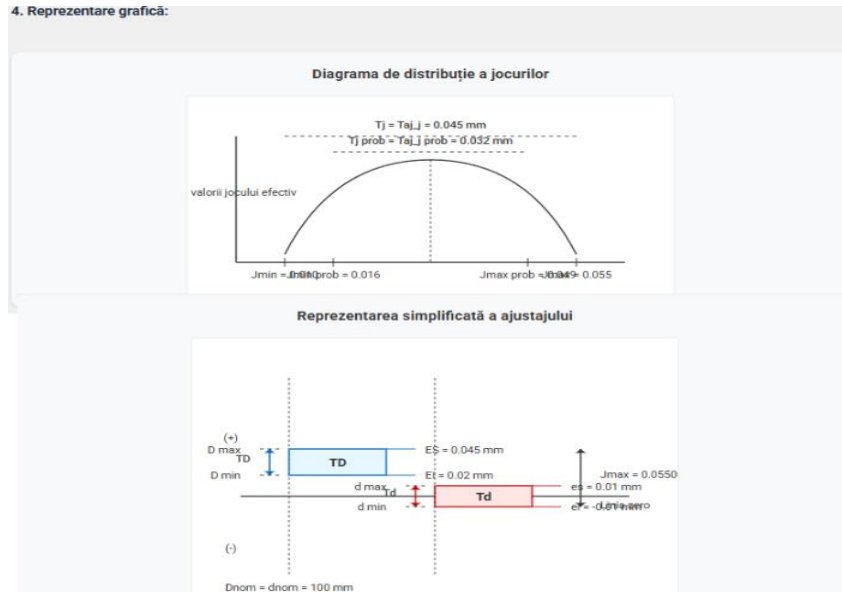


Fig. 3. Clearance fit graphs

To perform these calculations, I used the following formulas:

$$TD = ES - EI, Td = es - ei, \quad (1)$$

$$D_{max} = D_{nom} + ES, D_{min} = D_{nom} + EI, \quad (2)$$

$$d_{max} = D_{nom} + es, d_{min} = D_{nom} + ei,$$

$$J_{max} = ES - ei, J_{min} = EI - es, \quad (3)$$

$$J_{med} = (J_{max} + J_{min})/2,$$

$$S_{max} = -J_{min}, S_{min} = -J_{max}, \quad (4)$$

$$S_{med} = (S_{max} + S_{min})/2,$$

$$T_j = J_{max} - J_{min}, T_s = S_{max} - S_{min} \quad (5)$$

$$T_{jprob} = \sqrt{TD * TD + T_d * T_d},$$

$$J_{maxprobs} = J_{max} - (T_j - T_{jprob})/2, \quad (6)$$

$$J_{minprobs} = J_{min} + (T_j - T_{jprob})/2,$$

$$J_{probu1} = J_{min} + (1/3) * T_j,$$

$$J_{probu2} = J_{max} - (2/3) * T_j, \quad (7)$$

$$S_{maxprob} = S_{max} - (T_j - T_{jprob})/2,$$

$$S_{maxprobs} = S_{max} - (T_s - T_{jprob})/2,$$

$$S_{minprobs} = S_{min} + (T_s - T_{jprob})/2$$

## 6. Engineering assistance provided by AtlasBot

If in the previous chapter we focused on the importance of standardization in preventing AI hallucinations, in this section we will explore how an AI agent can be trained to answer specialized technical questions. The year 2025 is considered by many as the birth of AI agents [7]. The central idea is that, starting from a vast processing capacity and a highly diversified database of large language models (LLM), we direct this general intelligence towards a very precise niche. It's as if, from an apparently chaotic system, we extract a clear and coherent line.

Through this "narrowing" process, the agent becomes an expert in a well-defined technical field. We train it to recognize engineering concepts, understand the structure of questions, access relevant

information from standardized databases, and, most importantly, provide clear, coherent, and correct answers. Thus, not only do we improve the relevance of the responses, but we also significantly contribute to reducing the phenomenon of AI hallucination, which is crucial in engineering, where precision is absolutely critical.

One of the main features of AtlasBot is the CNC Code Generator. With a simple click on the button next to the text bar, the user is greeted by an intuitive and user-friendly window, designed to simplify the code generation process. In this interface, the user can select the desired type of operation: if it's a drilling operation, the interface will display a specific set of fields; if it's contour milling (see figure 4), the layout and available fields will be adapted accordingly.



```

***gcode
%
O0001
(AUTO-GENERATED CNC PROGRAM)
(OPERATION: CONTOUR)
G90 G54 G17
G21
T2 M6
S2000 M3
G0 Z50
G0 X0 Y0
G0 Z5
G1 Z-5 F75.0
G1 X50 Y0 F150
G1 X50 Y50 F150
G1 X0 Y50 F150
G1 X0 Y0
G0 Z50
M5
M30
%
  
```

Fig. 4. Milling Operation Interface

After selecting the operation type, the user can choose the type of numerical control command used by the CNC machine (Fanuc, Siemens, or Haas). For drilling operations, the user will enter values for the X and Y positions, drilling depth, drill diameter, feed rate, and spindle speed. In the case of contour milling, the user will enter the cutting depth, feed rate, spindle speed, specify whether the contour is closed or open, and the coordinates of the contour points. There is also the option to add additional points to complete the desired shape.

Once the fields are completed, by pressing the "Generate CNC Code" button, AtlasBot automatically creates a simple, functional, and user-adapted code (see figure 5).

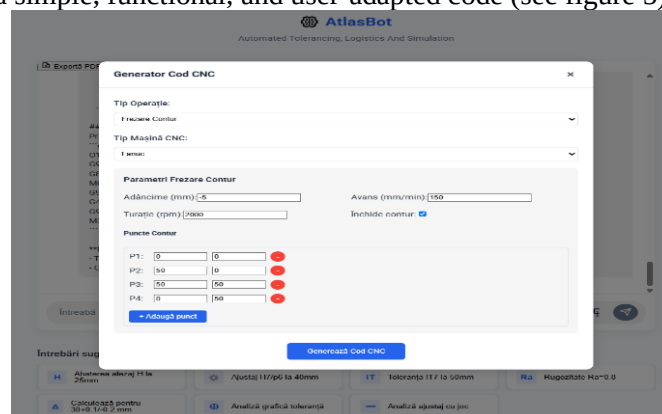


Fig. 5. Automatically Generated G-Code

Next, another function is activated that sends the generated code to the LLM, where it is processed to provide a detailed explanation of the program, possible optimizations, recommendations, and advice regarding practical implementation (see figure 6).

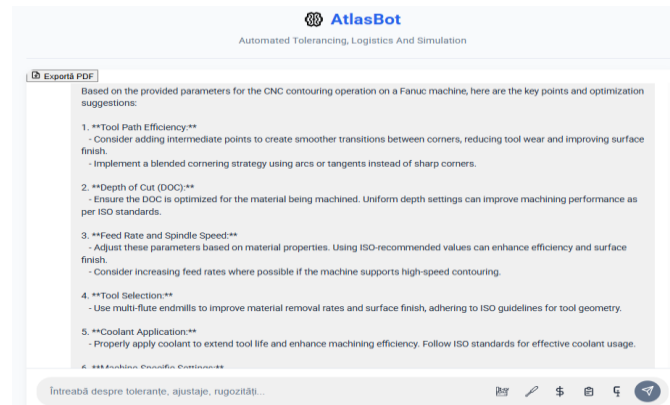


Fig. 6. Recommendations processed by LLM

Through this system based on intelligent selections and automatic text generation, we demonstrate how engineers are directly assisted by computers, saving valuable time, reducing the risk of manual errors, and increasing efficiency and work speed in the industrial environment.

This is just the beginning. This paper focuses on demonstrating that such a modular system can support engineers across multiple fields and categories of activity. The following functionalities are developed based on a principle similar to the CNC Code Generator, thus expanding AtlasBot's range of applicability.

One of these functionalities is the Chip Removal Parameter Calculator. Through this function, the user can select the desired operation type (turning, milling, drilling, or grinding), the material of the part (e.g., alloy steel, stainless steel, cast iron, aluminum, etc.), the tool diameter, the desired roughness, and the type of cooling. Based on these selections, AtlasBot uses standardized formulas to calculate cutting speed, rotation speed, feed rate, and cutting depth. Moreover, it provides a critical evaluation of these parameters, along with recommendations for optimizing the processing.

Another important functionality is the Manufacturing Cost Simulator. In this section, the user can input the material type, its weight, the loss factor (%), and select the involved processes (turning, milling, drilling, grinding, EDM, laser cutting, welding, or assembly). Additionally, information about the part's complexity (simple, medium, high, or very high), setup and processing times, additional costs (heat treatments, finishing, quality inspection, special packaging), and production data (batch size and annual volume) is entered. AtlasBot processes these data and generates an estimated manufacturing cost, ideal for industries that require quick and precise estimates. Finally, the LLM offers optimization recommendations to reduce costs and streamline manufacturing processes.

There is also the Process Planning functionality, where the user can select the part geometry type (revolution, prismatic, or complex), dimensions, part characteristics (holes, threads, grooves, etc.), process requirements (material, tolerance class, roughness, heat treatment), and production volume. Based on these data, AtlasBot generates an optimal sequence of operations, along with suggestions for improving and optimizing the technological process.

The last presented functionality is the Fixture Configurator. The user selects the shape and dimensions of the part, the type of machining operation, the involved surfaces, cutting forces, vibration risks, and additional requirements for the fixtures (desired precision, part change frequency, batch size, and allocated budget). AtlasBot performs a complete evaluation of the proposed configuration, providing advice to minimize deformations, maximize precision, identify possible alternatives, and draw practical conclusions.

Thus, through these functionalities, we demonstrate how such a modular model can assist engineers in optimizing manufacturing processes, reducing manual effort, increasing productivity, and significantly improving the accuracy of technical decisions.

## 7. Conclusions

Therefore, "the purpose of artificial intelligence systems in engineering is not to replace human engineers. Rather, such systems will enhance human capabilities by freeing engineers from routine manual labor." [8]

This paragraph emphasizes that, with the advent of these models, we are called upon to develop systems that are increasingly efficient, optimized, and easy for engineers to use, with the goal of fostering creativity and innovation.

Through this paper, we have demonstrated that such systems significantly contribute to improving the quality and precision of manufacturing processes. While the technology in the era of Industry 4.0 focused on cloud integration, IoT, and automation, Industry 5.0 "combines subjectivity and human intelligence with the efficiency, artificial intelligence, and precision of machines, thus reflecting a humanistic value and evolving toward a symbiotic ecosystem." [9]. We have shown that Industry 5.0 is inevitable, and that rapid adaptation becomes essential.

In line with these directions, the AtlasBot application represents a concrete example of implementing Industry 5.0 principles. With its functionalities, from automatic CNC code generation to chip removal parameter calculations, manufacturing cost estimation, process planning, and fixture configuration, AtlasBot assists engineers in making complex technical decisions, thus enhancing the efficiency and quality of their work.

As a development perspective, AtlasBot has almost exponential potential for progress. With the acceleration of technological progress, "periods in which one or more technologies are replaced by others within a very short time frame" [10] are becoming more and more frequent. In this dynamic, AtlasBot can integrate new technologies: more powerful and precise artificial intelligence models, with expanded and standardized databases, reducing the phenomenon of AI hallucinations.

The application could acquire advanced image processing capabilities, such as interpreting technical drawings to answer questions, identifying defects, or suggesting optimizations for assemblies. Furthermore, integrating voice recognition would allow users to interact naturally and quickly with the AI agent. From here on, the possibilities are limitless, and creativity will become the main driving force of evolution.

In conclusion, AtlasBot is not just an application; it is a bridge between human thought and the power of machines. It marks the beginning of a new era in engineering, where artificial intelligence does not replace but amplifies human talent. In a world where the technological pace is accelerating faster than ever, those who dare to embrace this symbiosis will shape the future. AtlasBot demonstrates that the limit is no longer the sky, but only our imagination. The future belongs to those who do not fear change but transform it into opportunity.

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## 9. Notations

The following symbols are used within the paper:

LLM = Large Language Model; AI = Artificial Intelligence;  $T_D$  = bore tolerance [mm];  $T_d$  = shaft tolerance [mm];  $E_S$  = upper deviation of bore [mm];  $E_I$  = lower deviation of bore [mm];  $e_s$  = upper deviation of shaft [mm];  $e_i$  = lower deviation of shaft [mm];  $D_{max}$  = maximum size [mm];  $D_{nom}$  = nominal size [mm];  $D_{min}$  = minimum size [mm];  $J_{max}$  = maximum clearance [mm];  $J_{min}$  = minimum clearance [mm];  $J_{med}$  = average clearance [mm];  $S_{max}$  = maximum interference [mm];  $S_{min}$  = minimum interference [mm];  $S_{med}$  = average interference [mm];  $T_j$  = clearance tolerance [mm];  $T_{jprob}$  = probable clearance tolerance [mm];  $J_{maxprob}$  = probable maximum clearance [mm];  $J_{minprob}$  = probable minimum clearance [mm];  $S_{maxprob}$  = probable maximum interference [mm];  $S_{minprob}$  = probable minimum interference [mm];

## IMPLEMENTATION OF A WAREHOUSE STOCK MONITORING SYSTEM

IVAN Victor Ștefan, MANOLACHE Daniel Silviu (Conducător științific)

Faculty: Industrial Engineering and Robotics Specialization: Applied Informatics in  
Industrial Engineering Year of Study: IV E-mail: [paulaivan98@gmail.com](mailto:paulaivan98@gmail.com)

**ABSTRACT:** *This paper presents the implementation of an automated stock monitoring system using a hardware platform based on Arduino and a graphical interface developed in LabVIEW. The system identifies products using QR codes and compares them against the digital inventory stored in CSV files. The robot follows a predefined route, detects obstacles, and transmits images to a computer where they are processed in real time. Labeling is based on a logical structure that reflects the physical location of products in the warehouse. The proposed solution is accessible, scalable, and easily adaptable for educational environments or industrial prototypes.*

**KEYWORDS:** *logistics, robotic system, identification.*

### 1. Introduction

Efficient stock monitoring is essential for the proper functioning of modern warehouses and logistics centers. Manual product tracking is time-consuming and inappropriate, especially in dynamic environments [1], where the flow of goods changes rapidly. With the adoption of various automation technologies in the industrial sector, stock monitoring systems have become more accessible, flexible, and easy to implement [2].

The aim of this paper is to present the implementation of such a stock monitoring system, designed to identify and report the presence of products on warehouse shelves. The system consists of an Arduino-based development board and a program developed in LabVIEW. Product groups are labeled using unique QR codes, which are scanned and interpreted in real time. This information is then compared with a pre-existing inventory file to verify stock accuracy.

By implementing this solution, the applicability of Internet of Things (IoT) technologies [3] and autonomous robots [4] in logistics is demonstrated, contributing to increased operational efficiency and the reduction of human errors in product handling and inventory management processes.

### 2. Verification and Labelling Method

For the automated stock monitoring system to function properly, it is essential that each product or group of products can be clearly and accurately identified [5]. Proper labeling ensures the link between the physical location of products in the warehouse and the digital records, allowing the system to verify stock accuracy at any time.

In this project, products are identified using QR codes applied either directly to the packaging or to the shelf where they are stored. These codes are scanned automatically by the robot during movement and are interpreted by the graphical interface. After recognition, the

code is compared with the existing stock file to determine whether the product is present and correctly placed.

Two types of codes are used. Some are assigned to entire stacks of products, corresponding to a complete and uniform inventory unit. Others are intended for individual remaining products from an opened stack, where the stack no longer matches the exact quantity recorded in the inventory file. In this case, warehouse employees must replace the old label with new labels for each remaining product. This way, the system can correctly identify changes and report shortages or discrepancies.

The QR code structure is designed to show the exact product location. A format such as R1C1N2-S1 or R1C1N2-I1 is used, where R1 represents the row, C1 the column, N2 the vertical level, and the final part indicates the group type. If marked **S1**, it denotes a full stack; **I1** indicates an individual product. If the initial "I" is followed by a number other than 1, it represents the exact quantity of products in that group. These codes help both the robot and warehouse staff quickly and accurately identify the position of each product.

An important aspect is that if a product is replaced with a different one, the QR codes do not need to be changed. The position identifier remains the same, and only the digital inventory file is updated with the new product name. Thus, the system continues to function without requiring physical label replacement, which is a significant advantage for efficient warehouse management. The only exception applies when rows are partially used, requiring new codes for individual products, but even then, the effort remains minimal.

Labels are generated using simple applications, printed on physical media, and applied at the appropriate locations. Upon scanning, the code is automatically checked in the database, and the system determines whether the product is correctly placed, missing, or erroneously added. This labeling method significantly reduces inventory errors and supports the smooth functioning of the automated stock verification process.

### 3. Current Status of the Analyzed Problem

In recent years, automated stock monitoring and management systems have evolved significantly, being widely adopted in logistics and commercial industries. The most commonly used solutions include systems based on RFID (Radio-Frequency Identification), industrial cameras integrated with PLCs (Programmable Logic Controllers), or ERP (Enterprise Resource Planning) platforms with automatic inventory modules.

These solutions generally involve high acquisition and implementation costs, requiring dedicated equipment, qualified personnel, and robust infrastructure. For small warehouses or startups, these requirements can become a major barrier, as you can see the difference between prices in the table 1.

**Table 1. Comparison of Stock Monitoring Solutions**

| System                         | Technology Used              | Estimated Cost   | Requires Qualified Personnel          | Hardware Requirements            |
|--------------------------------|------------------------------|------------------|---------------------------------------|----------------------------------|
| RFID System                    | RFID + PLC + ERP [6][7]      | >5000 EUR [6][7] | Yes – automation & integration [6][7] | RFID readers, tags [6][7]        |
| Industrial Camera Solution     | Camera + AI + Network [8]    | >10000 EUR [8]   | Yes – computer vision & AI [8]        | Industrial camera, AI server [8] |
| ERP System (e.g., SAP, Oracle) | ERP Software + Databases [6] | >25000 EUR       | Yes – IT, Accounting, ERP [6]         | Servers, software licenses [6]   |

|                   |                                    |          |                                     |                        |
|-------------------|------------------------------------|----------|-------------------------------------|------------------------|
| Proposed Solution | Arduino +<br>LabVIEW + QR<br>Codes | <500 EUR | No – easy to learn<br>and implement | Arduino, webcam,<br>PC |
|-------------------|------------------------------------|----------|-------------------------------------|------------------------|

The project presented in this paper proposes an affordable, scalable, and easily customizable alternative using the Arduino platform and the LabVIEW graphical interface. This approach enables product QR code scanning, automatic stock presence verification, and report generation in CSV format, without requiring industrial equipment.

#### 4. Hardware Components of the System

The proposed stock monitoring system is built on a simplified architecture using components that are both cost-effective and widely available. The selected components ensure full functionality for autonomous navigation, visual detection, and data transmission to a graphical interface, without the need for expensive industrial infrastructure.

The core of the system is the **Arduino Mega** development board, chosen for its large number of I/O pins and compatibility with multiple peripheral modules. It controls the sensors, motors, and acoustic signals.

For autonomous navigation, an **ultrasonic distance sensor** is used, along with a **buzzer**. If the robot detects an obstacle, it first emits a sound similar to a car horn as a warning, and then, upon approaching, it maneuvers to avoid the obstacle. The robot follows a predefined route based on distances between points of interest in the warehouse. Movement is ensured by two **TT motors** controlled via an **L298N driver**, which allows for direction and speed control.

For product detection, the robot is equipped with an **ESP32-CAM module**, integrating a camera and Wi-Fi module responsible for capturing QR code images and transmitting them to the PC interface.

The system is powered by **Li-Ion batteries** connected through an **LM2596 step-down regulator**, ensuring stable power for all components.

All components can be easily mounted on a standard chassis kit, which includes dedicated spaces for motors, sensors, and control boards. Additionally, a camera support must be added to achieve optimal QR code reading distance. Hardware integration is thus achieved without complex mechanical operations or specialized tools, making the system ideal for quick assembly.

Connections between hardware components can be made modularly using jumper wires and standard connectors, allowing quick and adaptable assembly. Motors are the only components requiring permanent soldering, which is the only task that needs professional tools.

The complete connection diagram can be seen in Figure 1, where all components, connections, and power lines are clearly illustrated. This diagram serves as a reference for the correct assembly of the system, ensuring that each module is properly integrated into the overall architecture of the robot.

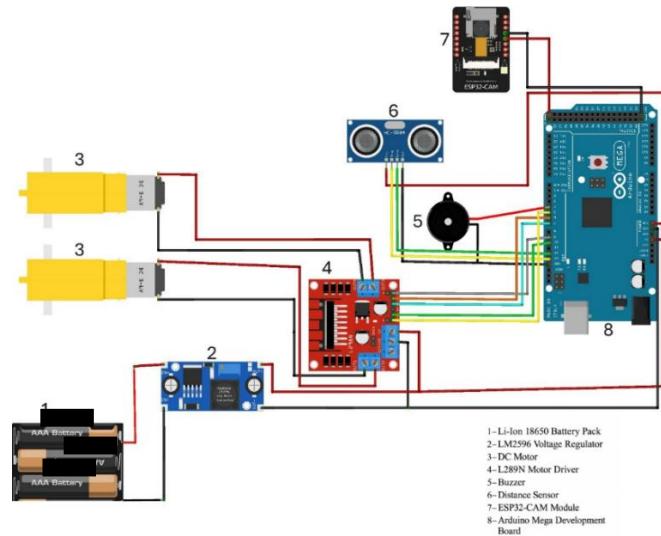


Fig. 1. Connection diagram

## 5. Graphical Interface and LabVIEW Diagram

In designing the program, the user interface was kept as simple and intuitive as possible, so it would be easy to understand and operate even at a quick glance. The program starts directly upon execution and can be stopped by pressing the "stop" button.

For efficient operation, several elements were added to the program interface to provide information about the current scanning status. The central element is the real-time image display using a dedicated indicator, which helps visualize exactly the perspective from which the program reads the codes. A highly important control element is "Session In", where the user can select which video input found by NI MAX to use. At this stage, the input number corresponding to the signal received from the ESP32-CAM is selected.

Two critical indicators are used to display the currently read code and the matrix of previously read codes. These indicators help verify the accuracy of code reading and eliminate potential errors. Error clusters display encountered error codes and their associated messages. The LED-type indicator turns off when the program successfully detects a code, making it easier to identify situations where a code is visible on the camera but not read by the program.

The program developed using the LabVIEW diagram automatically manages the product identification process, recognizes QR codes, verifies them against a stock file, and saves the results in CSV files. The system is designed to operate in real time, in a fully autonomous manner, serving as stock record software or a logistics verification tool. The program is divided into multiple logical sequences that handle file initialization, image capturing and processing, QR code recognition, code validation against existing stock, and result writing.

Initially, file paths are defined. Using Build Path blocks and string concatenation, the program generates a unique name for the output file that includes the current date and time. This ensures each scanning session is saved in a separate CSV file, preventing data overwriting. Time is automatically retrieved using the Get Date/Time In Seconds and Format Date/Time String functions.

The video camera is initialized with IMAQdx functions, and the image is captured and processed in real time. The QR recognition module extracts the code content, which is immediately displayed on the VI screen for visual validation.

After a code is identified, the program proceeds to verification. The stock file, saved in .csv format, is fully read using the Read From Spreadsheet File function, and the data is converted into a string array. A For loop analyzes each line in the file, extracting the corresponding product code using Index Array. The comparison between the read code and those in stock is performed using the "Equal?" operator. Verification is managed through a Case structure: if the product is found in the stock file, it is considered valid, and the QR code is saved in a results file. Informative messages such as "Code detected" are displayed, and a status indicator is updated. If the code is not found, the program does not perform any action. The validation result is saved in a CSV file using the Write to Spreadsheet File function, along with information about the time and the scanned code. Thus, each scanning session generates a detailed file and a summary file, useful for stock analysis and detecting possible shortages.

Finally, the LabVIEW interface provides the user with a live image, the identified code, and a set of control buttons. The program runs until the user explicitly stops it, and any errors are managed by a simple error handler module (Simple Error Handler). At the current stage of the project, only the first file containing the detailed stock with all codes has been implemented, and the error signaling function based on scanned codes has not yet been completed. The block diagram of the LabVIEW program, as shown in Figure 2, illustrates the logical structure and interconnections of the system's main functionalities.

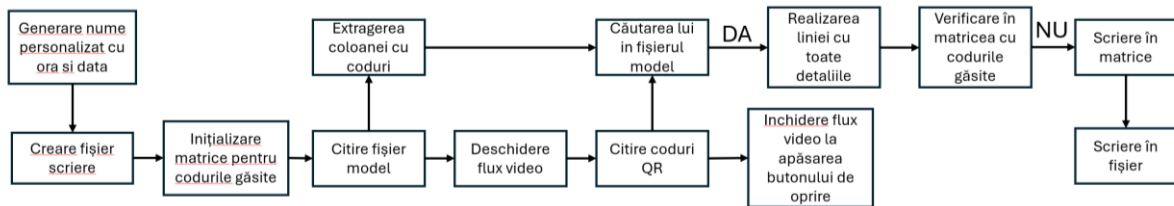


Fig. 2. LabVIEW Block Diagram of the Program

## 6. Robot Movement Programming

The robotic system is controlled via the Arduino Mega, handling movement, direction, and obstacle detection. The robot follows a predefined path based on calculations of speed, space, and time. Knowing the distances and robot speeds, motion times for each direction were set.

Movement and turning are controlled via the dual motor driver, managing the rotation direction and speed of each motor. Speed variations between the motors allow for turning, and stopping/starting is achieved by modifying these signals.

The robot does not use orientation sensors but follows a programmed path stored in the controller's memory. Each movement segment has a defined duration and speed, ensuring consistent motion.

An ultrasonic sensor mounted at the front detects obstacles. When an obstacle is detected within a critical range, the robot immediately stops, activates the buzzer, and executes an avoidance sequence. This logic is organized clearly in the program, allowing for easy code updates or additional functionality without affecting basic system behavior.

In the robot's programming, an important addition was the implementation of a waiting period at the beginning of the operation. After the robot starts, it enters a state of waiting for approximately 60 seconds. This pause allows the ESP32-CAM module to fully initialize,

establish the necessary Wi-Fi connection, and ensure that the video streaming and QR code scanning systems are fully operational before the robot begins its movement. Without this initial delay, the system might attempt to process images before the camera is ready, leading to errors or incomplete data collection. By introducing this waiting time, the system guarantees that all components are synchronized, and the scanning process begins in optimal conditions.

Another significant feature integrated into the robot's programming is the detection of a perpendicular line placed across the warehouse path. This line serves as a physical end-marker for the scanning routine. When the robot identifies this line using its sensors, it interprets the detection as a signal to stop. Upon detection, the robot halts all motor activity and emits a distinct sound sequence through the buzzer. This acoustic signal notifies the operator that the scanning process has been completed, indicating that the robot has reached the end of its programmed route and should be manually stopped or reset. This feature enhances the safety and usability of the system, ensuring that the robot does not continue moving beyond the intended path and clearly signaling the completion of its task.

## **7. Conclusions**

In conclusion, this paper focused on developing and testing an automated stock monitoring system suitable for organized storage environments. Using an accessible Arduino-based hardware platform and a LabVIEW graphical interface, a functional solution was created, capable of identifying products via QR codes and automatically comparing them with digital inventory records.

This project serves as a solid foundation for the development of more complex systems in the future. By integrating accessible hardware and straightforward programming logic, it demonstrates the feasibility of creating functional automation solutions at low cost. The knowledge and practical experience gained during the design, implementation, and testing phases of the robot will be invaluable for tackling more advanced projects, such as the development of fully autonomous systems capable of complex decision-making, integration with cloud platforms, or advanced data processing. These future directions can contribute significantly to the field of industrial automation and logistics, enabling smarter and more efficient warehouse management solutions.

The main advantage of the system is its simplicity and low cost, making it ideal for educational applications, research prototypes, or small-scale warehouses. Additionally, by introducing a standardized labeling system—where each QR code reflects the exact product position and storage type—clear traceability and efficient product verification were ensured.

The LabVIEW interface facilitated the integration of recognition, verification, and data saving functionalities, while the hardware handled controlled robot movement and obstacle avoidance. Together, the two components demonstrated that such a system can operate reliably without human intervention on a predefined route.

This project proved that affordable technologies like Arduino, camera modules, and visual development platforms can be combined to create practical solutions with real applicability in logistics and automation. The proposed system can be easily expanded by adding advanced reporting features, network connectivity, or integration into an ERP platform, making it a relevant example of practical automation and digital stock management.

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## COMPUTERIZED ASSEMBLY OF POLYMERIC PRODUCTS

**MIROIU Ana-Maria, OPRAN Constantin Gheorghe(Conducător științific)**

Faculty:Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering, Year of study:IV, e-mail:ana\_maria.miroiu@stud.fiir.upb.ro

***ABSTRACT:** The paper develops an automatic assembly system for polymeric products based on the use of a programmable controller integrated with LabVIEW and Factory I/O interfaces. The system implements a sequential structure of automated processes: starting the conveyor belt, detection and validation of parts through vision sensors, and assembly using a robotic arm. The correctness decision is based on color analysis (strictly simulated) – blue for caps, green for bases – with stopper control managed through a Case logic structure. The conclusions highlight the system's efficiency, precision of automatic assembly, and solution scalability. Future research directions include the integration of artificial intelligence for defect prediction, extension to other types of polymers, and optimization of energy consumption.*

***KEYWORDS:** LabVIEW, robotic arm, vision sensors, optimization, assembly.*

### 1. Introduction

Industrial process automation, a key pillar of today's industry, enhances the manufacturing of polymeric products in areas such as packaging, construction, and the automotive industry, replacing manual assembly, which is sometimes inefficient and error-prone, with advanced digital solutions. Polymeric products, due to their versatility—durability, ease of molding—are essential in various applications, from disposable containers to complex structural components. However, manual assembly processes involve risks and errors such as incorrect alignment, quality variations, and long production times, which affect sustainability.

The main objectives of the paper include the design of an automatic system capable of detecting and validating polymer parts (caps and bases) based on visual characteristics, performing automatic assembly using robotic technologies, and ensuring smooth transitions between process stages. To achieve these objectives, the paper integrates a programmable controller with LabVIEW and Factory I/O platforms, creating a simulated environment that allows testing and optimization of the process before large-scale implementation. Moreover, by using digital technologies, the paper contributes to promoting sustainable practices, reducing waste and unnecessary resource consumption. Thus, the research not only offers a practical solution for the polymer industry but also establishes a theoretical framework for future integration into industrial automation processes, such as artificial intelligence.

### 2. Problem analysis

Manual assembly of polymeric products involves many challenges, including difficulty aligning components of an assemblable product, variations in dimensions and shapes due to molding or injection, assembly issues, etc. Human operators are subject to fatigue, which can lead to repeated errors, and quality control becomes laborious and costly. These deficiencies have a massive impact on production: costs increase due to rejections and the need for reassembly or repair, and delays caused by these issues affect customer relationships. Additionally, strict environmental requirements, waste reduction, and recycling make manual methods less sustainable.

Automated solutions based on digital technologies become a viable alternative, reducing deficiencies through: high precision due to the use of sensors and robotic control, continuous operation capability, adaptation to production variations, minimal human intervention, and optimized process time.

### **3. Research objectives**

#### **3.1 Main objective**

The main objective of the paper is to develop an automatic assembly system that optimizes industrial processes by eliminating errors and increasing efficiency and productivity.

#### **3.2 Specific objectives**

- I. Part detection and validation: implement a system that identifies and verifies polymeric parts based on visual characteristics such as color, shape, using vision sensors.
- II. Automatic assembly: use a robotic arm to precisely assemble components, reducing production time.
- III. Transition optimization: design a control and command mechanism that ensures smooth and efficient transitions between assembly stages, with minimal interruptions.

### **4. Theoretical aspects**

#### **4.1 Operating Principles of Vision Sensors and Data Processing**

Vision sensors use cameras and image processing algorithms to detect colors or shapes, converting data into digital signals that are analyzed through automated decisions – e.g., acceptance or rejection of a part.

#### **4.2 Sequential Logic and Case Structure in LabVIEW**

Sequential logic involves executing process steps in a predetermined order, and the Case Structure in LabVIEW allows managing these steps through logical conditions, facilitating transitions between states such as "Start" or "Assembly."

### **5. Proposed Solution**

The system combines a LabVIEW program for programming and control and Factory I/O for simulation, facilitating process testing before real implementation. This approach can reduce risks and initial costs.

The process is structured in several steps: starting the conveyor belts, feeding parts, component detection via sensors, stopping them for visual characteristic validation, and assembly with a robotic arm, all controlled by sequential logic.

Validation is based on analysis of part colors or shapes, performed via vision sensors, and the stoppers are managed through logical structures and stop or release the parts depending on analysis results.

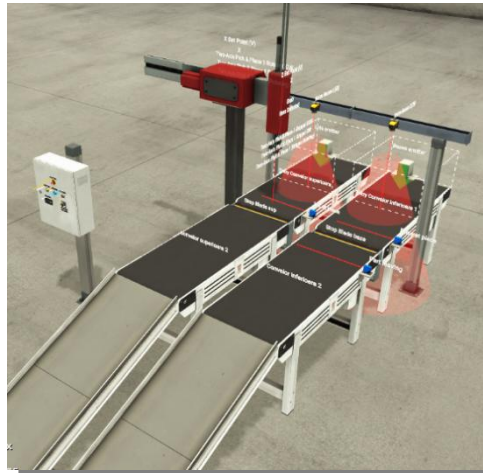


Fig. 1 Automated assembly line

## 6. Current stage

The simulated scene in Factory I/O reflects an industrial assembly system with conveyor belts, proximity sensors, a vision sensor, and a robotic arm. We configured two main conveyor belts—an upper and a lower—for transporting polymeric parts. The upper belt is controlled by an input belt and the "upper conveyor" of upper parts. The lower belt is controlled by an input belt and the "lower conveyor" of lower parts. At the start of each input belt, we placed emitters for both base and cap, set to generate parts with varied visual characteristics for the most realistic testing.

We installed proximity sensors to detect the presence of parts, positioned immediately as the part enters the work area. We added vision sensors for visual characteristic analysis, configured to detect colors. We configured mechanical stoppers to control the part flow, positioned at the intersection points of the belts. The robotic arm is placed centrally, facilitating part handling from one belt to another. At the end of the belt, we integrated a remover that eliminates non-compliant parts at the end of the line.

Communication between Factory I/O and LabVIEW was established via the Modbus protocol, configuring Factory I/O as the server and LabVIEW as the client through server 172.0.0.1 and port 502. We also selected digital writing to input, digital read on coils, register write to input register, and register read on holding register.

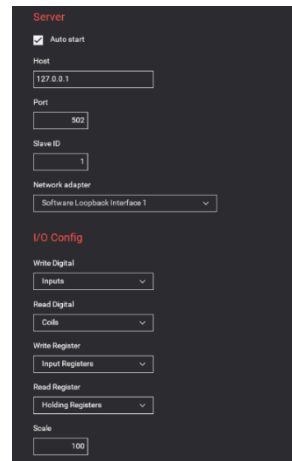


Fig. 2. Configuration Modbus

We mapped all inputs and outputs in the Modbus register, tested the scene by running the simulation, and adjusted parameters to optimize the process flow. The scene allows adding new components or modifying the configuration to ensure scalability.

| (127.0.0.1:502)<br>Slave ID: 1 |               |         |                        |
|--------------------------------|---------------|---------|------------------------|
| Item Detected                  | Input 0       | Coil 0  | Entry Conveyor stop    |
| Lid at place                   | Input 1       | Coil 1  | Stop Blade base        |
| Base at place                  | Input 2       | Coil 2  | conveyor supercar      |
| Part leaving                   | Input 3       | Coil 3  | Entry Conveyor infer   |
| Start Button 1                 | Input 4       | Coil 4  | Stop Blade sup         |
| Reset                          | Input 5       | Coil 5  | Conveyor inferiera 2   |
| Stop Button 1                  | Input 6       | Coil 6  | Grab                   |
| Emergency stop                 | Input 7       | Coil 7  | Start Button 1 (Light) |
| Auto                           | Input 8       | Coil 8  | Reset light            |
| CTORY I/O (Running)            | Input 9       | Coil 9  | Stop Button 1 (Light)  |
| X                              | Input Reg 0   | Coil 10 | Bases emitter          |
| Z                              | Input Reg 1   | Coil 11 | Lids emitter           |
| Vision Sensor 0 (ID)           | Input Reg 2   | Coil 12 | Remover 1              |
| Vision Sensor 1 (ID)           | Input Reg 3   | Coil 13 | Remover 2              |
|                                | Holding Reg 0 |         | X Set Point (V)        |
|                                | Holding Reg 1 |         | Z Set Point (V)        |
|                                | Holding Reg 2 |         | Counter                |

Fig. 3. Mapping of sensors and actuators

The program developed in LabVIEW implements a complete solution for assembly control, using a sequential structure integrated into a While loop that runs continuously until it is stopped manually or by an interruption condition. We began by creating a string enumeration on the front panel, which serves as a selector for a main Case Structure. This structure contains several distinct states: "Stand By," "Start Conveyor," "Correctness Decision," "Assembly," "Assembly 2," "Assembly 3," and "Assembly 4," each representing a specific stage of the assembly process.

In the "Stand By" state, we configured all actuators (COIL 0-13) to be deactivated. We added a check for the start button, using a "select" that checks if the button is pressed (Start Conveyor) or unpressed (Stand By).

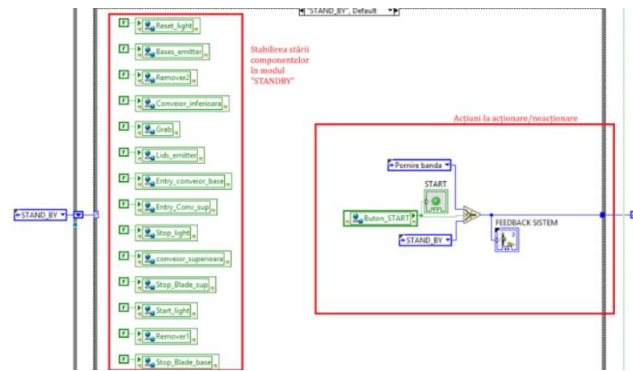


Fig. 4. STANDBY mode

In the "Start Conveyor" state, we activated the conveyor belts by connecting the variables to Boolean TRUEs. We configured the emitters to generate parts (Boolean TRUEs), also set the values for the robotic arm position on X and Z, and added a transition logic, using an AND to check for the presence of both parts, then moving to "Correctness Decision" if the condition is met. If the condition is not met, the stop belt does not lower but remains raised, blocking access to the next conveyor belt.

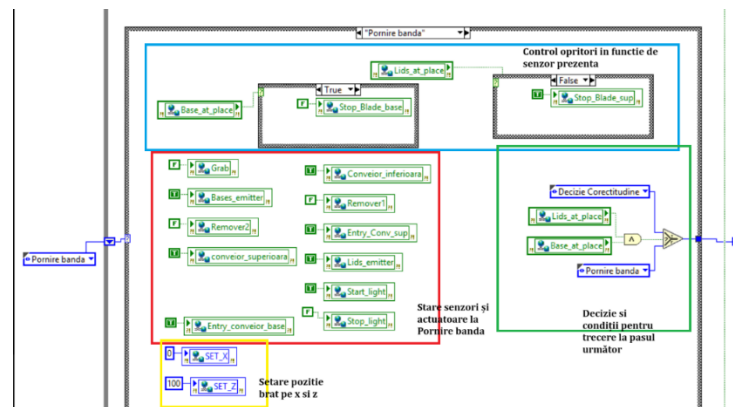


Fig. 5. START state, control pannel

The "Correctness Decision" state is essential for part validation. We read the values from the sensors and with the help of equal? nodes we compared each sensor to a numeric constant representing a certain color. The comparison results were combined in an arithmetic node to confirm that the parts are present and meet visual criteria. If the condition is TRUE, the stoppers are raised to hold the parts in position, then we move to assembly; otherwise (parts are not present or do not meet the established criteria), we lower the stopper, release the parts to the reject line (Receiver), and return to "Start Conveyor."

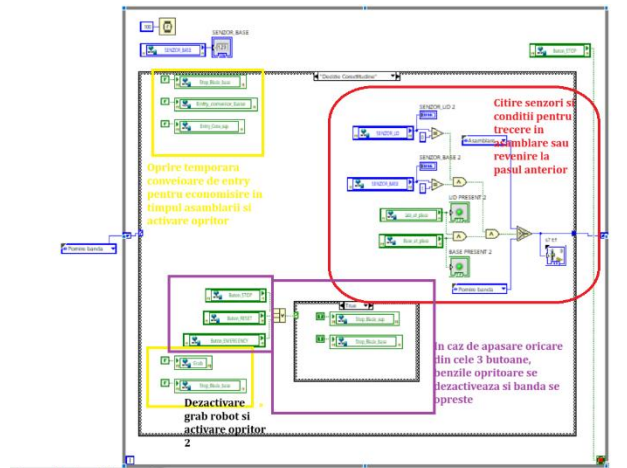


Fig. 6. Control panel of Corectness Decision state

The "Assembly" state and associated states "Assembly 2," "Assembly 3," "Assembly 4," represent the actual assembly process of polymeric parts. The "Assembly 1" subdiagram represents the initial stage of the automatic assembly process. This stage checks the presence of parts and initiates their handling by the robotic arm. We read the presence sensors, added constants 2,3,5,6 for comparison and a not equal? Comparing with 2,3,5,6 is done to check the sensor states and part position. All these are integrated into an AND that determines if all conditions are met to proceed with the process. The robotic arm is activated by connecting the "Grab" property node to a Boolean TRUE.

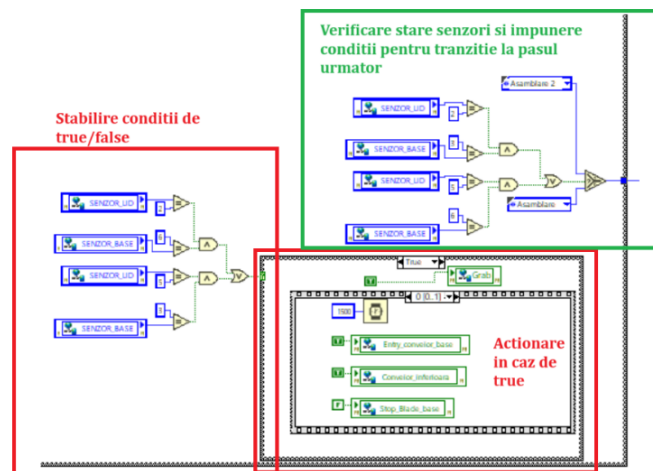


Fig. 7. Control panel of assembly state

The "Assembly 2" subdiagram lowers the robotic arm. SET\_X to 130, SET\_Z to 1000 sets the initial position. The While loop and 50 ms Wait control the descent. If the Flat sequence cases are TRUE, it proceeds to "Assembly 3."

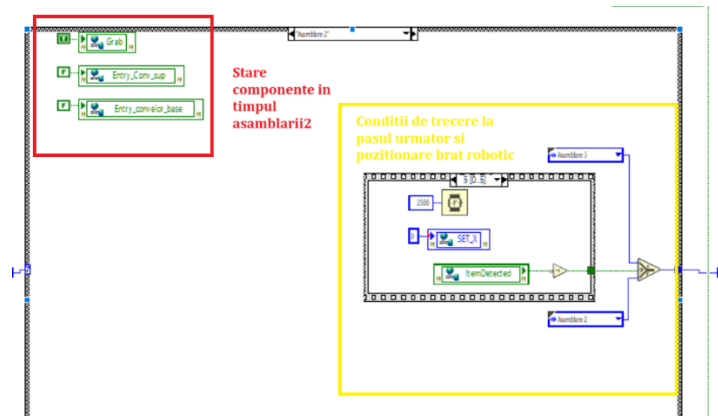


Fig. 8. Control pannel Assembly 2

The "Assembly 3" subdiagram adjusts the robotic arm to join the parts. SET\_X is set to 200, SET\_Z to 10 for precise alignment. An Equal? node combined with AND is connected to a selector—if TRUE, Grab becomes FALSE (release), transitioning to "Assembly 4."

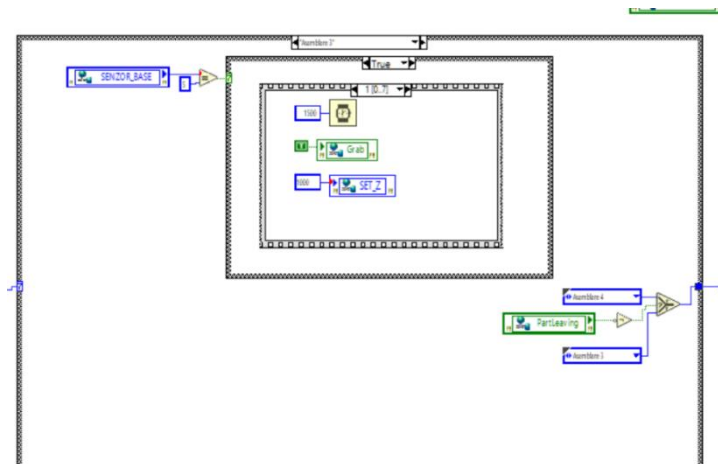


Fig. 9. Panou de control asamblare 3

The "Assembly 4" subdiagram finalizes the assembly. Stoppers become FALSE (release parts). The part exit sensor triggers reset to "Start Conveyor." It checks the emergency button for interruption to "Stand By."

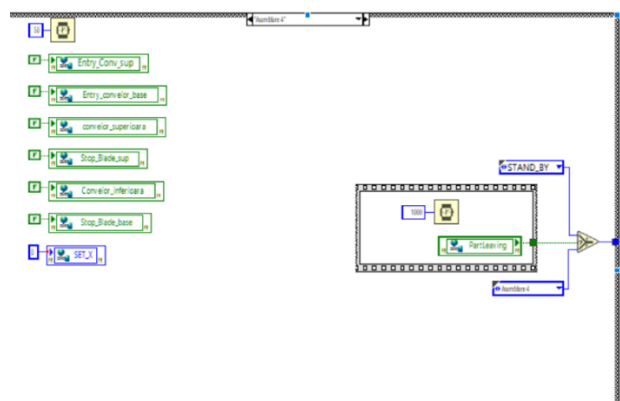


Fig. 10. Panou de control asamblare 4

## **7. Conclusions**

### **7.1 Results summary**

The automated polymeric product assembly system implemented in LabVIEW and Factory I/O demonstrated efficient functionality. The "Assembly 1" to "Assembly 4" subdiagrams coordinated the robotic arm, setting precise positions (SET\_X: 130, SET\_Z: 1000) and verifying parts in optimal time.

### **7.2 Contribution Importance**

The project contributes to the automation of polymer production, reducing human errors and increasing assembly precision through sequential logic and robotic control, applicable in Industry 4.0.

### **7.3 Future directions**

Future developments may include AI integration for flow optimization, expansion to more types of parts, and testing in real production environments.

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## EFFICIENT AND COMPACT TRANSPORT SYSTEMS IN THE MANUFACTURING OF POLYMER PRODUCTS

**CIOCODEICĂ Alexandru-Daniel, OPRAN Constantin-Gheorghe, Loredana-Andreea ALBU(Conducători științifici)**

**Faculty:** FIIR, **Specialization:** IAI, **Year:** IV, **e-mail:** [alexandrucioodeica20@gmail.com](mailto:alexandrucioodeica20@gmail.com)

***Abstract:** This research paper presents a transport system for small-size polymer products injected into molds, using ergonomic and efficient methods that meet the sanitary standards for products that come into contact with food. The focus is on automating the transport of injected products from the injection machine to a workstation under hygienic conditions. Transport is carried out using HACCP-compliant hoses and vacuum generators made by SMC. These operate on the principle of pneumatic tubes with varying cross-sections and specially designed components such as the parts collection funnel and the workstation. This research aims to develop a transport system where the injected parts do not come into contact with the surrounding environment, which reduces the risk of contamination by dust or other impurities.*

**KEYWORDS:** Transport, automation, polymer products, vacuum generators

### 1. Introduction

Injection molding is the operation where a mono-material or composite material in a fluid or semi-fluid state is introduced under high pressure, and usually under heat, into a closed space, such as an injection mold cavity [1]. This is one of the most widely used manufacturing technologies for commercial products. Polymer and composite materials are used for a wide range of products, serving industries from toys to household goods, and even the automotive and aerospace sectors.

This research presents an automated transport system for molded parts, improving the process in terms of both efficiency and hygiene standards. Previously, the packaging process was entirely manual: the operator had to retrieve parts from the machine and place them on a table for inspection and sorting, ensuring they were uncontaminated before packaging them in bags or boxes depending on usage and requirements.

With compressed air-based transport systems, operations formerly done by humans are minimized. Operators are only responsible for packaging, while the transport from the machine to the workstation is entirely handled by air-flow ducts.

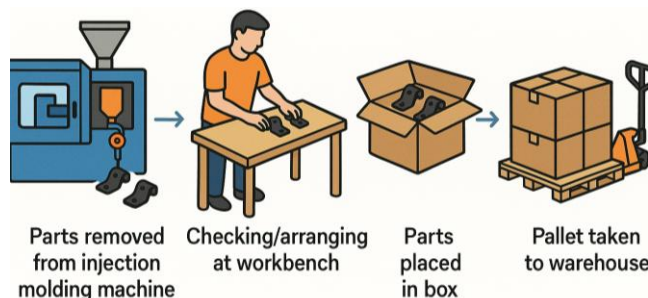


Fig. 1. The process of packaging and storage of plastic products

Vacuum generators and air or vacuum-based transport systems are used in many categories of industrial applications. These systems are typically used to transport small objects, raw materials, or to vacuum and transport waste. In the industrial applications of factories manufacturing molded parts, raw material in granule form is transported from industrial dryers or from material containers to machines using a centralized system based on vacuum pumps that suction the granules and carry them to the machine hopper.

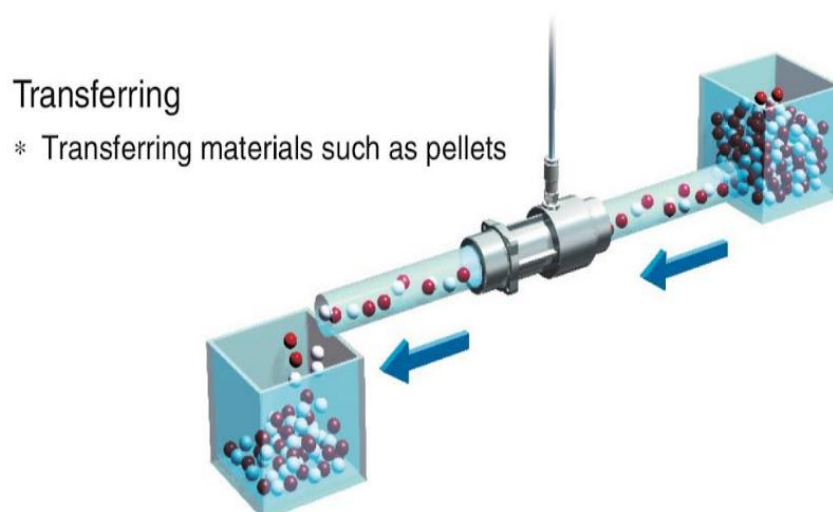


Fig. 2. Transport principle using airflow [2]

Vacuum generators use the Venturi effect to create an air stream in a specific direction. The Venturi effect occurs when a fluid (in this case, air) passes through a narrowed section of a pipe, increasing velocity and decreasing pressure. These generators use this effect and air friction to create vacuum at one end and a controlled air stream at the other, without moving parts.

The vacuum generators used in this project are manufactured by SMC, with an inner diameter of 42mm (SMC Vacuum Flow). They are made from aluminum alloys, cylindrical in shape, where compressed air is released under pressure through a cylindrical opening, and the Venturi effect together with air friction generates a controlled air flow along the cylinder axis, as shown in Fig. 3.

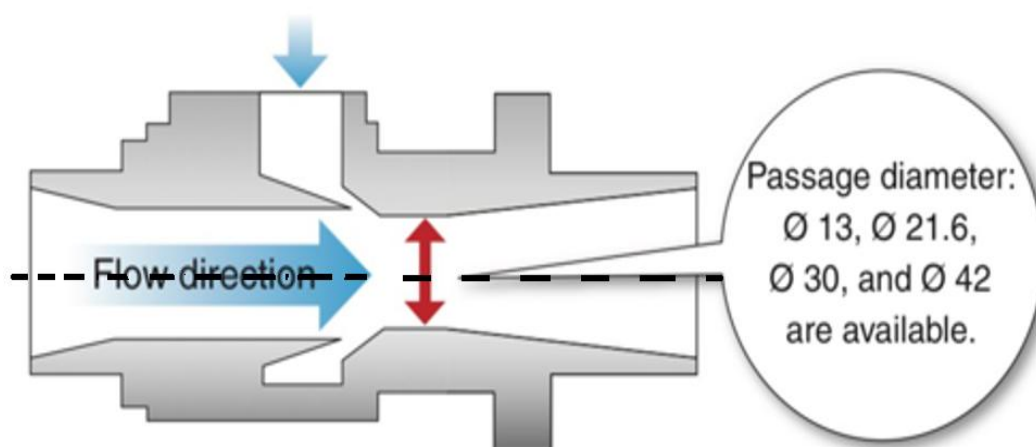
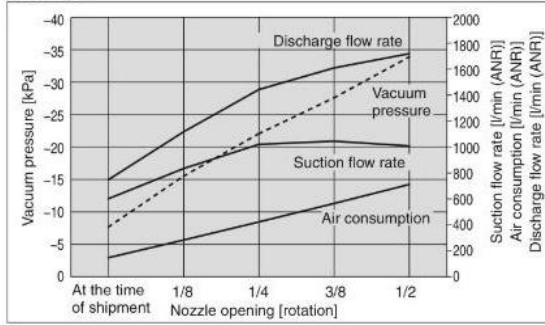
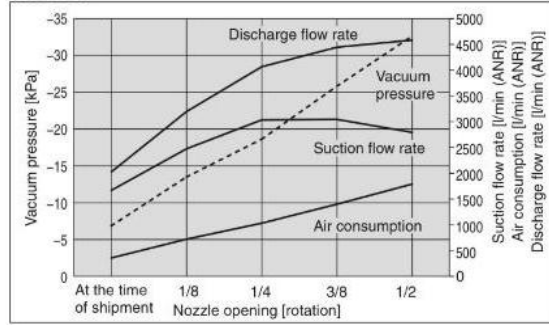
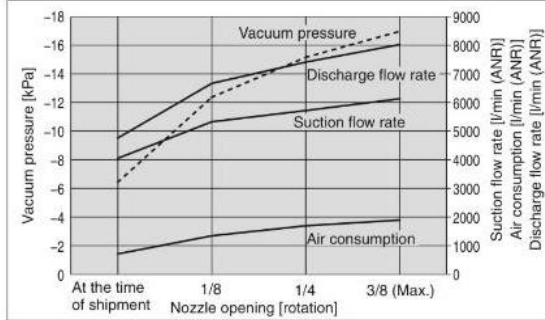
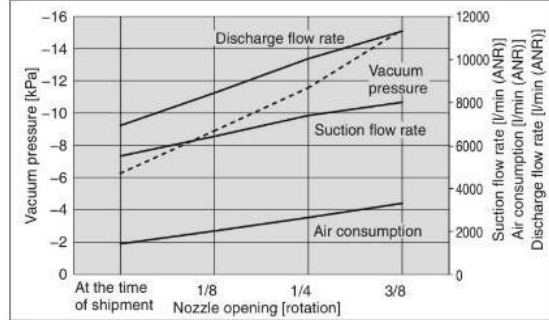


Fig. 3. Section view of the vacuum generator [2]

Depending on the supply pressure, the SMC Vacuum Flow can generate a pressure between 0 and 0.7 MPa. This pressure is sufficient for applications involving small parts, granules, or particles. In this research project, the transport system using these vacuum generators will help handle parts from toys, which range from 2 to 35 mm in size (maximum distance between two points).

**Exhaust Characteristics (at the time of flow rate adjustment, with supply pressure of 0.5 MPa)****ZHV10****ZHV20****ZHV30****ZHV40**

\* Suction flow rate is a theoretical value.

\* The above characteristics are when the discharge outlet is under atmospheric pressure.

Fig. 4. Specification tables of vacuum generators [2]

Vacuum generators are connected to hoses that carry and guide parts using airflow. Hose length is a key factor affecting system efficiency. Air behaves as a fluid inside the hose and experiences friction against the walls, reducing pressure and flow rate along the length. To verify if the system is feasible, if the generated pressure and flow rate are sufficient, and if the system will function as intended, the Darcy-Weisbach equation (1) for straight pipes will be used [3].

$$\Delta P = f * \frac{L}{D} * \frac{\rho v^2}{2} \quad (1)$$

Where:

$\Delta P$  = pressure loss (Pa)

$f$  = friction factor (depends on Reynolds number and roughness)

$L$  = hose length (m)

$D$  = internal diameter of the hose (m)

$\rho$  = air density ( $\text{kg/m}^3$ )

$v$  = air velocity in the hose (m/s)

The pressure of the airflow inside the hose is directly influenced by the hose length. If the hose is too long, the pressure generated by the vacuum flow component will not be sufficient for the air to maintain peak pressure and flow.

## 2. Current Status

A system configuration was built for functionality testing, including: a polymeric funnel, hoses, vacuum generator, and a container for discharging transported parts.

The funnel was built as shown in Fig. 5, with a 45-degree angle and treated with silicone spray to reduce the friction coefficient so that falling parts slide instead of sticking. If parts stick, they may block the hose or multiple parts may enter simultaneously, causing jams.

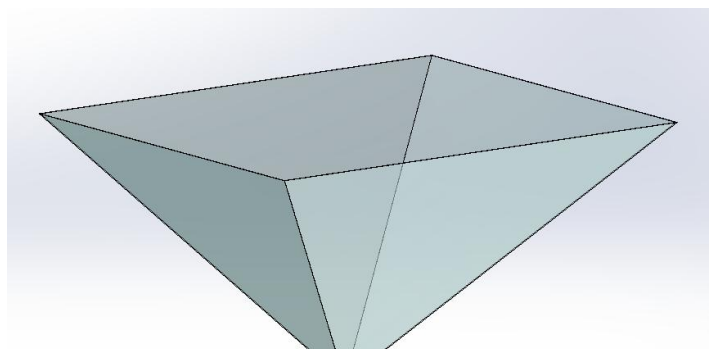


Fig. 5. Plexiglass funnel.

The hoses comply with HACCP standards, specifically designed for the food industry. They are made from reinforced polymer with a helical spring for strength and flexibility. The funnel is placed below the injection mold to directly receive parts ejected from the mold and then transport them to the workstation.

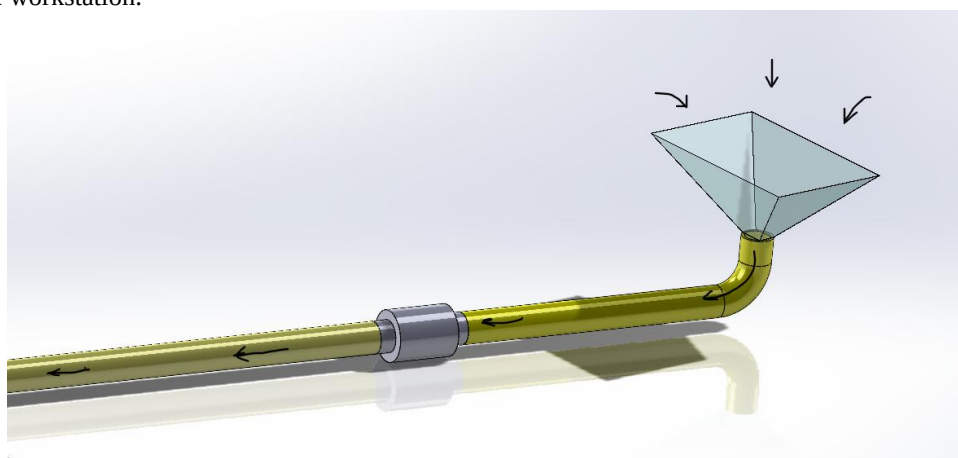


Fig. 6. 3D-designed prototype of the transport system

To ease the operator's work, these hoses can be positioned in special workbenches that collect parts from multiple injection machines. This eliminates the need for the operator to move from one machine's workbench to another, increasing efficiency. Moreover, if any machine experiences technical issues, real-time monitoring allows operators to request immediate technical support.

To avoid mixing different parts, which would slow down packaging due to extra sorting, a workstation was designed in SolidWorks to separate the 4 distinct parts from 4 different injection machines. The stand is made from stainless steel and plexiglass, non-corrosive materials that comply with sanitary regulations.

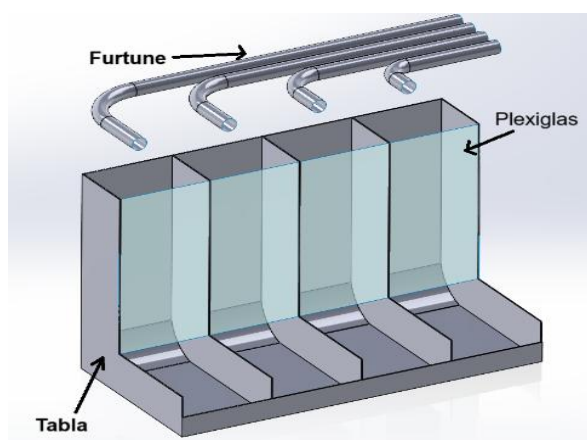


Fig. 7. Workbench for packaging parts from 4 different machines

### 3. Conclusions

The system improves production efficiency by automating tasks currently done manually.  
Reducing operator tasks increases production capacity.  
Simplifying transport operations reduces the risk of part contamination.  
The transport system will be further developed and optimized using sequential airflow control.  
An automatic quality control and sorting system will be developed.



Fig. 8. Image of the system working in a factory

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## DEVELOPMENT OF THE EDUCATIONAL MOBILE ROBOT AMR2AC INTEGRATED INTO ROS2 AND NAV2

**CONSTANTIN Rareș-Marian, GHEORGHIU Alexandru-Dan,  
SCHMIDT Mario-Dragoș, SLĂVESCU Andrei-Sebastian,  
ABAZA Bogdan-Felician, DOICIN Cristian-Vasile (Conducători științifici)**

Faculty of Industrial Engineering and Robotics, Specialization: Industrial Economic Engineering,  
Year of Study: II, e-mail: [alex dangh@gmail.com](mailto:alex dangh@gmail.com)  
Faculty of Industrial Engineering and Robotics, Manufacturing Engineering Department

**ABSTRACT:** *This work introduces AMR2AC, an autonomous differential-drive robot developed in ROS 2 and Nav2 for educational and research purposes. The platform integrates a modular aluminum chassis, 3D-printed enclosure, 2D LIDAR, IMU, and dual-channel motor control via ESP32 and Raspberry Pi 4. Autonomous navigation is realized through SLAM and dynamic trajectory planning, indoor validated via teleoperation, goal-based routing, and waypoint tracking. The robot evolved from open prototypes to an enclosed version, with mechanical and software refinements guided by test feedback. Fully compliant with Mobile Intelligent Autonomous System (SAIM) specifications, AMR2AC supports both educational deployment within the Faculty of Industrial Engineering and Robotics and indoor intralogistics tasks. It offers a scalable foundation for future developments in autonomous perception, control, and navigation.*

**KEYWORDS:** *autonomous robot, indoor navigation, ROS2 educational platform, differential drive control, 3D CAD modeling.*

### 1. Introduction

This study is carried out within the strategic research direction defined by the coordinating academic team, focusing on the development of Mobile Intelligent Autonomous Systems (SAIM). These systems are based on a modular architecture that integrates perception, localization, path planning, control, visualization, and adaptive behavior capabilities [1,2,3]. From an educational perspective, the initiative aims to strengthen collaboration and hands-on engineering skills by engaging students in the complete development cycle of a mobile robotic platform designed for autonomous indoor navigation using ROS 2 middleware [1,4].

To support this objective, a set of general design specifications was established for a ROS 2-compatible robotic platform [1,2]. The robot is intended to operate in a controlled indoor laboratory setting with flat surfaces and consistent lighting, minimizing environmental variability and improving reproducibility. The chassis is constrained to a maximum footprint of 500×500×400 mm (L×W×H), supports a payload of up to 20 kg, and allows integration of top-mounted modules within a 200×200×200 mm volume. Locomotion is achieved via a differential drive system with two or four DC motors [14], managed through a Pololu VNH5019 dual-channel motor driver and an ESP32 NodeMCU-32S microcontroller [12,13].

The onboard perception system comprises a 9-axis BNO055 IMU [11] and a 2D LDROBOT STL-19 LiDAR sensor [10], with optional visual input from a Logitech C922 Pro HD RGB camera [7]. The platform is powered by a 12 V rechargeable NiMH battery and runs on ROS 2 Humble Hawksbill [1,8], with autonomous behavior managed through the Nav2 navigation framework [2,4,5].

The mechanical structure and payload configuration are optimized for extensibility, allowing the integration of additional modules. This flexibility enables the platform to support both educational

use within the Faculty of Industrial Engineering and Robotics [1,5] and applied intralogistics scenarios that simulate operations in industrial and logistics environments [1,5].

## 2. Defining the Architecture of the Educational Autonomous Robot

This study focuses on the development of AMR2AC - in accordance with specific constraints related to dimensions, sensor integration, and processing capabilities [1,2,10,11,12,13,14]. The platform also functions as an educational tool, supporting hands-on learning of key concepts in mobile intelligent autonomous systems [1,3,4,5]. The following section outlines the hardware configuration and software architecture that enables its autonomous operation [1,3,4,5].

### 2.1. Subsystems

The system architecture, initially defined by the coordinating team (Fig. 1), was iteratively refined to address technical requirements. The platform comprises a mechanical subsystem, including the structural frame and actuation elements, and an electronic subsystem, consisting of sensors, control units, actuators, and power components [1,12,13,14].

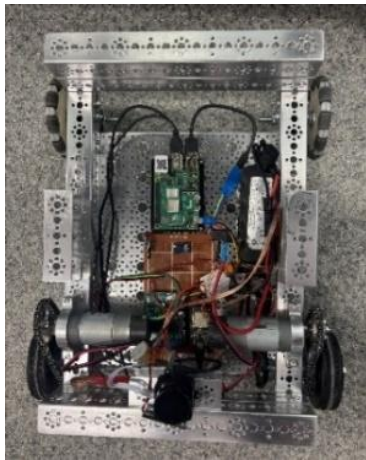


Fig. 1 General view of the robot

Locomotion is achieved through two 12 V DC motors, each coupled with a 40:1 gearbox and integrates quadrature encoder (~1440 pulses per revolution) [13]. Power is transmitted via tensioned chains that drive steel sprockets mounted on the wheel axles, effectively reducing motor speed while increasing ground torque for controlled motion. The motors are symmetrically positioned at the front of the chassis, offering both shock protection and easy maintenance access.

The drive system includes two Ø100 mm rubber-coated wheels mounted on the motor axles, providing propulsion and traction on smooth surfaces. To maintain stability, two omni-directional wheels are placed at the rear, opposite the motors (Fig. 1) [9,14]. These enable passive lateral movement during turns, reducing pivot resistance and preventing mechanical lock-up. The symmetrical wheel layout ensures a low, stable center of gravity, while the differential drive configuration enhances maneuverability in constrained environments.

### 2.1.2. Electronic Subsystems

The electronic subsystem comprises control units, sensing components, and power management - for autonomous functionality. A Raspberry Pi 4, running ROS 2 Humble, make localization, motion planning, and sensor data processing [1,2,8], while an ESP32 microcontroller handles low-level motor control and encoder feedback [12]. Inter-module communication is facilitated via Wi-Fi, USB, I<sup>2</sup>C, and GPIO interfaces. The system is powered by a 12 V rechargeable NiMH battery, with energy routed to the Pololu VNH5019 dual-channel motor driver and associated logic circuits through a stabilized voltage regulator [13] (see Table 1).

Table 1. Electronic components – roles and connectivity

| Component            | Primary Function                               | Connectivity                                           |
|----------------------|------------------------------------------------|--------------------------------------------------------|
| Raspberry Pi 4       | ROS 2 processing, localization, planning       | USB (LIDAR, ESP32), I <sup>2</sup> C (IMU), Wi-Fi      |
| ESP32                | Motor control, encoder data acquisition        | UART (Raspberry Pi), GPIO (driver, sensors)            |
| VNH5019 Driver       | DC motor current control                       | GPIO from ESP32, 12 V power input, output to motors    |
| DC Motors + Encoders | Locomotion, odometry feedback                  | Powered via driver, encoders connected to ESP32        |
| LIDAR STL-19         | 2D scanning for obstacle avoidance and mapping | USB and 5 V to Raspberry Pi                            |
| IMU BNO055           | Orientation and acc. estimation                | I <sup>2</sup> C to Raspberry Pi                       |
| 12 V NiMH Battery    | Main power supply                              | Motor driver, 5 V regulator for Raspberry Pi and ESP32 |

## 2.2. Operating Principle of the Robot

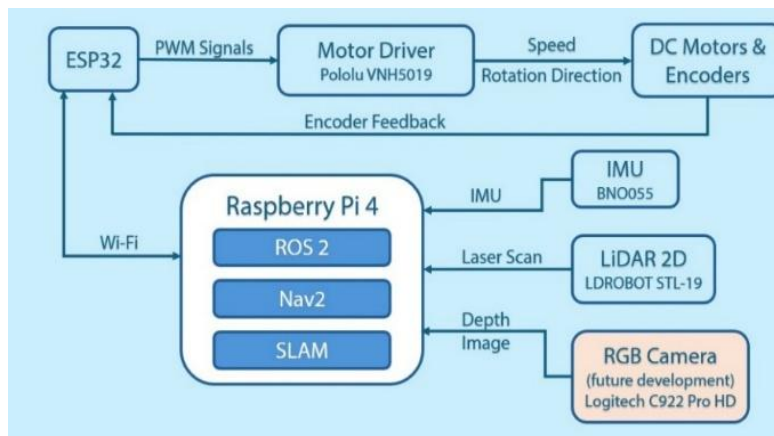


Fig. 2 The architecture of the autonomous robot

AMR2AC employs a distributed architecture in which a Raspberry Pi 4, running ROS 2, Nav2, and SLAM, processes data from the BNO055 IMU and STL-19 LiDAR, and transmits motor commands to the ESP32, which controls actuation via the VNH5019 driver [1,2,10,11,12,13] (Fig. 2). The robot uses the coordinate frames `base_link`, `odom`, and

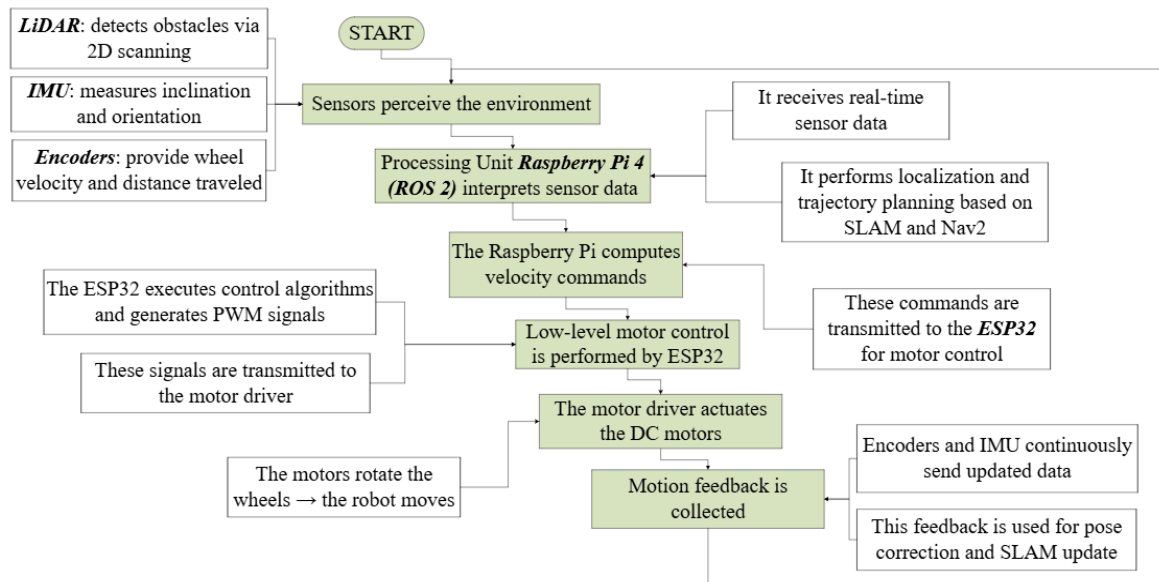


Fig. 3 The functional scheme of AMR2AC

map as defined in REP-105 specifications to ensure compatibility between localization and planning modules in ROS 2 [2,3,4]. Communication occurs via USB and Wi-Fi, supporting indoor autonomous navigation, with optional RGB vision expansion [7].

The diagram (see Fig. 3) illustrates the closed-loop operational architecture of the AMR2AC robotic system, beginning with sensor-based perception and trajectory planning via the ROS 2 framework, and continuing through low-level motor control and feedback integration. This structured process enables autonomous navigation by ensuring real-time environment interpretation and continuous pose correction.

### 2.3. Software Subsystem

The AMR2AC platform operates on ROS 2 Humble Hawksbill, installed on Ubuntu 22.04 LTS, which provides a distributed middleware architecture for reliable communication between software nodes [2,14]. Autonomous navigation is implemented via the Nav2 stack, enabling localization, mapping, path planning, and kinematic control [1,3].

System functionality was validated across three operational modes. Initially, teleoperation was enabled using the *teleop\_twist\_keyboard* node, allowing manual control for verifying motor actuation, ESP32–Raspberry Pi communication, and system responsiveness (Fig. 6) [6]. Point-to-point navigation was achieved through RViz tools (“2D Pose Estimate” and “2D Nav Goal”), with execution launched via *ros2 launch amr2ac amr2ac.launch.py slam:=False* [10]. For autonomous multi-goal navigation, the *waypoint\_follower\_node.py* node was used and tested in extended indoor environments using pre-built maps (Fig. 5) [11].

Mapping was performed using the SLAM module, which fuses LiDAR and odometry data to build real-time maps and estimate pose. The SLAM process was initiated with *ros2 launch amr2ac amr2ac.launch.py slam:=True*, and map saving was done using *ros2 run nav2\_map\_server map\_saver\_cli* (Fig. 4) [12].

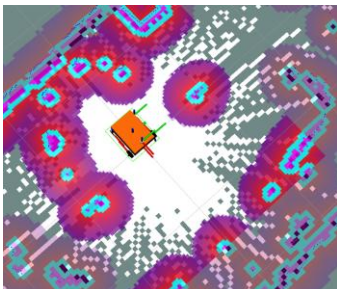


Fig. 4 View in SLAM scanning mode

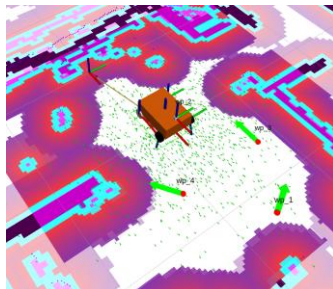


Fig. 5 View in sequential waypoint navigation mode

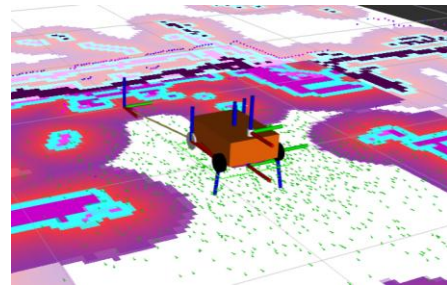


Fig. 6 View in teleoperation mode

## 3. The Design of the Robot

The AMR2AC chassis was iteratively designed in OnShape [8, 15], with focus on modularity, accessibility, and component integration, in line with SAIM constraints. The structure evolved through four versions (V1–V4), and a functional 3D-printed enclosure was developed to protect and organize internal components [9].

The initial version (Fig. 7) featured a minimalist layout with a 416×288 mm GoBilda frame [14], two drive wheels, and two rear passive wheels. Early tests revealed instability due to rear tilting and chassis contact with the ground during obstacle traversal, affecting both balance and sensor performance. In version V2 (Fig. 8), the rear wheels were replaced with omni-directional wheels of equal diameter [8,14], ensuring a uniform 40 mm ground clearance and improved stability. The

internal layout was also optimized by repositioning the motors, battery, and controllers to lower the center of gravity and improve accessibility.

For V2, a functional enclosure was designed in OnShape to provide protection, structural reinforcement, and sensor mounting capability [8]. The modular design was divided into four segments, front-left, front-right, rear-left, and rear-right (Fig. 9), to ensure compatibility with standard FDM printer volumes [9]. The external dimensions ( $427 \times 337 \times 115$  mm) were optimized to enclose all subsystems, including the battery, motor driver, ESP32, Raspberry Pi, IMU, and wiring, while maintaining a 20 mm ground clearance [12,13].

A min. 5 mm internal clearance was ensured above the tallest components. Segment joints were designed with  $\pm 0.3$  mm tolerances for precise alignment, and the enclosure was mounted to the aluminum frame using M3 screws at all four corners [14]. Additional snap-fit joints improved assembly rigidity. Integrated cable channels facilitated wiring management and prevented interference with moving parts [12]. The enclosure was 3D printed in blue PLA with 3 mm wall thickness and 20-30% infill, balancing structural strength and material efficiency [9].

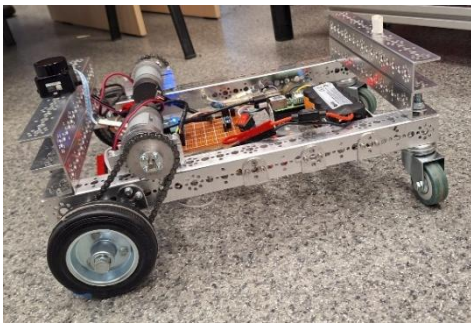


Fig. 7 Version 1 (V1) of the robot

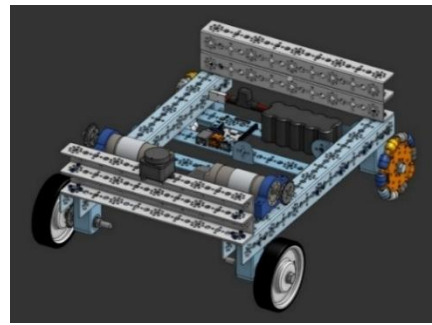


Fig. 8 Improvements implemented in V2

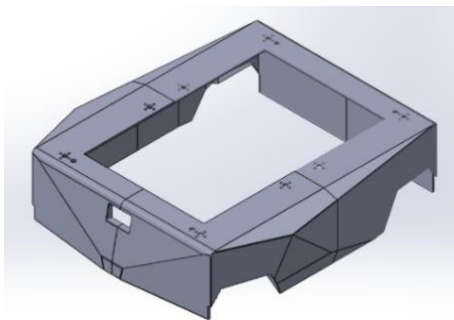


Fig. 9 CAD model of the enclosure

The upper section of the enclosure was designed as a modular cover, split into four equal plates of approximately  $200 \times 160$  mm, each featuring an  $8 \times 8$  mm grid of standardized mounting holes for accessories such as RGB cameras, robotic arms, displays, or sensors (Fig. 10) [13]. This design enables rapid reconfiguration of the platform to meet diverse educational and research needs, in line with SAIM specifications [1]. Each segment is individually detachable and includes mounting holes aligned with the enclosure beneath. The total flat mounting area measures approximately  $400 \times 300$  mm, remaining within the  $200 \times 200 \times 200$  mm upper kit constraint defined in the design requirements [1].

A dedicated 3D-printed PLA mount was designed for the STL-19 2D LiDAR sensor and placed centrally at the front of the top cover to ensure symmetrical environmental coverage (Fig. 11) [9,10]. The clamp-style geometry features a flat base, two M3 threaded holes for fixation, and integrated cable channels for clean wiring. The design also incorporates a slot for a 0.96" OLED display ( $15 \times 46$  mm), powered directly by the ESP32 microcontroller, used to monitor battery voltage during testing [12]. The sensor's central positioning and rigid mounting significantly enhanced SLAM mapping accuracy [1,5] and contributed to trajectory stability during autonomous operation.

#### 4. Implementation and Testing

The implementation phase of the AMR2AC platform encompassed both mechanical and electronic integration, accompanied by iterative prototype testing aligned with parallel software development. Versions V2, V3, and V4 were evaluated under controlled laboratory conditions to verify chassis geometry, system stability, component interoperability, and seamless integration within the ROS 2 middleware environment [1,2]. All tests adhered to SAIM-defined operational parameters, utilizing flat indoor surfaces and constant lighting conditions [1].

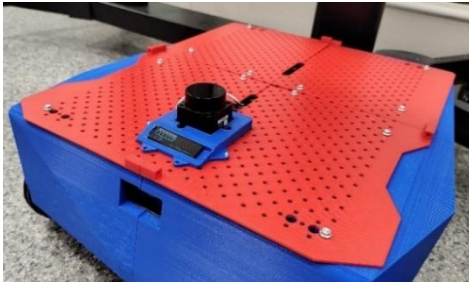


Fig. 10 Fabricated modular cover

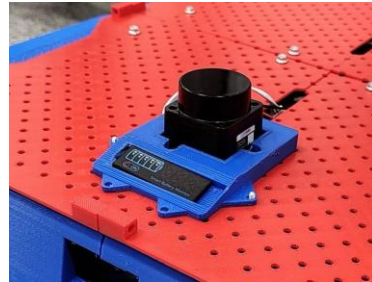


Fig. 11 3D-printed LIDAR mount

**Version V2** represented the first fully operational prototype, constructed with a metallic chassis featuring two drive wheels and two omni wheels for passive stabilization. Electronic modules were externally mounted, allowing direct access during validation. This stage emphasized evaluation of drivetrain behavior, motor driver performance, and bidirectional communication between the ESP32 and Raspberry Pi units [12]. Teleoperation was conducted using the `teleop_twist_keyboard` package in ROS 2 [6], confirming reliable system responsiveness to linear and angular velocity commands. However, cable-induced vibrations were noted, prompting the development of a protective enclosure to mitigate mechanical instability. The LiDAR unit, temporarily affixed for mapping validation, exhibited scan inconsistencies due to flexural movement, underscoring the necessity for a rigid, centralized mounting structure [9].

**Version V3** introduced structural improvements, including a dedicated LiDAR bracket and internal component repositioning to optimize mass distribution (Fig. 12). Functional testing targeted autonomous navigation using the Nav2 framework [2,3], while SLAM Toolbox was employed to generate environmental maps [1,5]. The robot demonstrated accurate localization and trajectory execution via the Nav2 Goal interface [10], successfully avoiding static obstacles. The newly implemented enclosure allowed full rotation of the drive wheels through hexagonal apertures and ensured secure placement of internal components [9].

**Version V4** featured a refined four-point mounting system for the enclosure and a modular top panel (Fig. 13) [8], enhancing protection and mechanical robustness. Validation procedures focused on autonomous waypoint navigation in RViz [4,11], with the robot accurately localizing and traversing between user-defined goal positions while avoiding mapped obstacles. An OLED display, integrated on the front panel and powered by the ESP32 module [12], provided real-time feedback on battery voltage (Fig. 11). The results confirmed platform stability and full compliance with the mechanical and software design criteria established in the initial development phase [1,3,5,8].

## 5. Discussions

The AMR2AC platform meets the design and operational criteria defined under the SAIM framework, which emphasizes modularity, safety, and autonomous navigation in structured indoor environments. The platform's actual dimensions ( $445 \times 410 \times 387$  mm) remain within the  $500 \times 500 \times 400$  mm constraint, and the modular top cover accommodates additional kits up to  $270 \times 400 \times 200$  mm, surpassing the required  $200 \times 200 \times 200$  mm volume. Autonomous functionality

was implemented using ROS 2 and Nav2, including localization, trajectory planning, and obstacle avoidance. Mapping was validated through the SLAM Toolbox, with laboratory testing confirming stable operation, trajectory deviations under 10 cm, and system response times below 0.5 s. The use of accessible hardware (ESP32, Raspberry Pi 4, 2D LiDAR) and open-source software (ROS 2 Humble) aligns with the SAIM principles of replicability and educational value. As such, AMR2AC fully satisfies the functional, safety, and extensibility requirements established by the project coordinator.



Fig. 12 Version 3 (V3) - physical implementation

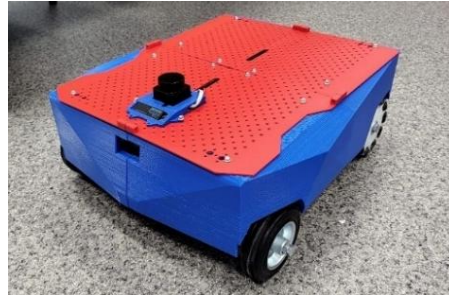


Fig. 13 Version 4 (V4) -fully assembled physical robot

Early 3D-printed components exhibited tolerance inconsistencies, requiring manual adjustments for proper alignment and enclosure assembly. Mechanically, accurate alignment of wheels and motors was essential to prevent uneven wear and trajectory drift. Vibrations affecting the LiDAR sensor degraded scan quality and were mitigated through a custom rigid mount. The compact internal layout also necessitated optimized cable routing and signal isolation to avoid electrical interference. On the software side, initial Nav2 and AMCL parameter settings led to localization errors and trajectory oscillations. These were addressed by increasing odometry update rates, filtering IMU data, and enlarging the local costmap. Due to processing constraints, the Raspberry Pi 4 struggled to run RViz and Nav2 concurrently, prompting the use of an external laptop for visualization.

Integrating a 3D LiDAR sensor would enable volumetric mapping and obstacle detection, extending the robot's applicability in complex environments. Replacing the Raspberry Pi 4 with a Raspberry Pi 5 or a more powerful computing unit is also recommended, allowing real-time visual data processing and neural network inference.

To improve localization accuracy and reactive control, advanced sensor fusion is proposed, combining odometry, IMU, LiDAR, and future RGB-D inputs using robust filtering techniques. Enhancing autonomy through a self-docking charging station is another priority. This would allow the robot to locate and connect to a charging point using visual or geometric markers, an approach widely adopted in industrial and educational AMR systems. Finally, transitioning testing and algorithm training to a virtual environment such as Gazebo is envisioned. This would enable rapid, risk-free validation of navigation and control algorithms across diverse and non-reproducible scenarios.

## 6. Conclusions

The AMR2AC project has demonstrated the feasibility of developing a differential-drive autonomous robotic platform aligned with the SAIM framework, which supports indoor navigation through teleoperation, SLAM-based mapping, and waypoint execution, implemented using ROS 2 and the Nav2 framework. Experimental validation in controlled environments confirmed stable operation, defined accuracy and responsiveness thresholds. The platform's modular hardware and software architecture enabled efficient integration of components and adaptation to technical

constraints. Its physical dimensions, mechanical design, sensor suite, and processing architecture complied with the specifications outlined by the project supervisor. In the short term, AMR2AC meets the foundational requirements of an educational autonomous mobile robot while in the long term, it offers a robust foundation for further functional expansion. By integrating a 3D LiDAR sensor, enhanced processing hardware, autonomous docking functionality, and advanced perception and control algorithms, the platform is expected to evolve into a mature and versatile system, suitable for deployment in complex academic and industrial scenarios.

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# DESIGN AND IMPLEMENTATION OF AN EXPERIMENTAL MODEL OF A ROBOTIC SYSTEM FOR SCREW ASSEMBLY

POPA George-Adrian, GHEORGHITĂ Vlad(Conducător științific)

Faculty: Industrial Engineering and Robotics, Specialization Applied Computer Science in Industrial Engineering,

Year of Study: 4, e-mail: [adrianpopa0522@gmail.com](mailto:adrianpopa0522@gmail.com)

*ANSTRACT: For an assembly process to be efficient and reliable in industrial production, it is necessary to automate repetitive operations such as screwing by using robotic systems. The aim of this project is to develop an experimental system that integrates a robotic arm, a screw feeding system, and an automatic screw picking and fastening device, in order to optimize the assembly process and reduce cycle time and manual intervention. The implementation of such robotic solutions contributes to increased productivity, ensures the quality of assemblies, and aligns industrial processes with modern automation and standardization requirements.*

*KEYWORDS: Automation, Product Design, Automated Assembly, Robotic Arm*

## 1. Introduction

In modern industries, the automatic screwing process presents a significant challenge due to the requirements for precision, speed, and reliability. In many industrial applications, manual screwing is inefficient because it can lead to variations in tightening force, human errors, and long execution times [1].

In conventional production lines, parts are moved on a conveyor belt, and workers manually screw them using electric screwdrivers. In this case, productivity depends on the workers' experience, as well as the reliability and quality of the assembly. However, it is not easy for every company to adopt the automation process due to high costs [2].

Threaded fasteners are widespread in modern manufacturing industries. As the demand for automation in production increases, so does the demand for automated threaded fastening systems. However, many fundamental problems and engineering challenges still hinder the robustness of automation, especially for smaller screws and critical product finishing requirements [3].

One solution to reduce production costs and increase both efficiency and precision in the assembly process is the use of a robotic arm along with an algorithm designed to perform its movements in key areas, assisted by a specially adapted device for picking up and screwing components onto workpieces. All of this is coupled with a feeding system that prepares the screws by bringing them into an ideal position for pickup and assembly.

This process revolves around three essential components: the robotic arm, a screwing device, and a screw feeding system, which work together for efficient assembly. The process can be described in a simplified manner through the following steps:

1. The workpiece is manually positioned and fixed in the designated area for assembly. Through the developed interface, the operator signals the robot to begin the assembly.
2. The robotic arm starts by picking up the screwing device located nearby, while the feeder begins bringing the first screw to be picked up.
3. With the device held in its gripper, the arm positions itself towards the screw pickup area. Here, the first screw, brought to the end of the feeder's chute, is centered and magnetically attached to the device's hex key.
4. The next step is for the arm to precisely move to the pre-established coordinates of the workpiece hole, at which point the screwing device begins to operate.
5. Once the screw is threaded and successfully secured, steps 3 and 4 are repeated depending on the number of holes on the workpiece.
6. Finally, the robot retracts, awaiting the next workpiece.

## 2. Current Stage

The work is divided into 3 subsections as follows: the 3D model and electronic system of the Feeder, the 3D model and electronic system of the Screwing Device, and the computer system.

### 2.1. The 3D Model and The Electronic System of the Feeder

This subsection will present the essential components for screw feeding and positioning them in a favorable position for pickup by the robotic arm, as well as elements that are part of the electronic system. Table 1 lists the main components of the feeder, and Figure 1 highlights them as follows:

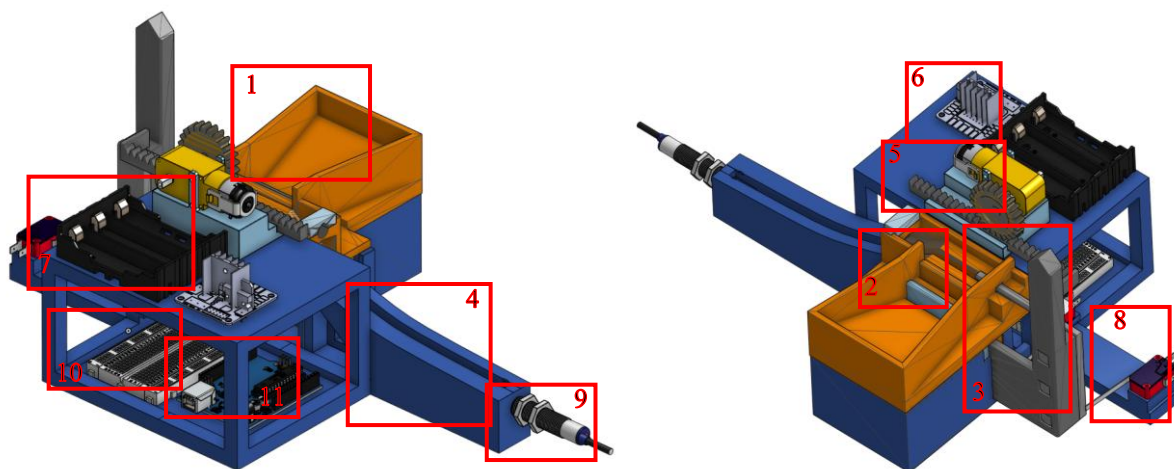


Fig. 1. The 3D Model of the Feeder

\* - Some of the 3D components used in the project were imported from external sources

| Nr.crt | Component                                                                                                                                                                                                                          |
|--------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1*     | The area where screws will be poured by the operator [4]                                                                                                                                                                           |
| 2*     | A ladder-type mechanism used for sorting and advancing screws to the placement area, where they will fall head-up, which is a favorable position for pickup [4]                                                                    |
| 3*     | A mechanism for pushing the screws towards the pickup area [4]                                                                                                                                                                     |
| 4      | The gutter, where screws accumulate as the previous mechanisms bring them. This also serves as the location for picking up the first screw at the end. With a slight inclination of the path, it promotes movement towards the end |
| 5*     | A Pinion-Rack mechanism attached to the handle of the pushing mechanism. This is powered by a motor, automating the sorting, advancing, and pushing actions [5]                                                                    |
| 6      | L298N Driver, which allows control of the motor's direction and speed                                                                                                                                                              |
| 7      | A battery holder that will externally power the driver and the motor                                                                                                                                                               |
| 8      | Limiters placed at the ends of the travel, which the handle will reach, changing the motor's direction                                                                                                                             |
| 9      | A proximity sensor placed at the end of the chute that detects the presence of the first screw in the tail and confirms that a screw is present for pickup                                                                         |
| 10     | A breadboard for wiring connections                                                                                                                                                                                                |
| 11     | An Arduino controller for programming the components                                                                                                                                                                               |

and integrated as part of the overall assembly, while others were custom-designed to meet the functional and dimensional requirements, except models of electrical components.

### Electronic System of the Feeder

The electronic components were selected based on specific technical characteristics, purchased, and individually tested to ensure they function properly. The blue piece called "Extension" in Figure 1 was designed in such a way as to allow for proper assembly and positioning of the components, while maintaining an organized appearance with components and wires hidden.

The 3D models were made from PLA, and some of them were custom-designed, such as the chute, the motor holder, and the box on which the components are placed (which was later made from metal profiles and rivets).

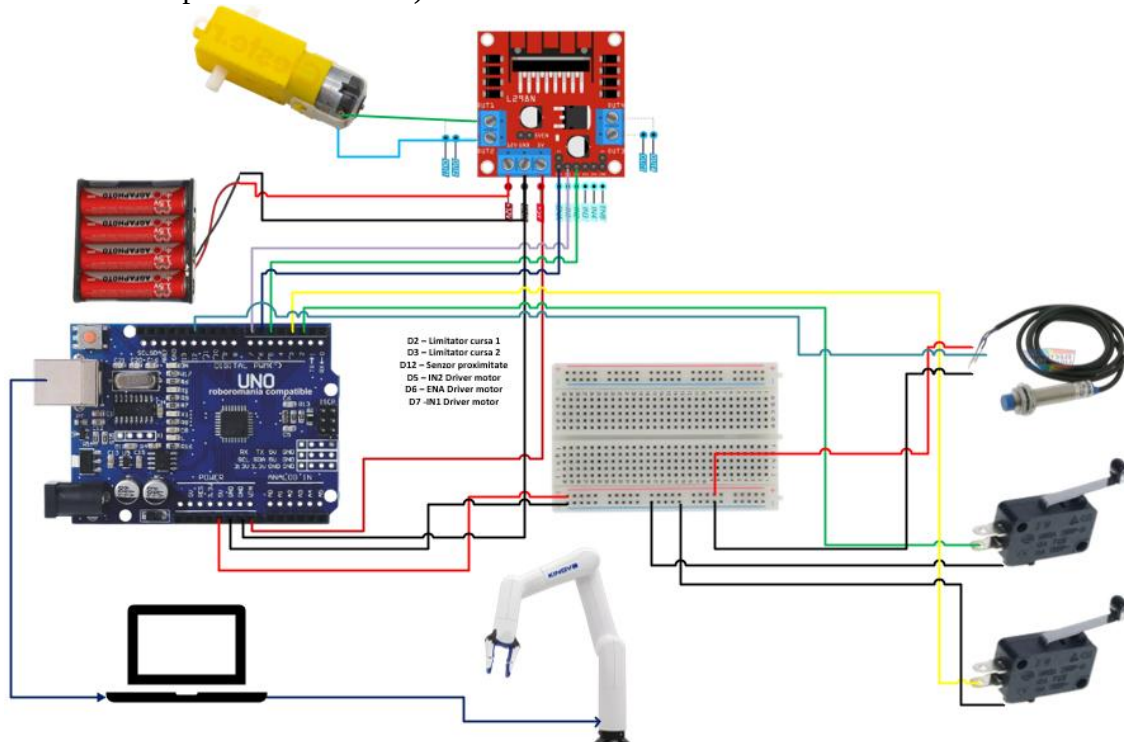


Fig. 1. Electrical Schematic

**Figure 2** shows the electrical schematic of the system. The motor is controlled by the L298N driver, which regulates the direction and speed through the PWM signal. The sensors (NPN inductive and limit switches) provide feedback on the presence of screws and the position of the mechanism.

The motor is powered by an external source, while the sensors receive 5V from the Arduino. All signals are connected to the digital pins of the controller, allowing the programming of the operational logic.

The breadboard extends the power supply to the sensors, and USB communication allows both the programming of the robot based on the screw's status and real-time monitoring.

## 2.2. The 3D Model and Electronic System of the Screwing Device

This subsection presents the essential components of the screwing device, which is designed for picking up the screw and performing the screwing operation on the workpiece, under the action of the robotic arm's gripper. It also describes the elements of the electronic system that ensure the device's functionality. Table 2 lists the main components of the screwing assembly, and Figure 3 highlights them as follows:

Table 2

| Nr.crt | Component                                                                |
|--------|--------------------------------------------------------------------------|
| 1      | Component housing                                                        |
| 2      | JGY370 High-Torque Gear Motor                                            |
| 3      | Rotating Part with Hex Key (Allen key) for Screwing, Driven by the Motor |
| 4      | Motor Driver for Controlling Motor Direction and Speed                   |
| 5      | TOF400 VL53L1X Laser Distance Sensor                                     |

|   |                                                                                                                                 |
|---|---------------------------------------------------------------------------------------------------------------------------------|
| 6 | Power Supply Board with USB-C Port and Level Converter Set to 9V, allowing the battery to deliver power to the driver and motor |
| 7 | Level Converter to Limit the 9V Current to 5V for the Controller                                                                |
| 8 | ESP32-C3 Super-Mini Controller, used for programming the components                                                             |
| 9 | 9V Battery, used to externally power all components                                                                             |

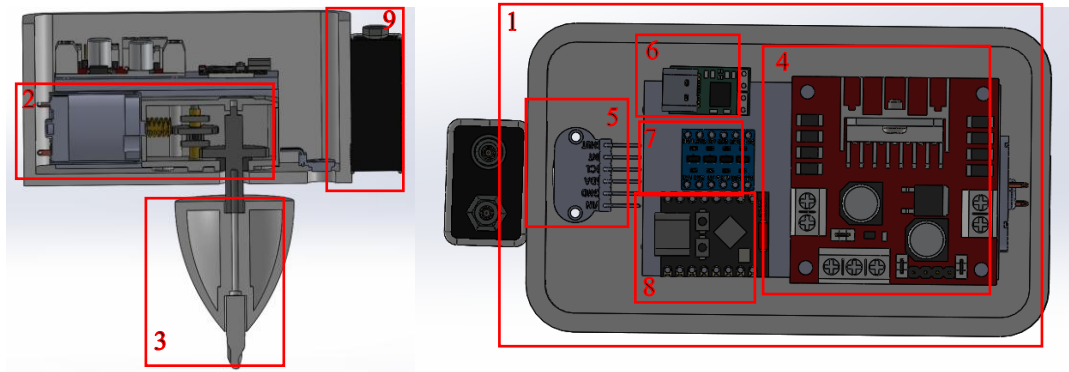


Fig. 3. The 3D Model of the Screwing Device

### Electronic System of the Screwing Device

The electronic components were selected based on specific technical characteristics, with the main focus on choosing components with low weight and compact dimensions so that the robotic arm could support the device (maximum 500g [3]).

The assembled device currently weighs a total of 350g. Another important factor was the motor torque, which had to be sufficient to ensure complete screw insertion.

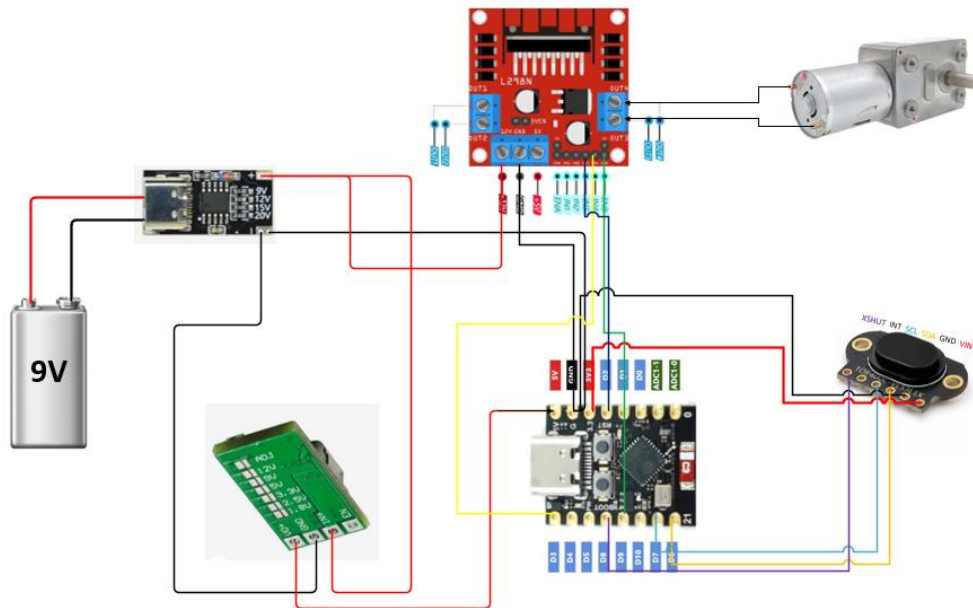


Fig. 4. Electrical Schematic

Figure 4 shows the electrical schematic of the assembled system.

The system is powered by a 9V battery through a voltage converter that supplies 5V to the ESP32-C3 Super Mini board. The L298N motor driver controls the screwing motor and is powered directly from the 9V source. The VL53L1X laser distance sensor is connected to the board,

ensuring position measurement relative to the workpiece. All electronic components share a common ground to ensure proper system functionality.

### 2.3. Application for Programming the Components

The Arduino IDE software was used to program both controllers as well as the electronic components used in this project.

```

1  int in1 = 5;
2  int in2 = 7;
3  int ena = 6;
4  int switchDR = 2; //Limitator de cursa Dreapta
5  int switchST = 3; //Limitator de cursa Stanga
6  int senzorInductiv = 12; // Senzor inductiv
7
8  bool motorPornit = false;
9  bool surubDetectatAnterior = false;
10
11 void setup() {
12   pinMode(in1, OUTPUT);
13   pinMode(in2, OUTPUT);
14   pinMode(ena, OUTPUT);
15   pinMode(switchDR, INPUT_PULLUP);
16   pinMode(switchST, INPUT_PULLUP);
17   pinMode(senzorInductiv, INPUT);
18   Serial.begin(9600);
19   digitalWrite(in1, HIGH);
20   digitalWrite(in2, LOW);
21   analogWrite(ena, 255);
22 }
23
24 void loop() {
25   int readingDR = digitalRead(switchDR);
26   int readingST = digitalRead(switchST);
27   int stareSenzorInductiv = digitalRead(senzorInductiv);
28
29   // Control manual cu butoane
30   if (readingDR == LOW) {
31     oprireMotor();
32     delay(50);
33     digitalWrite(in1, LOW);
34     digitalWrite(in2, HIGH);
35     analogWrite(ena, 255);
36     delay(50);
37   }
38   else if (readingST == LOW) {
39     else if (readingST == LOW) {
40       oprireMotor();
41       delay(50);
42       digitalWrite(in1, HIGH);
43       digitalWrite(in2, LOW);
44       analogWrite(ena, 255);
45       delay(50);
46     }
47     // Control automat cu senzor inductiv
48     if (stareSenzorInductiv == HIGH) { // Niciun surub detectat
49       if (!motorPornit) {
50         pornireMotor();
51         Serial.println("Motor pornit (surub lipsa)");
52         motorPornit = true;
53       }
54       surubDetectatAnterior = false; // resetare stare
55     }
56     else { // Surub detectat
57       if (motorPornit) {
58         oprireMotor();
59         Serial.println("Motor oprit (surub detectat)");
60         motorPornit = false;
61       }
62       if (!surubDetectatAnterior) {
63         Serial.println("Surub disponibil pentru prelevare");
64         surubDetectatAnterior = true;
65       }
66     }
67   }
68   void oprireMotor() {
69     analogWrite(ena, 0);
70     digitalWrite(in1, LOW);
71     digitalWrite(in2, LOW);
72   }
73   void pornireMotor() {
74     digitalWrite(in1, LOW);
75     digitalWrite(in2, HIGH);
76     analogWrite(ena, 255);
77   }

```

Fig. 6. The code used for the feeder functionality

The code shown in Figure 6 controls the screwing motor both manually (via limit switches) and automatically (using an inductive sensor).

In manual mode, activating either limit switch (right or left) stops the motor and briefly reverses its direction, simulating a return motion.

In automatic mode, the absence of a screw starts the motor to initiate feeding, while the detection of a screw stops the motor, signaling that a screw is available for pickup by the robot.

```

53 void loop() {
54   int dist = sensor.read() + offset;
55
56   Serial.print("Distanța: ");
57   Serial.print(dist);
58   Serial.println(" mm");
59
60   // Dacă distanța este mai mare decât pragul de pornire, motorul stă oprit și se resetează contorul
61   if (dist > pragPornire) {
62     contorSubPrag = 0; // Resetare contor
63     if (motorPornit) {
64       Serial.println("Oprire motor (distanța mare, peste 180mm)");
65       opresteMotorul();
66       motorPornit = false;
67     }
68   }
69   // Distanța e sub pragPornire și peste pragOprire => măsurătoare validă
70   else if (dist <= pragOprire && dist > pragPornire) {
71     contorSubPrag++; // Măsurare validă
72
73     // Dacă sunt destule măsurători valide la rând, motorul porneste
74     if (contorSubPrag >= masuratorNecesar && !motorPornit) {
75       Serial.println("Pornesc motorul (infilare...)");
76       pornesteMotorul();
77       motorPornit = true;
78     }
79   }
80   // Distanța e sub pragOprire => se opreste motorul
81   else if (dist <= pragOprire) {
82     contorSubPrag = 0; // Resetăm contorul
83     if (motorPornit) {
84       Serial.println("Oprire motor (ajuns la piesa)");
85       opresteMotorul();
86       motorPornit = false;
87     }
88   }
89   delay(100);
90 }
91
92 void pornesteMotorul() {
93   digitalWrite(IN1, HIGH);
94   digitalWrite(IN2, LOW); // Motor merge în sensul de infilare
95 }

```

Fig. 7. Part of the Screwing Device code

The code presented belongs to the Screwing Device and serves to automate the process using a distance sensor to monitor the position of the tool relative to the assembly piece. Based on the measured distance, the device's motor is automatically started or stopped to ensure proper screw insertion and to avoid overloading the mechanism.

#### **2.4. Functionality of the Entire Assembly Together with the Robotic Arm**

In the designed robotic system, the automated screwing assembly is functionally integrated with a robotic arm, which ensures precise positioning of the tool relative to the workpiece. The collaboration between these two components enables the complete automation of the screwing assembly process, reducing human intervention while improving the accuracy and repeatability of the operation.

To ensure coherent and repeatable functioning of the robotic screwing system, all components have been physically integrated onto a specially designed support platform. This platform serves as a fixed positioning board, establishing the exact location of each element in the assembly so that the robotic arm's movements and the process flow occur in a predictable manner.

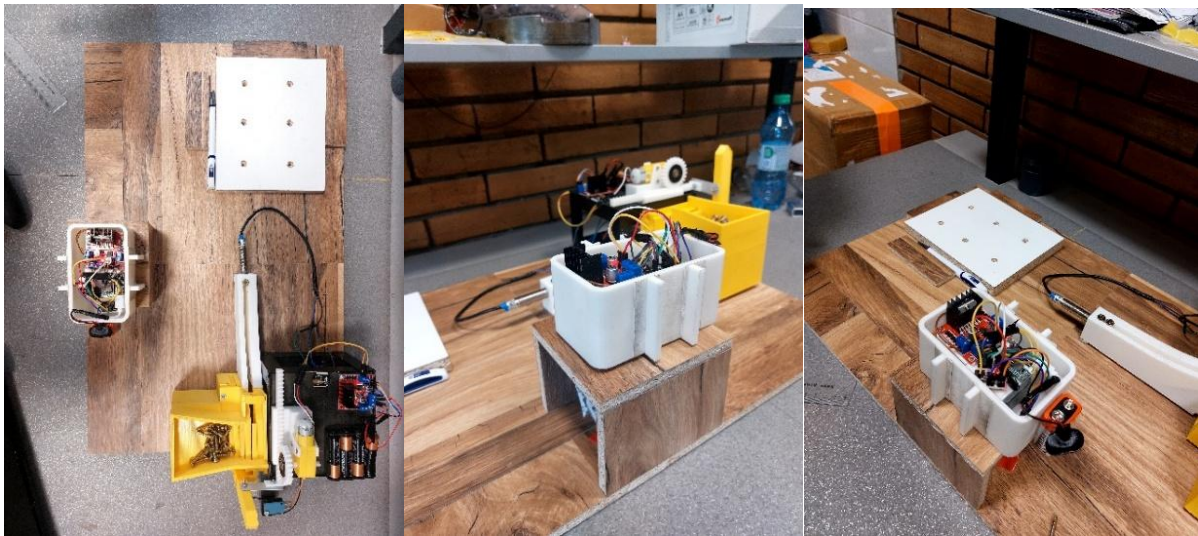


Fig. 8. Pictures of the physical assembly

For programming the robotic arm, in this case the Kinova Gen 3 Lite, the Visual Studio Code environment was used along with the Python programming language.

The source code includes calls to functions from the official Kinova SDK library, which allows for control and coordination of the Kinova robotic arm [3].

Additionally, movements to predefined coordinates are implemented, corresponding to the fixed positions of the components within the assembly (Figure 9).

```

57 # Coordonatele si orientarea tinta deasupra obiectului
58 target_x = 0.485
59 target_y = -0.01
60 target_z = 0.230
61
62 target_theta_x = 0.0 # -0 grade
63 target_theta_y = 178.0 # -178 grade
64 target_theta_z = 88.3 # -88.30 grade
65
66 # 1. Deplasează deasupra obiectului
67 self.move_to_cartesian_pose(
68     x=target_x,
69     y=target_y,
70     z=target_z,
71     theta_x=target_theta_x,
72     theta_y=target_theta_y,
73     theta_z=target_theta_z,
74     action_name="Deasupra obiectului"
75 )
76
77
78 # 2. Coborâre la poziția de destinație pentru apucare
79 target_x_pick = 0.485 # Noua poziție x
80 target_y_pick = -0.01 # Noua poziție y
81 target_z_pick = 0.093 # Noua poziție z
82 self.move_to_cartesian_pose(
83     x=target_x_pick,
84     y=target_y_pick,
85     z=target_z_pick,
86     theta_x=target_theta_x,
87     theta_y=target_theta_y,
88     theta_z=target_theta_z,
89     action_name="Coborâre pentru apucare"
90 )
91
92 # 3. Închide gripper-ul
93 self.control_gripper(position=1.0, mode=Base.ph2.GRIPPER_POSITIVE)
94
95 # 8.2. Deplasează obiectul cu surub deasupra primei gauri
96 final_x = 0.323
97 final_y = 0.173
98 final_z = 0.158
99 self.move_to_cartesian_pose(
100     x=final_x,
101     y=final_y,
102     z=final_z,
103     theta_x=target_theta_x,
104     theta_y=target_theta_y,
105     theta_z=target_theta_z,
106     action_name="Deplasează la poziția deasupra primei gauri"
107 )
108
109 # 9. Coborâre încet pentru înfiletare
110 print("[Încep coborârea lentă pentru înfiletare...]")
111 start_z = 0.118
112 end_z = 0.083
113 steps = 3
114 z_values = [start_z - i * (start_z - end_z) / steps for i in range(1, steps + 1)]
115
116 for z in z_values:
117     self.move_to_cartesian_pose(
118         x=0.323,
119         y=0.173,
120         z=z,
121         theta_x=target_theta_x,
122         theta_y=target_theta_y,
123         theta_z=target_theta_z,
124         action_name=f"Înfiletare la z={z:.3f}m"
125     )
126
127 # 10. Deplasează obiectul cu surub deasupra primei gauri
128 final_x = 0.325
129 final_y = 0.173

```

Fig.9. Code from the movement program

### 3. Conclusions

The assembled system successfully demonstrated the correct operation of the robot-assisted screwing process, with all components integrated onto a support platform for fixed positioning.

For future improvements, it is proposed to develop a monitoring interface, increase actuation speed, enhance accuracy through fine calibration, and add a camera for automatic hole recognition — thus eliminating the need for fixed positioning of the workpiece.

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## CONTROLLING A VISION-GUIDED ROBOTIC ARM THROUGH NATURAL LANGUAGE INSTRUCTIONS USING LLMS AND YOLO

SĂROI Dragoș-Gabriel, GHEORGHITĂ Vlad (Conducător științific)

Faculty: Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering, Year of study: 2, e-mail: [dragosgabriel1505@gmail.com](mailto:dragosgabriel1505@gmail.com)

*ABSTRACT: This research proposes the development of a system enabling a robotic arm to perform object manipulation tasks based on natural language instructions. This system integrates a web-based interface for user input, a large language model (LLM) for interpreting user commands and a YOLO-based computer vision algorithm for object recognition. Commands such as "Please, move the apple in the box." are processed, allowing the robotic arm to locate and manipulate the object requested by the user. The goal of this paper is to show how we can simplify the interaction between humans and robots, reducing the programming knowledge needed to operate robotic systems and significantly decreasing the training time required for the end-users.*

**KEYWORDS:** robotic arm, image processing, large language model, YOLO, ROS2

### 1. Introduction

Robotic arms have become fundamental elements of industrial automation, used in operations such as assembling components, manipulating parts and performing precise machining processes. Their ability to operate continuously, reducing human error and increasing efficiency and speed, is contrasted by the high level of technical expertise required for classical robot programming, which considerably increases implementation costs. Moreover, in [1] the presence of an upward trend of the need not only for fully autonomous robotic systems, but also for semi-autonomous systems that allow human interaction is mentioned.

The aim of this work is to provide a solution that facilitates intuitive human-robot interaction without the need for technical knowledge [2]. It is thus necessary to develop a method that allows the user to communicate in natural language with the robotic arm. In this context, a pre-trained Large Language Model (LLM) becomes capable of converting instructions formulated in natural language, e.g. "Hello, please lift the screw.", into JSON-like structures that can be easily integrated with robotic control flows.

Complementarily, image processing and object recognition algorithms provide the capability to identify and locate objects mentioned in user commands in the workspace of the robotic arm.

The system proposed through this research can be described in five fundamental steps:

1. Design a web interface that allows the user to enter the command in natural language;
2. Semantic interpretation to extract the user's intent, action and desired object via an LLM running on a local server;
3. Forwarding the results generated by the LLM in JSON format to an image processing algorithm based on OpenCV and YOLO (images are taken with a camera on the robotic arm that sees from above its workspace);

4. Determining the contour of the object, calculating the center of gravity, the angle of rotation relative to the horizontal and two collinear points with the center of gravity that are on the extremities of the contour that will become the target coordinates of the gripper;
5. Execute the command with ROS2 by transmitting the coordinates and orientation to a node and visualize a simulation of the motion of the robotic arm and its end-effector.

The main objective is to demonstrate a significant reduction in the need for programming and training time required for users, facilitating the rapid adoption of robots in a variety of manufacturing and logistics environments.

## 2. Current state of research

Currently, the research has completed the fundamental stages of design and validation of the main system components: the web interface for natural language input of commands, the LLM module for semantic interpretation, and the image processing module for accurate localization of objects in the workspace.

The modules highlighted in gray in the architecture diagram, seen in Figure 1 - the transmission of results to ROS2 and the actual integration with the robotic arm hardware - are under development. The implementation of these modules will advance the research towards a fully operational solution, directly impacting the efficiency and accessibility of robotic systems in industrial and non-industrial applications.

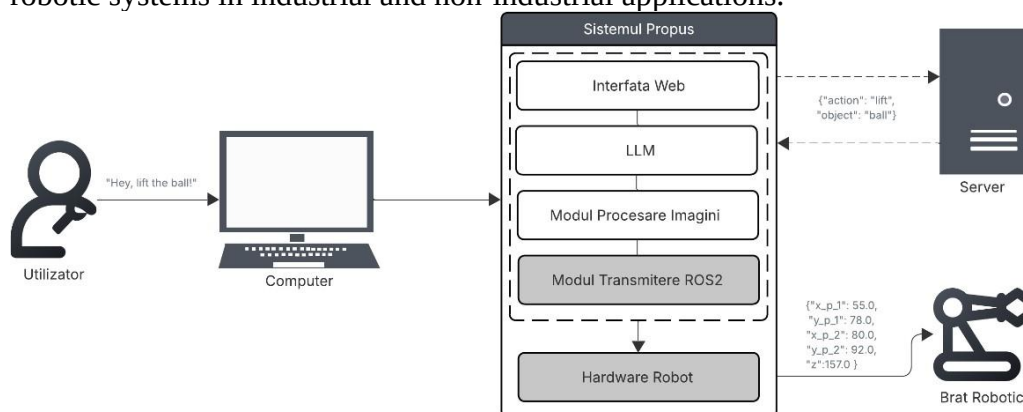


Fig. 1. Diagram of the proposed system.

### 2.1 Web interface

In this first sub-chapter, the main steps for realizing a simple web interface, which can be seen in Figure 2, will be presented, where the user will submit the desired commands and receive feedback. The implementation was realized on three technological levels as follows:

#### a. Web document - HTML:

The interface structure is built in a file called *"index.html"*, which defines two main sections: the chat area where the user can enter and send instructions via an `<input>` element and a `<button>` element, and the feedback area which integrates a `<video>` element that allows real-time playback of the camera feed mounted on the robotic arm.

b. Web document styling - CSS:

The styling is done through the `"styles.css"` file, for the two-column layout of the two main sections. A minimalist design and neutral colors have been used to maintain simplicity.

c. Running the web application on the local server - Python Flask:

For the back-end, the Python Flask framework was used, with a main route `"@app.route("/")` which ran the template `"index.html"` and the static route for the stylization file `"styles.css"`. Natural language processing is also performed in the server script.

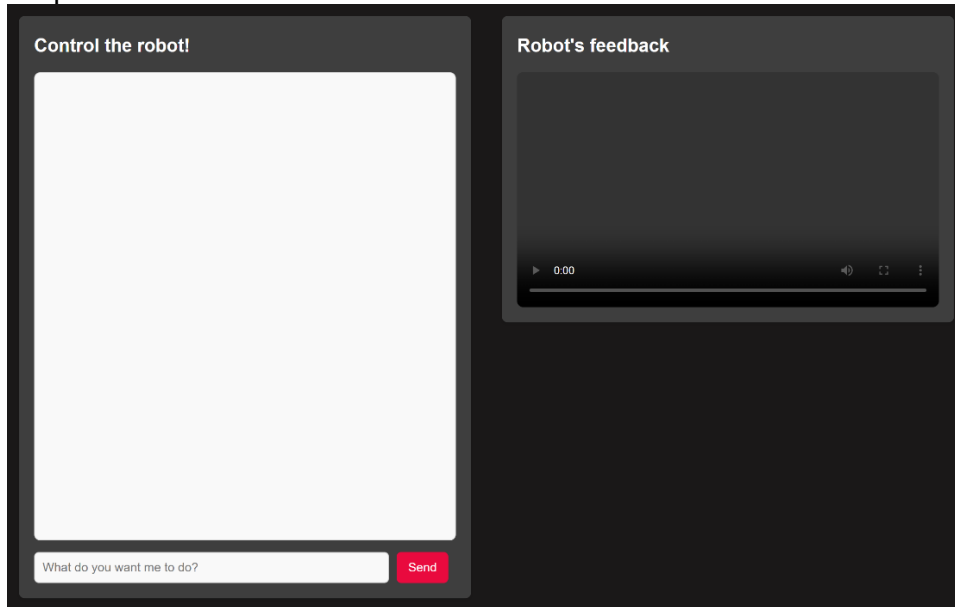


Fig. 2. Interface of the proposed web application.

## 2.2 Natural language processing module

In this subchapter we will present how user commands are sent to the back-end and how they are processed.

In the proposed architecture, the commands in the `<input>` field are fetched with JavaScript at the moment the `"Send"` or `"Enter"` button is pressed and sent to the server. We use AJAX technology to transmit the data asynchronously and avoid reloading the page each time a command is sent, keeping the conversation visible in the `<chatbox>` section.

At the back-end level, the Llama 3.2-1B model provided by Meta is used, which has a billion parameters, making it suitable for local running through Ollama. The model has been trained specifically for the research purpose, being assigned a clear set of instructions and examples built based on *"The Instruction Set Completeness Theorem"* [3], so that it learns to exclusively extract the action and object desired by the user in JSON format, which will be saved in the file `"1_command.json"`. Figure 3 shows the functionality of the program:

**You:** Hello, please lift the apple from the table. Thanks!

**LLM:** `{"action": "lift", "object": "apple"}`

Fig. 3. Transforming natural language into a JSON instruction.

## 2.3 Image processing and analysis module

In order to identify the position of the object specified in the command, the camera with which this system will be provided takes a central image, perpendicular to the workspace, each time the robot returns to its initial position. The image is then processed in two steps by the Python scripts - *"object\_detector.py"* and *"contour\_processor.py"*, as will be presented in sections 2.3.1 and 2.3.2.

### 2.3.1 Object detection and localization using YOLO

The script *"object\_detector.py"* uses the YOLOv8 object recognition model trained on about 2600 fruit pictures in various shapes, positions and lighting conditions. The objects identified by this algorithm are stored in a JSON file (*"2\_detect\_yolo.json"*), to be iterated in a for-loop until the user's desired object (Figure 2) is found in the results returned by YOLO. Once found, the file *"3\_coord\_ob\_command.json"* is created, where the name of the object and the coordinates of the bounding rectangle that encloses it, observed in Figure 4, are stored:

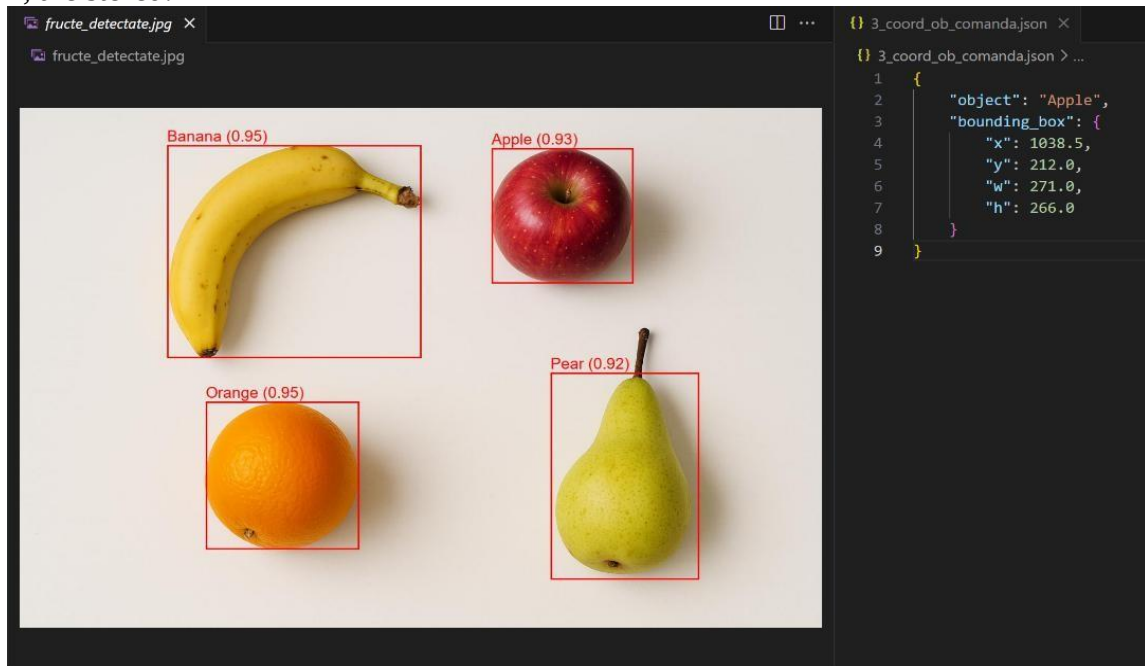


Fig. 4. Detected fruits and coordinates of the object specified in the command.

### 2.3.2 Object contour extraction and calculation of final coordinates

The *"contour\_processor.py"* script uses the OpenCV library to compute the final coordinates that will allow the robotic arm to manipulate the object. We create a mask around the object, extract the color plane and by applying a threshold we determine the contour of the desired object. Using the contour, we calculate the center of gravity and generate a rotated rectangle that will determine the angle of rotation of the object relative to the horizontal. In order to determine the x-axis and y-axis coordinates that the gripper will have to reach so it can grasp the object, we need two points collinear with the center of gravity, located on the extremities of the contour (Figure 5). We determine the distance between the center of gravity and the center of the surrounding rectangle (1), the angular projections on the axes (2), the distances from the center of the rectangle to the gripper points (3) and finally, the coordinates of the gripper points in the global reference (4):

$$v_x = x_c - x_{cd}, v_y = y_c - y_{cd} \quad (1)$$

$$d_x = v_x \times \cos \alpha, d_y = v_y \times \sin \alpha \quad (2)$$

$$t_1 = 2 - d_x, t_2 = -2 - d_y \quad (3) \quad -$$

$$x_{p1} = x_c + t_1 \times \cos \alpha, x_{p2} = x_c + t_2 \times \cos \alpha, \\ y_{p1} = y_c + t_1 \times \sin \alpha, y_{p2} = y_c + t_2 \times \sin \alpha \quad (4)$$

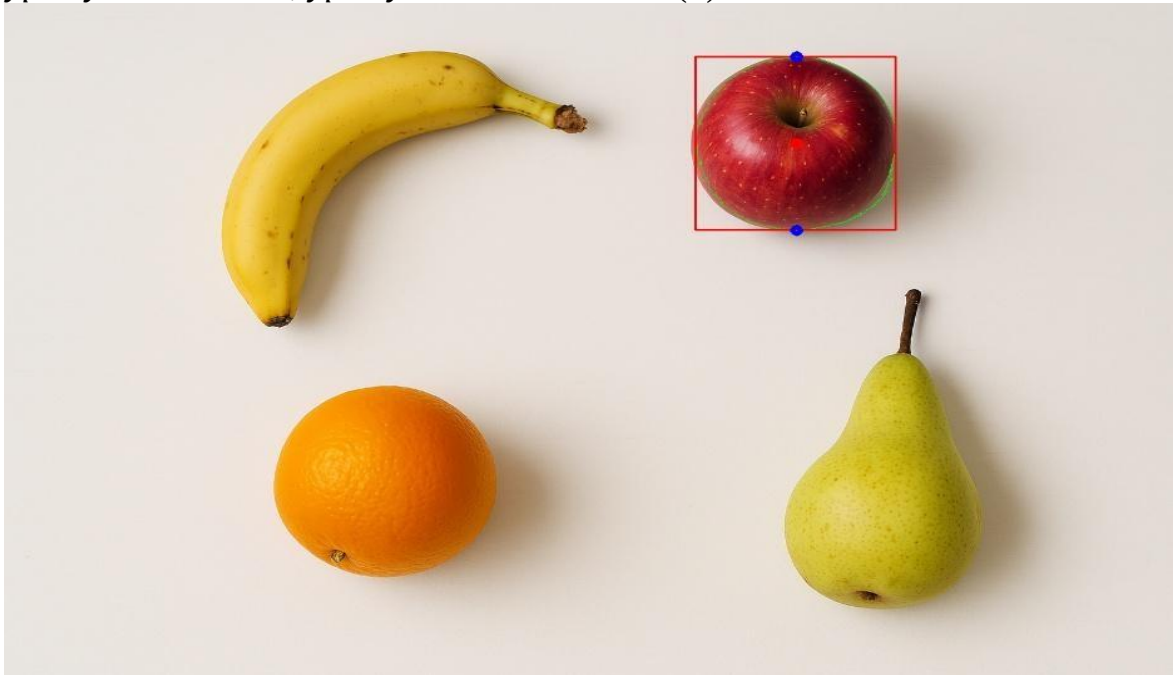


Fig. 5. Outline of the desired fruit (green line) and the two points.

By combining the two modules, the system precisely localizes the object named in the command and provides the exact coordinates needed for further end-effector trajectory planning in ROS2.

### 3. Performance

The proposed system was tested on a local server with an AMD Ryzen 7 6800HS CPU, 32 GB of RAM and an NVIDIA GeForce RTX 3050 GPU. In order to measure the performance of the pre-trained LLM used, we compiled a validation dataset consisting of 50 prompts with different expressions, tones, actions and objects, each manually correlated with the expected JSON form (the "action" and "object" fields) and the one obtained by testing. For the evaluation we used two metrics:

- "BLUE - General", measures the percentage of n-grams overlap in JSON responses.
- "Exact Match", measures the percentage of predictions in which the complete field or individual fields perfectly match the reference.

The values obtained are illustrated in Figure 6:

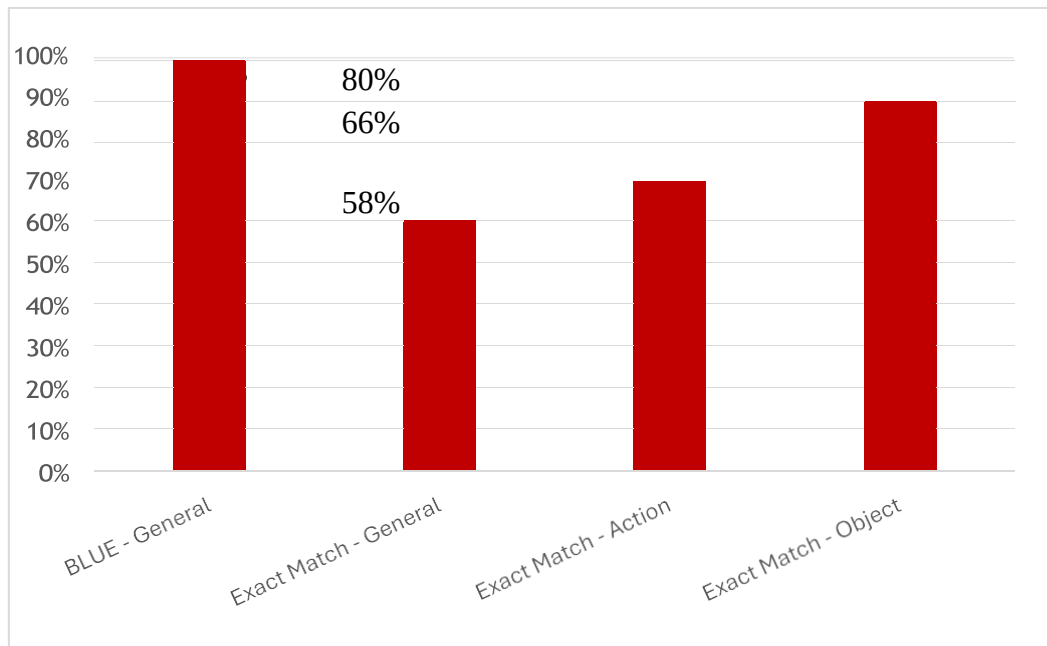


Fig. 6. LLM performance on the test set.

The obtained results highlight an overall high performance of command interpretation (91.04%) and a satisfactory accuracy of object identification (80%), while action extraction remains the most vulnerable (66%), decreasing the overall score of exact matching of the user's desire with the result returned by the proposed system (58%). The scores thus suggest the need for adjustments to the examples provided to the LLM, in particular the expansion of the action- specific vocabulary. The method used for training, "*few shot learning*", easily allows for modifications, making the model learn quickly and adapt to new situations encountered [4]. We also note as an important metric the response time of the system running on the local server, an average of 7 seconds from sending the command to getting the result.

#### 4. Future work, challenges and improvements

##### a. Implementation and testing in ROS2 and Gazebo:

A first next step is to integrate the Gazebo simulation environment with ROS 2 Humble, using WSL2. Although WSL2 provides a convenient use of Linux on Windows, it behaves similar to a virtual machine without direct access to hardware resources such as GPU or USB. In practice, it has been observed that on the local server with WSL2, Gazebo can run in graphical mode, but limitations arise (high CPU load, additional latencies, intermodular communication problems, "*black- screen*", etc.) Consequently, the identified limitations can be solved either by software optimizations or by switching to a dedicated Linux machine. It is shown in Figure 7 the successful implementation in RViz of a complete virtual model of the robotic arm by creating an URDF model with 6 joints, followed by the configuration of the control in Gazebo, in order to then be able to transmit the data obtained with the system created through the ROS2 nodes and validate the proposed solution.

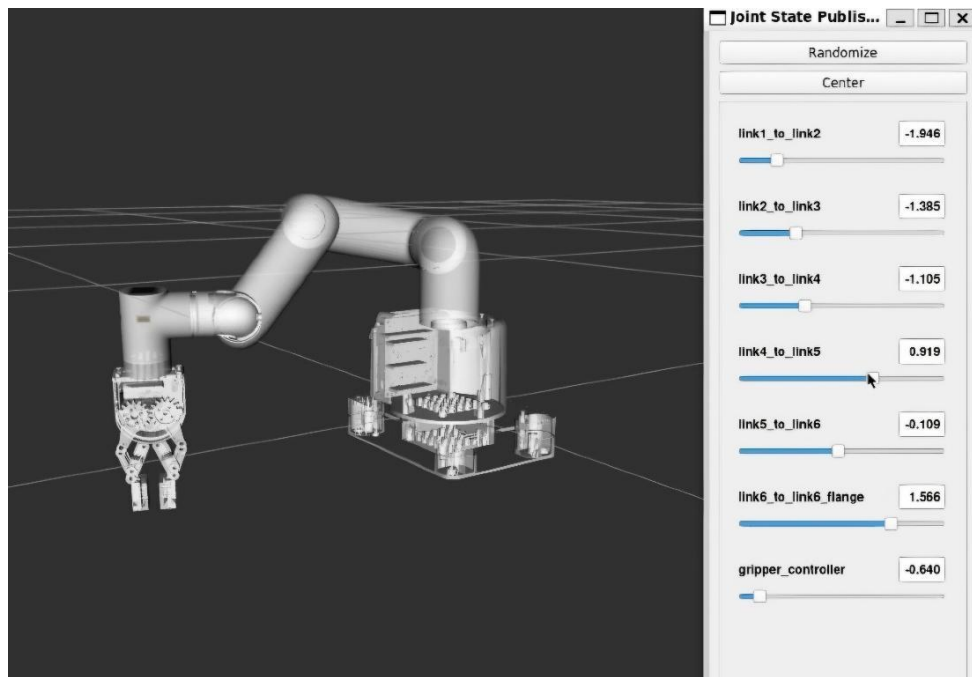


Fig. 7. Simulation of the robotic arm model in RViz.

b. Generating the coordinates for motion planning:

In order to plan the motion, the pixel coordinates corresponding to the objects must be transmitted in ROS2 spatial coordinates. Due to the perpendicular mounting of the camera, if the plane of the workspace is known (e.g. a table at a fixed height), a constant distance to the camera can be assumed or we can use plane calibrations to compute the actual object coordinates. Since a simple video camera does not provide depth information, alternative solutions will be analyzed. LIDAR sensors or depth cameras (RGB-D/stereo) can be used. Each method has advantages and disadvantages: time-of-flight/LIDAR systems can provide measurements over long distances and under varying conditions, but are expensive; *stereo/structured-light* cameras are often more affordable and can be easily integrated, but accuracy decreases in low light or at long distances.

c. Improvements to NLP and the YOLO model:

Both components can be enhanced by adapting to the application-specific data desired by the user. For the natural language processing module, terminology-specific patterns of objects in the workspace can be trained or configured so that common user commands are correctly recognized. In ambiguous situations (e.g. "Please move the red cube." when there are two red cubes), the system might ask additional questions for clarification. For YOLO, the need for additional training ("*fine-tuning*") on environment-specific images is felt. Fine-tuning a pre-trained model on generic data leads to significant increases in accuracy, as the model learns details specific to objects and lighting/positioning conditions.

## 5. Conclusions

In this paper we have demonstrated the feasibility of a new stage of human-robot interaction, based on the combination of a large language model (LLM) with image processing algorithms (YOLO, OpenCV). By designing a simple web interface, natural

interpretation of commands and extraction of coordinates of objects in the workspace, the effort required to control a robotic arm can be significantly reduced.

The industrial relevance of the research lies in the ability to rapidly integrate robotic manipulators into production and logistics flows without the need for complex interventions. Moreover, such solutions open up the idea of AGI (Artificial General Intelligence) systems, in which robots will understand and execute complex requests in a way as close as possible to natural human dialog [4]. Moreover, the extraordinary capabilities of LLMs have been shown not to be fully understood or used by researchers, which was analyzed in [5], denoting a great potential for discovering new industrial applications in which they could be used.

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## 7. Notations

The following symbols are used throughout the paper:

- $x_c, y_c$  = The coordinates of the object's center of gravity;
- $x_{cd}, y_{cd}$  = Coordinates of the center of the oriented rectangle;
- $\alpha$  = The angle of rotation of the rectangle relative to the horizontal;
- $l$  = The width of the bounding box;
- $v_x, v_y$  = Axes projections;
- $d_x, d_y$  = Displacement projections on the local axes of the rectangle;
- $t_1, t_2$  = The distances from the center of the rectangle to the attachment points;
- $x_{p1}, y_{p1}, x_{p2}, y_{p2}$  = Coordinates of the grasp points in the global reference.

# CHASSIS DEVELOPMENT OF AN AUTONOMOUS EDUCATIONAL ROBOT AMR2AB INTEGRATED IN ROS2 AND NAV2

**PUFU Andrei Florin, NICA Daniel-Rareș, ANDREI Patrick Cristian,**  
**ODOROAGĂ Vlad-Ionuț, ABAZA Bogdan Felician and DOICIN Cristian-Vasile (Conducători științifici)**

<sup>1</sup>Faculty: Industrial Engineering and Robotics, Specialization: Industrial Informatics,  
Year of study: 2, e-mail: [vlad\\_ionut.odoroaga@stud.fiir.upb.ro](mailto:vlad_ionut.odoroaga@stud.fiir.upb.ro)

<sup>2</sup>Faculty of Industrial Engineering and Robotics, Manufacturing Engineering Department

***ABSTRACT:** This paper presents the development stages, objectives and results of a project aiming at the realization of an autonomous educational platform, characterized by stability, modularity and configurability, fully integrated in ROS2 and NAV2. The proposed objectives, implementation methods and development process of hardware and software components are detailed, including hardware selection, communication architecture and testing strategies. The paper provides a clear and coherent overview of the technical specifications of the robot, providing a solid framework for educational and research applications. It also presents the modifications made to the physical and numerical model, together with the motivations behind these adjustments, based on the functional requirements and test results.*

***KEYWORDS:** autonomous robot, indoor navigation, ROS2 educational platform, differential-drive robot, ROS 2, Nav 2.*

## 1. Introduction

In the current context of accelerated technological development, mobile autonomous systems are gaining an increasingly important role in education, research and industry. The present work aims to develop a mobile autonomous robotic autonomous system integrated in the ROS2 ecosystem, with educational and experimental applications. The basic idea of the project is to create a versatile tool for active learning and familiarization with basic concepts in robotics and engineering. The research fits in the direction indicated by the coordinators from the very beginning: the development of Autonomous Intelligent Mobile Intelligent Systems - SAIM based on environment perception, planning, control, localization, visualization, flexible behaviors [1].

The educational objective is to strengthen competence in the field of mobile autonomous systems. It addressed a complete development cycle, from the conceptual design stage to its physical implementation and then experimental validation. The project supports the formation of an engineering mindset and the development of problem-solving skills for problems of medium to high complexity.

Short-term technical objectives (3-4 months): In the first phase, the research focuses on the implementation of a basic system for robot teleoperation and autonomous navigation in an already known environment, using the standard packages provided by ROS2 (e.g. Gazebo and RVIZ) through which the robot is given points to reach. This step involves setting up the software architecture and integrating all hardware and electronic components with the ROS interface, as well as testing simple obstacle avoidance algorithms.

Medium-term technical objectives (1 year): during the year, the project will evolve towards advanced autonomous navigation based on dynamic scenarios and real-time processing of sensor data. This stage involves the development of real-time localization and mapping (SLAM) methods, improved trajectory planning and the introduction of other robot subsystems.

The goal is to obtain a robust, sufficiently strong and narrow platform that can move autonomously, with potential applicability in various tasks (e.g. guiding students in the faculty).

## 2. Defining the specifications of the autonomous educational robot

For the realization of this project, the following general specifications are proposed by the coordinators to develop the autonomous robot using the navigation software provided by ROS2 [1]:

1) Operating environment: controlled indoor environment, on flat surfaces, constant illumination to ensure repeatability and to minimize the influence of external (exogenous) factors such as unevenness of the action surface or light variation;

2) Chassis:

a. maximum dimensions: length x width x height=500x500x400 [mm];

b. maximum payload: 20 kg;

c. allows additional subsystems to be mounted on the upper part of the chassis, which can fit within the volume 200x200x200 [mm];

The chassis specifications, such as the footprint and payload will allow the mounting of modular kits (human communication interface, robotic arm, etc.) to extend the functionality of the robot. Also, the robotic platform will be able to perform both promotional activities within the faculty as well as perform intralogistics activities similar to industrial environments in production centers.

3) Mechanical and electronic components are chosen according to the constraints imposed by the robotics kit, and the generic structure of the autonomous robot is predefined by the coordinators.

**Table 1. Mechanical and electronic components used for the mobile platform**

| Category       | Component                          | Model                                                  | Functional Purpose                                                                                                | Connection                                                                        |
|----------------|------------------------------------|--------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Drive          | Two DC geared motors with encoders | Gobilda Yellow Jacket Planetary Gear Motor 223 RPM [1] | Wheels drive                                                                                                      | Mounted on the front side of the chassis connected by chains to the drive wheels. |
| Engine control | Engines Driver                     | Pololu VNH5019[2]                                      | Controls engine speed and direction.                                                                              | Connected to ESP32                                                                |
|                | Microcontroller                    | ESP32 NodeMCU-32S[3]                                   | Manages control signals sent to the driver.                                                                       | Connected via USB to Raspberry PI                                                 |
| Processing     | Processor                          | Raspberry Pi 4 Model B [4]                             | Running Ubuntu 22.04 LTS with ROS2 Humble; responsible for higher-level processing, sensor fusion and navigation. | N/A                                                                               |
| Sensors        | IMU                                | Sensor IMU BNO-055 [5]                                 | Inertial Unit of Measurement                                                                                      | Connected via USB to Raspberry PI                                                 |
|                | Lidar 2D                           | LDROBOT STL-19 [6]                                     | For environmental scanning and obstacle detection                                                                 | Connected via USB to Raspberry PI                                                 |
|                | RGB camera                         | Logitech C922 Pro HD [12]                              | Future integration with vision-based systems                                                                      | Connected via USB to Raspberry PI                                                 |
| Current        | Built-in rechargeable battery      | NiMH de 12V                                            | Robot power supply                                                                                                | Connected to Raspberry PI                                                         |

The present project aims at realizing an educational autonomous robot, compatible with the SAIM (Systems Autonomous Intelligent Mobile Systems) paradigm, focused on the integration of perception, planning, control, localization and flexible autonomous behaviors. Utilizing Robot Operating System 2 [7], a modern and extensible middleware dedicated to robotics, we aim to develop an intelligent mobile platform capable of dynamically interacting with its environment. The software architecture is built on the foundation of ROS 2 Humble [8] and Nav2 [9] whose modular structures enable application-oriented research-driven development. Nav2 (Navigation2) is an advanced navigation framework for intelligent mobile autonomous systems that facilitates the autonomous movement of mobile

robots in complex and dynamic environments. Through a modularized and extensible architecture, this system integrates key components such as localization, trajectory planning and collision avoidance into a workflow adaptable to various hardware configurations and application requirements. A key aspect of Nav2 is its flexibility, allowing customization of the navigation algorithms according to task specifics, from service robots to autonomous vehicles.

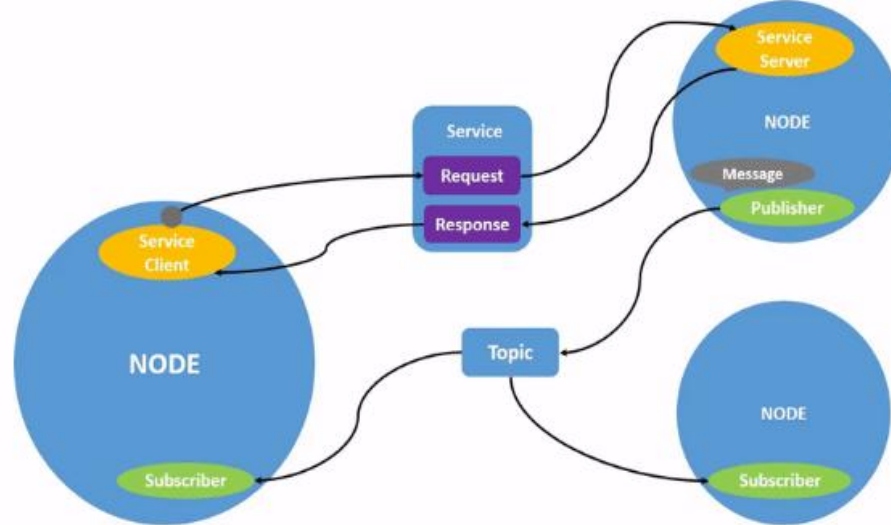


Fig. 1 – How the nodes work in Robot Operating System 2 [10]

The SLAM (Simultaneous Localization and Mapping) algorithm allows a mobile robot to localize itself in an unknown environment while simultaneously constructing a map of it. In the ROS2 framework, SLAM is implemented by integrating the Lidar sensor, processing their data and using probabilistic algorithms provided by the ROS2 library, namely slam toolbox. The robot collects information about the surrounding environment and associates it with the estimated position, continuously updated by a Bayes-ian filter (particle or extended Kalman), to correct localization errors and refine the map. ROS2 provides a distributed and efficient architecture, facilitating communication between the nodes that manage sensor data, localization, mapping, and motion planning [11].

### 3. Robot design

The robot design aimed to create a stable platform to support robotic systems weighing up to 20 kg (cameras, arms, etc.), considering the mode and placement requirements of the proposed sensors to be used for navigation.

The need for motor mounts compatible with the Gobilda Yellow Jacket Planetary Gear Motor 223 RPM Gobilda Yellow Jacket Planetary Gear Motor 223 RPM [1] is recognized, which are sized as follows: distance between mount mounting holes of 16 mm, motor diameter of 36 mm, motor length without shaft of 116.4 mm and motor mass of 437g (Fig. 3.1).

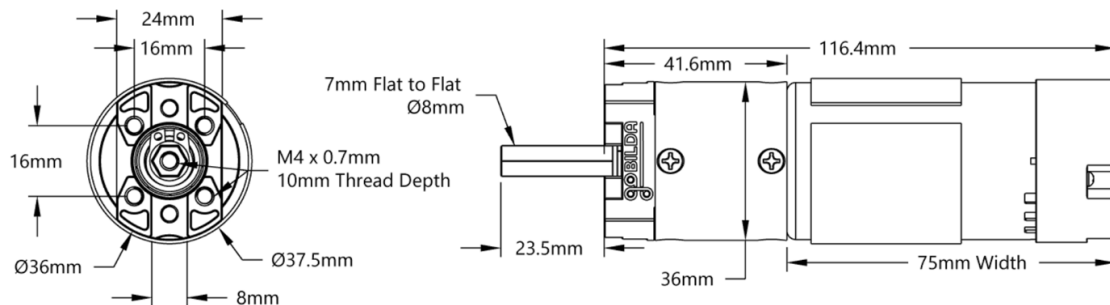


Fig. 3.1 Dimensional specifications Gobilda Yellow Jacket Planetary Gear Motor 223 RPM [1]

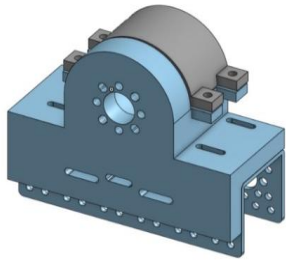


Fig. 3.2. Version 1 engine mounts

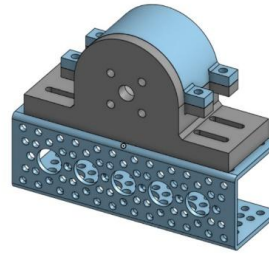


Fig. 3.3. Version 2 engine mounts

It is considered that the optimal method for creating holes is to design them before the part is manufactured to save material. Thus, variant 1 was born. An experimental design that was discarded on the grounds that it took up a lot of necessary space in the side of the robot, which would have resulted in additional spacing of the wheels from the chassis and thus unnecessarily increased the chassis gauge.

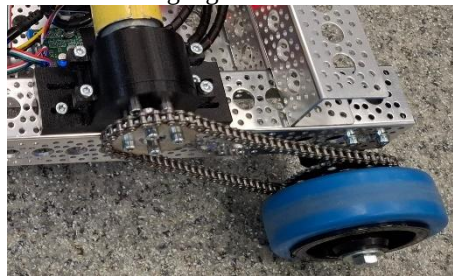


Fig. 3.4. Version 2 of the support in the physical model

After identifying some non-optimal design aspects of the first bracket variant, a second optimized version was designed and implemented and adopted as the final solution. The bracket is made of two pieces for a simple reason: to form a tight fit between the bracket and the motor, by default the diameter of the gripping part of the motor bracket to be larger than the diameter of the gripping part of the bracket. In this way, the motor is seated on the lower part of the bracket, and the upper part is tightened using bolts until the assembly is completely stable.

An important aspect in developing the bracket was the need to tighten the chain. During the design the position of the bracket was fixed, but in the future with the addition of elements to the chassis there may be a need to change the position. To allow the engine mount to be movable and at the same time the chain to be tensioned, the mounting holes on the chassis were lengthened as follows: the size of two detachable chain links was measured, translated into the lengthening of the holes and a margin of error was applied.

This was followed by the development of a protective and aesthetically pleasing enclosure. Starting from the numerical model of the chassis, the first one-piece version was designed to model the design. As the faculty's 3D printers have defined dimensions, the first variant was then "broken" into several pieces that could be 3D printed. In turn, the second variant requires improvements before being implemented, such as: creating Lidar support and updating for the latest chassis model.

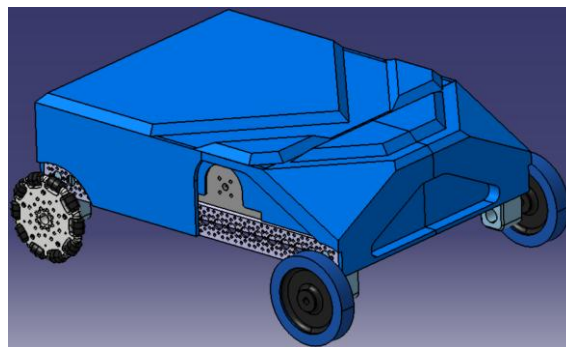


Fig. 3.5. Numerical model of the 'shell' type

Eventually the chassis took its final shape, which is the basis for further developments: defining the body and adding the mechanisms that will perform the necessary tasks. The chassis can be seen in its physical version in Fig. 3.6. and its numerical version in Fig. 3.7.

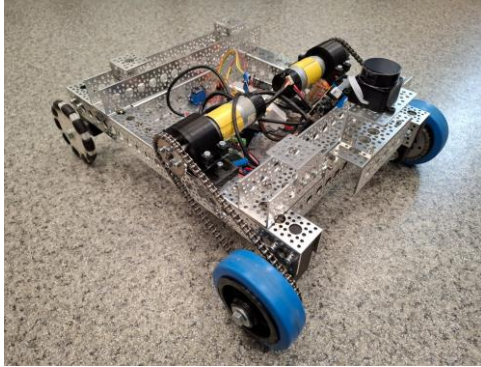


Fig. 3.6 Physical model current status

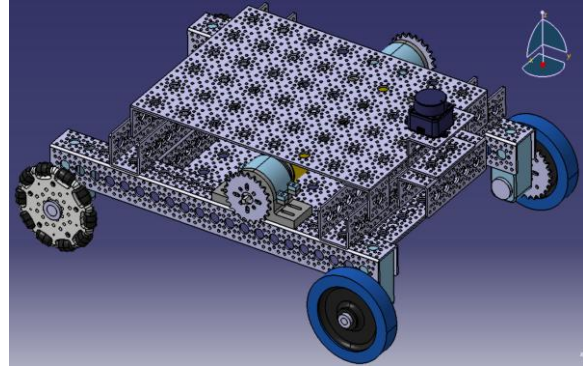


Fig. 3.7 Numerical model current state

#### 4. Realization and Testing

The realization of the robot consisted in identifying the available mechanical elements and making a numerical model based on the elements available in the laboratory.

The first step in the constitution of a mobile system is the choice of suitable motors for the proposed robot dimensions. This is done by testing existing motors and identifying their wear and tear. Following the tests performed on the motors, it is proposed to use two Gobilda motors with 26.9:1 transmission ratio, rated speed at 12V of 223RPM, maximum torque 2.1 Nm and with integrated magnetic encoder. Thus, in the proposed configuration, the robot can move at a speed appropriate to its tasks.

The robot has as main structural elements 2 metal profiles of 419.1 mm dimension placed in parallel, they are connected by means of two Actobotics profiles of 228.6 mm dimension. The placement of the electronic components is made on a 326g aluminum plate with gauge dimensions: 304.8 mm long, 228.6 mm wide. To move the robot, it is proposed to use two 100 mm diameter free omni-directional wheels located at the rear of the robot and two 100 mm diameter tank-type wheels driven by the two motors through a chain. The distance between an omni-directional wheel and a tank type wheel having as reference point the center of the circle determined by the circumference of the wheel is 380 mm and the distance between two wheels of the same type having the same reference points is 370 mm. This gives a rectangular footprint of the robot of 370 x 380 mm. These data give a correct structural analysis of the chassis, resulting in good structural rigidity due to the parallel mounting of the long metal profiles, and functional symmetry due to the balanced arrangement of the electronic components.

To ensure optimal functionality of the user-defined paths, the coordinates of the LiDAR and the IMU sensor were specified with respect to the robot's center of reference, which is considered with coordinates (0,0) at equal distance from the 2 motor-driven wheels.

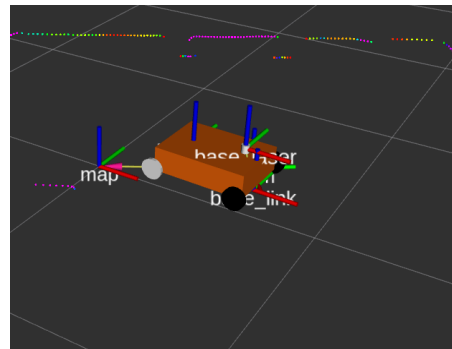


Fig. 4.1 Component coordinate systems in the Rviz interface

Fig. 4.2 Coordinate systems of the robot relative to the (0,0) point of the map

Operating scenarios of the robotic platform:

1) Moving environment scanning scenario using SLAM inside Rviz - in this scenario, the robot is started from the terminal, the connection to it is made, and from another WSL terminal with Ubuntu 22.04 and ROS 2 the Rviz application is launched, where the environment scan is visualized in real time. From the second terminal the teleoperation of the robot is started from the keyboard, and it is moved so that through the sensors the robot draws a map of its location.

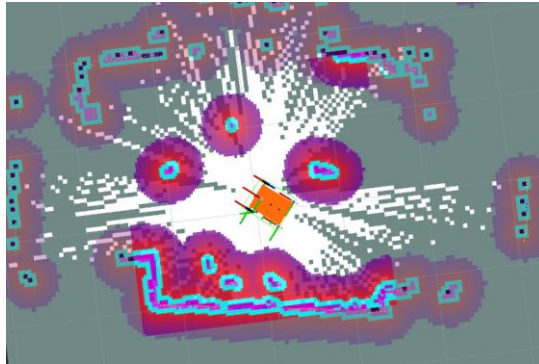


Fig. 4.3 Making a map through the Rviz application interface

2) Multi-point traversal scenario - in this scenario, the robot is started, the connection to the robot is established, and from the WSL terminal the Rviz application is launched, where the starting point of the robot is placed using coordinates in the xOy system and the points through which the autonomous traversal of the robotic platform is desired are defined.

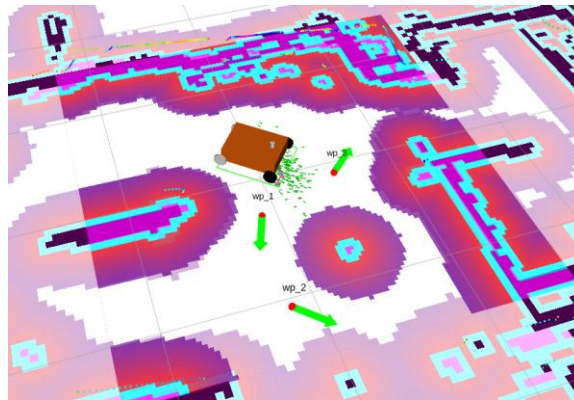


Fig. 4.4 Moving through 3 waypoints

## 5. Conclusions

In this study, a Mobile Intelligent Autonomous System has been realized, able to localize itself in a completely unknown environment and to build its map, thus providing a flexible autonomous behavior. The robot follows the general specifications given by the coordinators, with the following overall dimensions: 480 mm (length)  $\times$  430 mm (width)  $\times$  250 mm (height). The design of the robot was carried out according to practical requirements, providing a relevant and stable numerical model for the implementation of further developments. The construction of the robot was carried out in accordance with the numerical model, adapting various aspects according to the technical requirements and parts provided by the robotics kit.

It is proposed to implement a software intended to assist indoor navigation to predefined locations for students, teachers, and visitors by interacting with a web application to be accessed by the user. The interaction with the user can be performed either through the user's own mobile phone or through a screen integrated in the smart mobile

platform. In this way, the user selects the language in which he/she wants to communicate with the robot and transmits to the robot information about the location within the faculty where he/she wants to go, all from the application menu, and the robot creates the optimal route and accompanies the user to the destination, keeping the calculated route in case of disconnection from the internet. During the journey, the robot talks to the user and provides information about the room where the user is about to arrive. This system can be implemented via built-in speakers. The same system could be developed in a museum or archaeological site. Another direction of development is proposed, namely, to connect the robot to the timetable and room data assigned for various events provided by the faculty website. Subsequently, the robot can notify students whose lecture room is changed by the lecturer by seating them in the room listed in the timetable and providing them with information and directing them to the new room.

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# VIRTUAL INSTRUMENT FOR CALCULATING CENTERS OF MASS AND MOMENTS OF INERTIA FOR RIGID BODY SYSTEMS

SECIU Antonio Cezar, PĂUNESCU Oana Bianca, SPÂNU Paulina(Conducător științific)

Facultatea: Inginerie Industrială și Robotică, Specializarea:Inginerie Integrată, Anul de studii:I e-mail:antonio\_cezar.seciu@stud.fiir.upb.ro

**ABSTRACT:** *This paper presents the design and implementation of a virtual instrument developed in LabVIEW, aimed at solving a problem in the field of technical mechanics. The program enables the calculation of centers of mass and moments of inertia for systems composed of rigid bodies with various geometries. The user can input up to 10 elementary bodies (rectangles, circles, or point masses), and the algorithm uses standardized mathematical formulas from the specialized literature. When the application is run, both the system diagram and the calculated values for the centers of mass and moments of inertia are displayed.*

**KEYWORDS:** *LabVIEW, rigid bodies, technical mechanics*

## 1. Introduction

Solving problems in the field of technical mechanics, especially those related to determining the centers of mass and moments of inertia for rigid body systems, often involves extensive and error-prone mathematical calculations. Calculation mistakes can lead to incorrect results, and the time required to obtain those results and generate graphical representations is usually significant.

The developed virtual instrument allows for the rapid and precise calculation of the coordinates of centers of mass and moments of inertia for systems composed of up to 10 elementary bodies, with various geometric shapes, using standardized formulas from specialized literature

Regardless of the input values entered, when the application runs, the schematic of the analyzed system is automatically generated, along with the calculated values for the center of mass and moments of inertia of the assembly.

## 2. Current stage

The rigid body system consists of a material point, three bars of varying lengths, and two discs of different radius. The schematic is shown in Figure 1.

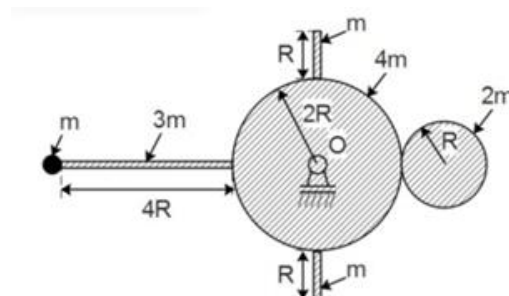


Fig. 1. Rigid body system

The system is composed of an assembly of rigid bodies, each having a well-defined geometry (rectangular, circular, or material point), positioned in a plane and connected to each other so as to form a composite body. For determining the essential geometric characteristics in technical mechanics, the self-weight of the bodies is neglected

### 3. Equations

For the calculation of the center of mass of the system composed of  $n$  elementary bodies, equations (1) and (2) were used:

$$X_c = \frac{\sum m_i \cdot x_i}{\sum m_i} \quad (1)$$

$$Y_c = \frac{\sum m_i \cdot y_i}{\sum m_i} \quad (2)$$

where:

- $m_i$  is the mass of body  $i$  (proportional to the area for plane sections of constant thickness);
- $x_c$  and  $y_c$  are the coordinates of the center of mass of body  $i$ .

The moments of inertia of the assembly concerning the principal axes were determined using equations (3) and (4):

$$J_O = \sum (J_i + m_i \cdot (OC_i)^2) \quad (3)$$

$$J_C = J_O + m_{total} \cdot (OC)^2 \quad (4)$$

where:

- $J_O$  is the total moment of inertia of the system with respect to a reference point  $O$ ;
- $J_i$  is the own moment of inertia of body  $i$  with respect to its center of mass;
- $m_i$  is the weight of part  $i$ ;
- $OC_i$  represents the distance between the center of mass of body  $i$  and point  $O$ .
- $J_C$  is the moment of inertia of the system with respect to another point  $C$ ;
- $m_{total}$  represents the total weight of the system.
- $OC$  is the distance between points  $O$  and  $C$  (usually between the center of mass and the new axis of calculation).

For the individual calculation of the moment of inertia depending on the shape of the body, the following formulas are used:

$$J_i = 0 \quad (5)$$

$$J_i = \frac{1}{12} \cdot m_i \cdot L^2 \quad (6)$$

$$J_i = \frac{1}{2} \cdot m_i \cdot R^2 \quad (7)$$

Where:

(5)-material point;

- (6)-rod;  
(7)-disc.

The calculation was implemented in a virtual instrument created in LabVIEW, which allows the input of geometric data for each body and automatically displays the system schematic, center of mass, and moments of inertia with respect to the principal axes.

#### 4. Description of the Operation of the Virtual Instrument

On the front panel, the following control elements are available, necessary for specifying the input data: a table consisting of numeric control elements, with 10 rows available for up to 10 bodies and 6 columns: weight of the body (m), length or radius depending on the body (R), positioning of the bodies on the OX axis, positioning of the bodies on the OY axis, type of object, and the angle at which the bodies are placed, only if needed.

When running the program, the virtual instrument will display the calculated results in numeric indicator elements named as follows:  $\sum m$ ,  $C_x$ ,  $C_y$ ,  $J_o$ ,  $J_c$ . Also, the virtual instrument will display in the XYGraph indicator element the diagram of the bodies declared in the table according to their displacement on the OX and OY axes.

Figure 2 shows the Front Panel of the virtual instrument with the control elements and indicator elements mentioned above.

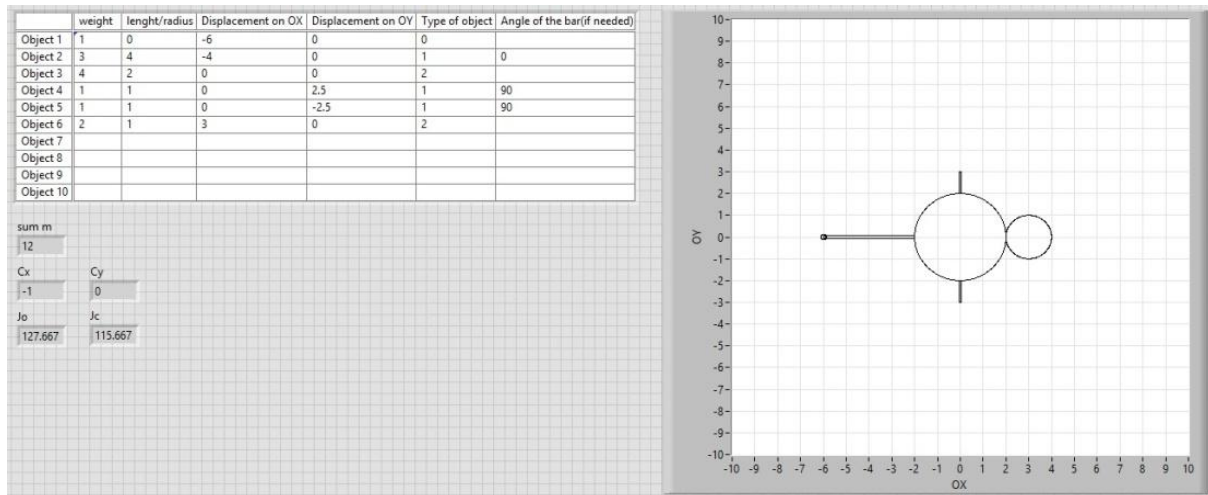


Fig. 2. Front Panel

#### 5. Description of the virtual instrument's algorithm

In the virtual instrument's diagram, the back-end solution consisted of constructing a For loop structure that sequentially processes each row from the input data table. Each row corresponds to an object in the graphical representation of the analyzed system.

Inside the For loop structure, recursive variables necessary for the final calculation were defined, such as: the total weight of the system, the coordinates  $x_c$  (1) and  $y_c$  (2) of the center of mass, as well as the total moment of inertia with respect to a reference axis ( $J_c$ ).

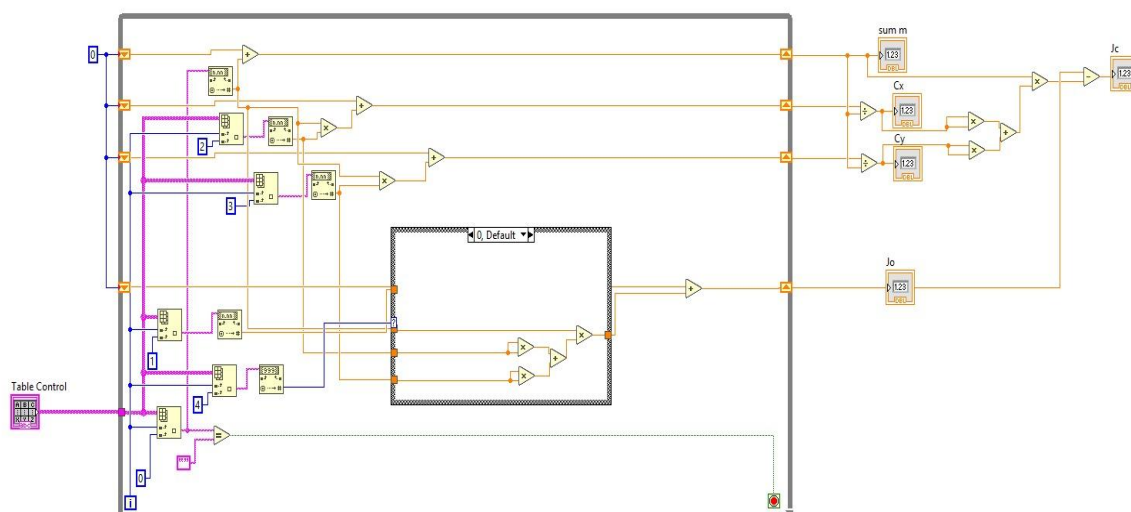


Fig. 3. Virtual Instrument Algorithm

For the calculation of the value  $J_o$ , I used a Case structure that adds to the sum the corresponding formula (5), (6), or (7) for each type of body.

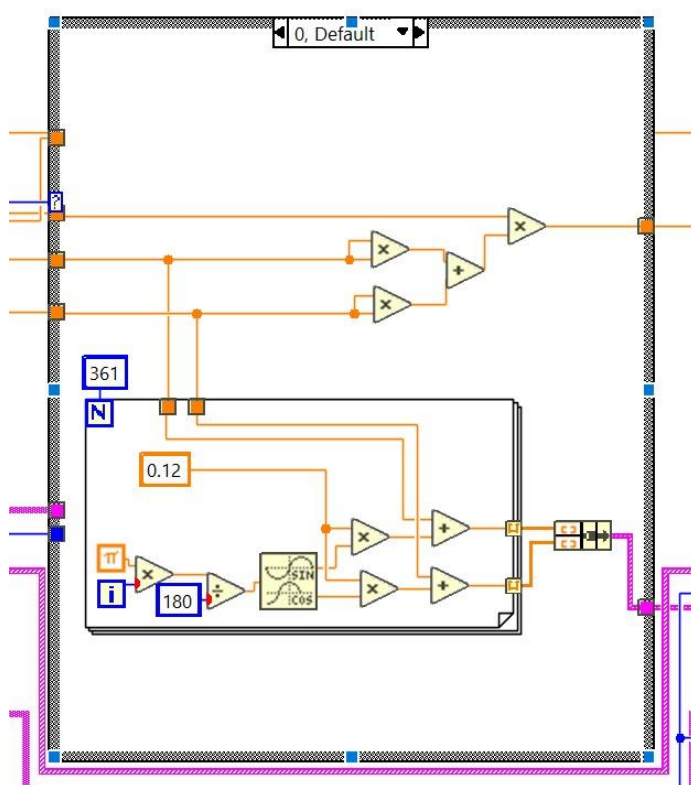


Fig. 4. Case – material point

These formulas were presented earlier and differ depending on the geometric shape of the object (material point (Fig. 4), bar (Fig. 5), disc (Fig. 6)).

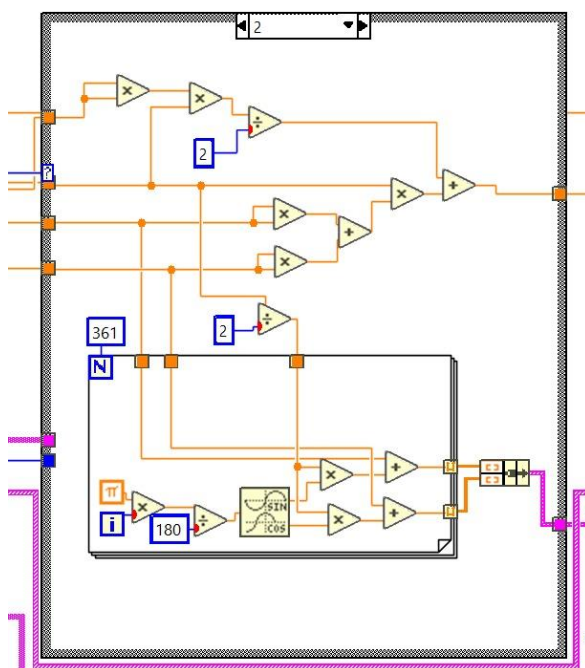


Fig. 5. Case - Rod

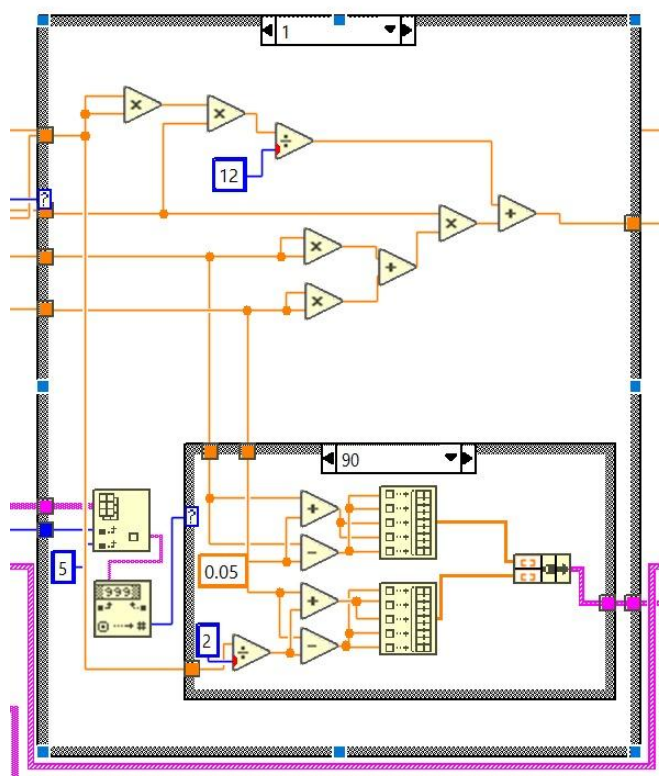


Fig. 6. Case - disc.

Finally, using equations (1), (2), (3), and (4), the algorithm calculates the value of the Moment of Inertia at the Center of Mass of the system.

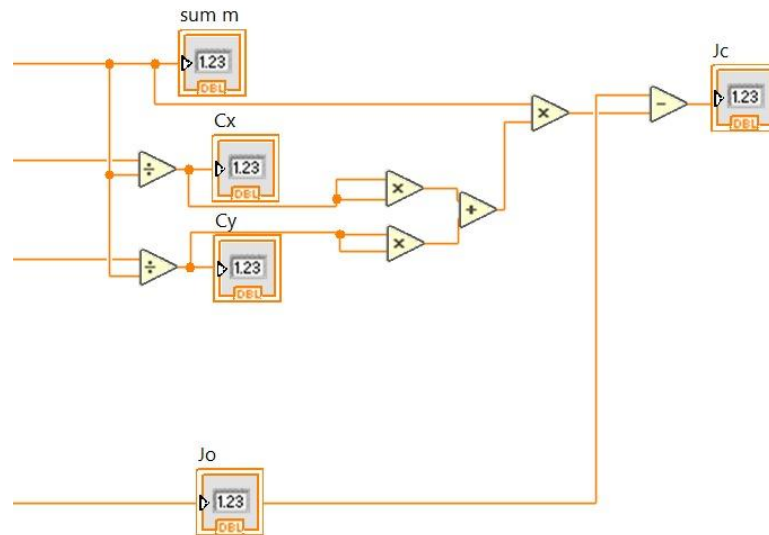


Fig. 7. Calculation of the Moment of Inertia.

## 6. Concluzii

The developed virtual instrument solves a technical mechanics problem correctly and efficiently based on formulas from the field. It has a simple, intuitive interface that is easy to use for users without programming experience.

As future research directions, it is recommended to improve the programmer interface by obtaining drawings using Picture-type functions.

Writing the calculated results and drawings into a report or files is also considered, as these would be accessible to any user without the need for LabVIEW software

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## RESEARCH ON THE CONTOUR LASER CUTTING PROCESS

**CHIVU Ștefan-Adrian<sup>1</sup>, CIOBANU Ștefan-Mircea<sup>2</sup>, DIACONU Andrei-Iulian<sup>3</sup>,  
Prof. Liviu Daniel GHICULESCU, Drd. Ing Andrei-Cosmin RUSU(Conducători  
științifici)**

<sup>1,2</sup>Faculty: Faculty of Industrial Engineering and Robotics, Field of study: Machine Construction Technology, Year of study: IV, e-mail: [chivustefan60@gmail.com](mailto:chivustefan60@gmail.com)

<sup>3</sup>Faculty: Faculty of Industrial Engineering and Robotics, Field of study: Economic Engineering, Year of study: IV.

*ABSTRACT: The paper refers to research on contour cutting using laser radiation and includes data on the current state of development in the field, experiments on various materials, computer modeling of the machining process using finite element analysis, conclusions regarding the validation of the computer model, and improvement solutions.*

**KEYWORDS:** laser, contour cutting, experiments, numerical simulation.

### 1. Introduction

The use of lasers for contour cutting in a wide range of fields—from advanced industries to those producing consumer goods—has experienced unprecedented growth due to the reduction in equipment costs, combined with the performance of laser beam machining (LBM), which provides a power density of  $10^{14}$  W/cm<sup>2</sup>, the highest value commonly encountered in industrial applications [1].

### 2. Current stage



**Fig. 1.** Complex shapes produced using laser contour cutting technology [2]

Laser contour cutting ensures high precision, with tolerances of  $\pm 50$   $\mu$ m, producing edges affected by thermal removal but is ideal for complex shapes due to temperature control, which prevents deformation – Fig. 1. The process is fast, maintaining consistent quality regardless of the material, making it suitable for applications requiring high-quality finishes and tight tolerances [3]. Modern equipment can process surfaces up to 2000 mm  $\times$  3000 mm, with maximum thicknesses depending on the material: carbon steel up to 25 mm, stainless steel 15–20 mm, aluminum 10–15 mm, and non-metallic materials (wood, acrylic, plastic) between 3–20 mm. Metallic materials such as carbon steel (easy to cut), stainless steel (precise edges), and aluminum (requires powerful lasers due to reflectivity) are processed efficiently [4]. Non-metallic materials, such as wood, acrylic (smooth finish), plastic, leather, and paper, allow for fine detailing in applications like fashion, signage, or prototyping. The cutting productivity for these materials is significantly higher.

**3. Characteristics of processed materials X6Cr13, EN AW-1050, and AISI 304, as well as the equipment used.**

The X6Cr13 alloy is a martensitic stainless steel with approximately 13% chromium content, characterized by good corrosion resistance, high hardness after heat treatment, and decent machinability. It is commonly used in the food industry, for household components, knives, or parts resistant to wear and moderate corrosion [5].

The EN AW-1050A (Al99.5) alloy is used in packaging, construction, electronics, and the chemical industry for its corrosion resistance and malleability. It has a high purity of aluminum, which gives it low reflectivity and good thermal conductivity, making it ideal for contour laser cutting. It is easy to machine and allows for clean, precise edges [5].

AISI 304 (S30400) is used in the food, chemical, construction, and medical industries for equipment, pipes, utensils, and cladding due to its corrosion resistance and formability. It is an austenitic stainless steel with good laser energy absorption, moderate reflectivity, and low thermal conductivity, making it suitable for precise contour laser cutting. Using fiber lasers and nitrogen as an assist gas, clean, oxidation-free edges can be obtained even for thicknesses of 2–4 mm [5].

The thermophysical characteristics of the materials used are presented in Table 1 [7]:

**Table 1.** Material Characteristics

| Material                                          | X6Cr13     | EN AW-1050  | AISI 304 (S30400) |
|---------------------------------------------------|------------|-------------|-------------------|
| Thermophysical and thermochemical characteristics |            |             |                   |
| Melting point                                     | 1400°C     | 650°C       | 1400°C            |
| Thermal conductivity coefficient                  | 17 W/m · K | 237 W/m · K | 16,2 W/m · K      |
| Absorptivity                                      | 0,37       | 0,10        | 0,37              |
| Emissivity                                        | 7,4        | 5,6         | 7,4               |

The processing machines used in the scientific research are as follows:

The **TruDisk 3001** laser from TRUMPF (Fig. 2) is a continuous solid-state laser with a power range between 80 and 3000 W and a wavelength of 1030 nm. It provides a high-quality beam (4 mm·mrad) and can use optical fibers starting from 100 μm. It is available with 2 or 4 optical fibers, has dimensions of 1175 x 1430 x 725 mm, and is ideal for welding, cutting, and other applications in the automotive industry [8].

The **TruLaser Cell 3010** (Fig. 3) is a 5-axis laser machine for 2D/3D cutting and welding, equipped with the TruFiber 400 source and the Siemens Sinumerik 840D CNC. It has a working stroke of 1000 x 500 x 400 mm, with B axes ±120° and a continuously rotating C axis, with a positioning tolerance of ±0.015 mm. The maximum speed on X/Y/Z is 50/50/30 m/min, and the rotational speeds for B/C are 120/750 rpm [9].



**Fig. 2.** Laser TruDisk 3001



**Fig. 3.** Trulaser Cell 3010

#### 4. Experimental data for laser contour cutting

În the contour laser cutting tests, one piece was made from the X6Cr13 alloy, four pieces from the EN AW-1050 alloy, and four pieces from the AISI 304 alloy.

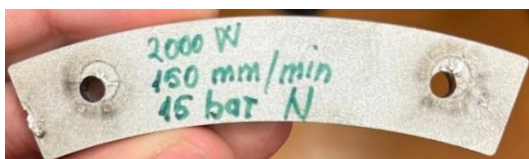
Each piece was obtained under different processing conditions to highlight the influence of technological parameters on the cutting quality and precision.

In Table 2, the parameters used and the resulting dimensions are presented.

**Table 2** Technological parameters for processing the used alloys

| The Piece nr.                                                                                                      | Laser power (W) | Assist gas pressure (MPa) | Spot diameter ( $\mu\text{m}$ ) | Travel Speed (mm/min) |
|--------------------------------------------------------------------------------------------------------------------|-----------------|---------------------------|---------------------------------|-----------------------|
| Material: <b>X6Cr13</b> : L = 75 mm, l = 15 mm, gp = 5 mm, inner circle diameter: $\varnothing 3,4$ , Ra = 3,2     |                 |                           |                                 |                       |
| 1                                                                                                                  | 2000            | 1,5                       | 100                             | 150                   |
| Material: <b>EN AW-1050</b> : L = 30 mm, l = 30 mm, gp = 0,4 mm, inner circle diameter: $\varnothing 5$ , Ra = 0,8 |                 |                           |                                 |                       |
| 1                                                                                                                  | 300             | 1,5                       | 100                             | 150                   |
| 2                                                                                                                  | 400             | 1,5                       | 100                             | 150                   |
| 3                                                                                                                  | 500             | 1,5                       | 100                             | 150                   |
| 4                                                                                                                  | 600             | 1,5                       | 100                             | 150                   |
| Material: <b>AISI 304</b> : L = 30 mm, l = 30 mm, gp = 3,1 mm, inner circle diameter: $\varnothing 5$ , Ra = 4,5   |                 |                           |                                 |                       |
| 1                                                                                                                  | 700             | 1,5                       | 100                             | 150                   |
| 2                                                                                                                  | 1000            | 1,5                       | 100                             | 150                   |
| 3                                                                                                                  | 1500            | 1,5                       | 100                             | 150                   |
| 4                                                                                                                  | 2400            | 1,5                       | 100                             | 150                   |

Figures 4-13 illustrate images of the pieces obtained through laser cutting.



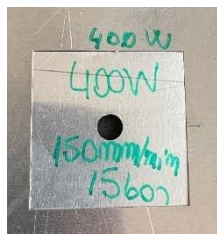
**Fig. 4** The first surface of the X6Cr13 piece.



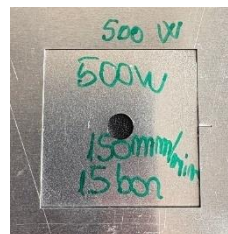
**Fig. 5** The second surface of the X6Cr13 piece.



**Fig. 6** Piece 1  
(300W) EN AW-1050



**Fig. 7** Piece 2  
(400W) EN AW-1050



**Fig. 8** Piece 3  
(500W) EN AW-1050



**Fig. 9** Piece 4  
(600W) EN AW-1050



**Fig. 10** Piece 1  
(700W) AISI 304



**Fig. 11** Piece 2  
(1000W) AISI 304



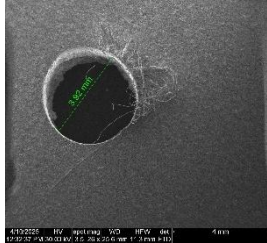
**Fig. 12** Piece 3  
(1500W) AISI 304



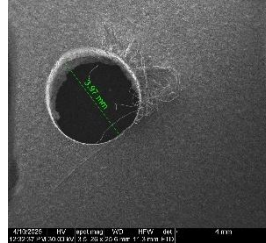
**Fig. 13** Piece 4  
(2400W) AISI 304

After performing the contour cutting of the pieces illustrated earlier in the figures above, a series of measurements were taken for the diameters of the inner holes using a QUANTA

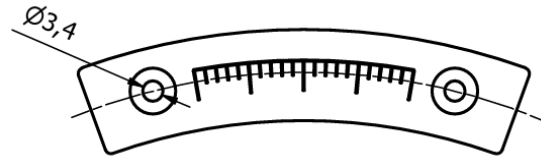
INSPECT F50 SEM scanning electron microscope with a resolution of 1 nm, from the National University of Science and Technology Polytechnic University of Bucharest. For each material, different powers were applied based on the cutting requirements, and the resulting diameters were compared to those initially specified in the piece's drawing. The analysis highlighted the precision differences, demonstrating how the power used affects the final diameter accuracy. The obtained results are illustrated in Fig. 14, Fig. 15, and Fig. 16, which show the deviations based on the processing regimes used for the X6Cr13 steel.



**Fig. 14** Hole obtained at P=2000W



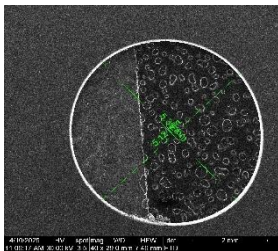
**Fig. 15** Hole obtained at P=2000W



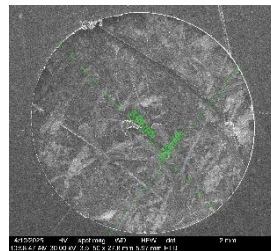
**Fig. 16** Execution drawing of the piece (highlighting the holes)

From Fig. 14, 15, and 16, it can be observed that there is a significant difference between the prescribed circle diameter ( $\text{Ø}3.4\text{mm}$ ) and the resulting diameter at a power of 2000W (3.92/3.97mm).

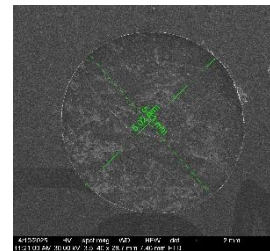
- For the EN AW-1050 material, analyzing figures 17-24, minimal deviations are observed for each regime, specifically  $\text{Ø}5\text{ mm}$  prescribed /  $\text{Ø}4.98\text{ mm}$  obtained, and radius at the outer corners with increasing values as the power increases.



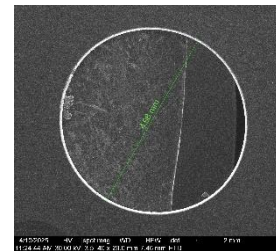
**Fig. 17** Hole obtained at P=300W



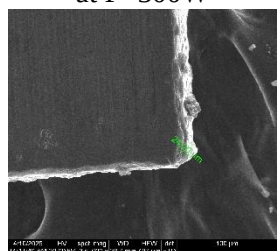
**Fig. 18** Hole obtained at P=400W



**Fig. 19** Hole obtained at P=500W



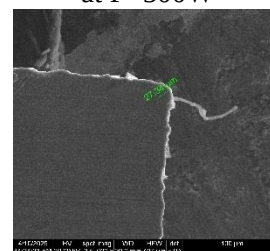
**Fig. 20** Hole obtained at P=600W



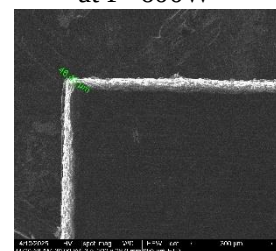
**Fig. 21** Outer corner radius at P=300W



**Fig. 22** Outer corner radius at P=400W

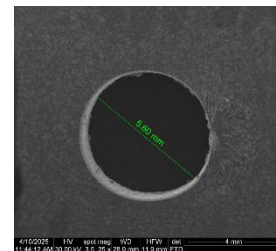
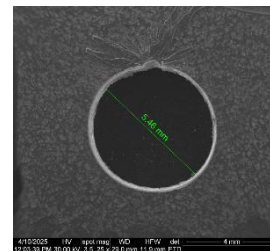
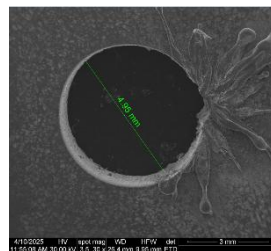
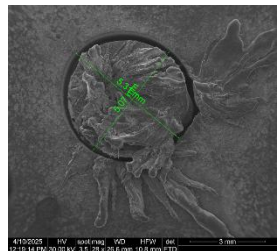


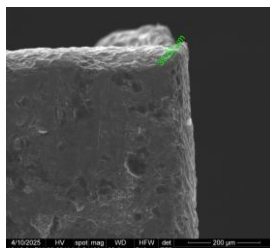
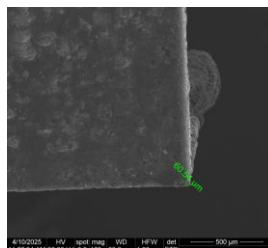
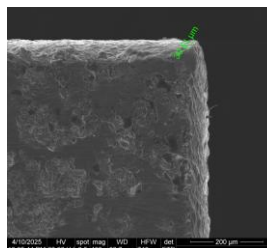
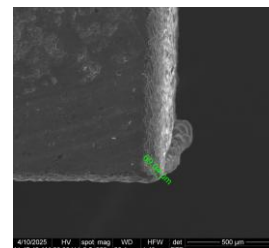
**Fig. 23** Outer corner radius at P=500W



**Fig. 24** Outer corner radius at P=600W

- For the **AISI 304** material



**Fig. 25** Hole obtained at P=700W**Fig. 29** Outer corner radius at P=700W**Fig. 26** Hole obtained at P=1000W**Fig. 30** Outer corner radius at P=1000W**Fig. 27** Hole obtained at P=1500W**Fig. 31** Outer corner radius at P=1500W**Fig. 28** Hole obtained at P=2400W**Fig. 32** Outer corner radius at P=2400W

From figures 25-32, it is clear that at 700 W, the cutting was not fully pierced, at 1000 W the deviation is minimal ( $\varnothing 5$  mm prescribed /  $\varnothing 4.95$  mm obtained), while at 1500 W ( $\varnothing 5.46$  mm obtained) and 2400 W ( $\varnothing 5.60$  mm obtained), the deviations are significant. The outer contour has minimal deviations in straightness at 1000 W. Similarly, the radii at the corners increase as the power (P) increases.

### 5. Numerical simulation of the laser contouring process

Numerical simulations were performed using COMSOL Multiphysics 5.5, in 3D space, with the "Heat Transfer in Solids" module, under the "Time Dependent" study regime. The following steps were followed:

#### A. Parameterization of the models for all three samples studied

One of the simulations, specifically the one for X6Cr13, used the following set of parameters, presented in Figure 33.

|       |                                    |                            |                                   |       |                                         |                                  |                                     |
|-------|------------------------------------|----------------------------|-----------------------------------|-------|-----------------------------------------|----------------------------------|-------------------------------------|
| dspot | 0.1[mm]                            | 1E-4 m                     | diametrul spotului laser          | lcerc | $\pi \cdot 2^2$ [mm]                    | 0.012566 m                       | lungime cerc, rc=2mm                |
| gp    | 5[mm]                              | 0.005 m                    | grosimea piesei                   | tp    | 0                                       | 0                                | timp prelucrare baleiat             |
| l1    | 75[mm]                             | 0.075 m                    | latimea piesa                     | xr    | $l1/2 + rc \cdot \cos(\omega \cdot tp)$ | 0.0392                           | coordonata x curenta a spotului     |
| l2    | 15[mm]                             | 0.015 m                    | lungime piesa                     | rc    | 1.7[mm]                                 | 0.0017 m                         | raza contur                         |
| rgaz  | 2[mm]                              | 0.002 m                    | raza spot gaz                     | omega | speed/rc                                | 1.4706 1/s                       | viteza unghiulara                   |
| Ttop  | 1450+273.15                        | 1723.2                     | temperatura de topire inox 304    | yr    | $l2/2 + rc \cdot \sin(\omega \cdot tp)$ | 0.0075                           | coordonata y curenta a spotului     |
| P     | 2000[W]                            | 2000 W                     | Putere laser                      | l1c   | 100[mm]                                 | 0.1 m                            | latime contur                       |
| sigma | dspot/6                            | 1.6667E-5 m                | abaterea medie patratica          | l2c   | 100[mm]                                 | 0.1 m                            | lungime contur                      |
| A1    | 0.8                                | 0.8                        | coeficient de absorbtie in otel   | tstop | 1.0676                                  | 1.0676                           | timpul de oprire, sfert de cerc [s] |
| emi   | 0.2                                | 0.2                        | coeficient de emisivitate         | y0    | l2/2                                    | 0.0075 m                         | coordonata y initiala a spotului    |
| h1    | $10[W/(m^2 \cdot K)]$              | $10 W/(m^2 \cdot K)$       | coeficient de transfer termic     | x0    | l1/2                                    | 0.0375 m                         | coordonata x initiala a spotului    |
| Ed    | $P/(\pi \cdot 0.25 \cdot dspot^2)$ | 2.5465E11 W/m <sup>2</sup> | Densitatea putere pe spotul laser | h2    | 25000[W/(m^2 \cdot K)]                  | 25000 W/(m <sup>2</sup> \cdot K) | coeficient racire forata gaz        |
| speed | 2.5[mm/s]                          | 0.0025 m/s                 | viteza spot                       | kerf  | 1[mm]                                   | 0.001 m                          | latimea taieturi                    |

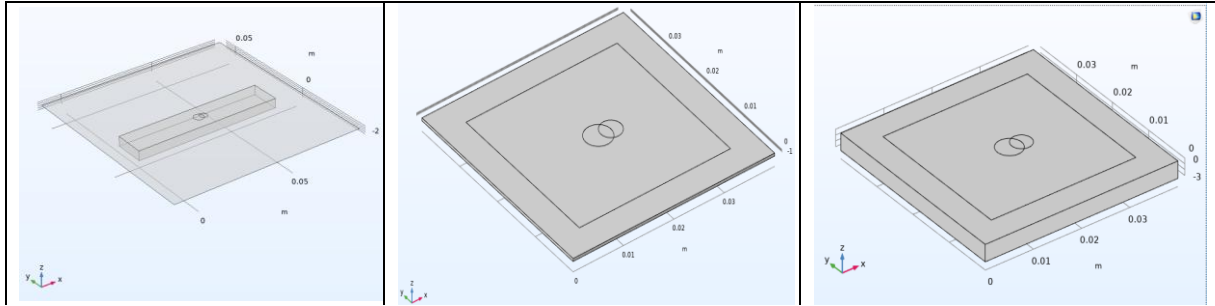
**Fig. 33** The parameters used for the X6Cr13 material

The simulations for the EN AW-1050 and AISI 304 materials used a similar set of parameters, with the existing differences found in the values of parameters related to the dimensions of the pieces, thermophysical and thermochemical properties, as well as the applied power, as noted in Tables 1 and 2.

Creation of the parametric geometry, based on the dimensions from the previous step (Fig. 33), was done using the "Geometry" module (Table 3) in "Model Builder." The finite element discretization (Table 4) was performed using the "Mesh" module. A moving mesh was used, which moved along with the laser spot on the contour.

**Table 3** The geometry of the pieces obtained in COMSOL Multiphysics 5.5

|                         |                             |                           |
|-------------------------|-----------------------------|---------------------------|
| Material: <b>X6Cr13</b> | Material: <b>EN AW-1050</b> | Material: <b>AISI 304</b> |
|-------------------------|-----------------------------|---------------------------|

**Tabel 4** The finite element discretization of the piece geometry and the corresponding statistics

|                                                                                                                                                                                                                    |                                                                                                                                                                                                                   |                                                                                                                                                                                                                     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                                                                    |                                                                                                                                                                                                                   |                                                                                                                                                                                                                     |
| Tetrahedra: 31492<br>Triangles: 18570<br>Edge elements: 790<br>Vertex elements: 28<br>Domain element statistics<br>Number of elements: 31492<br>Minimum element quality: 0.1824<br>Average element quality: 0.5968 | Tetrahedra: 11199<br>Triangles: 2064<br>Edge elements: 260<br>Vertex elements: 28<br>Domain element statistics<br>Number of elements: 11199<br>Minimum element quality: 0.2337<br>Average element quality: 0.6446 | Tetrahedra: 27296<br>Triangles: 14386<br>Edge elements: 1198<br>Vertex elements: 42<br>Domain element statistics<br>Number of elements: 27296<br>Minimum element quality: 0.1678<br>Average element quality: 0.6495 |

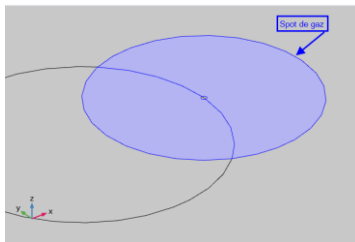
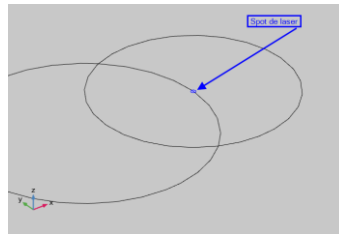
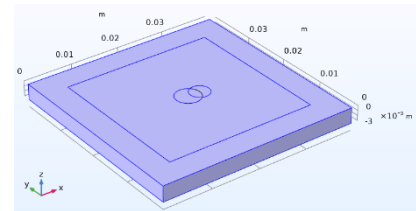
### B. Defining the variables

| Name    | Expression                      | Unit             |
|---------|---------------------------------|------------------|
| G_space | $\exp(-(x-x_r)^2/(2*\sigma^2))$ |                  |
| Plaser  | $A1*Ed$                         | W/m <sup>2</sup> |
| LHS     | $Plaser*G\_space$               | W/m <sup>2</sup> |

**Fig. 34.** Defining the energy distribution on the laser spot.

The energy distribution (Fig. 34) on the laser spot was defined using the Gaussian function (G-space) and the absorption coefficient of each material ( $A1$ ), which depends on the interaction of the laser radiation with the wavelength ( $\lambda$ ) and the surface condition and roughness.

D. Boundary conditions. Forced convective cooling through the assist gas spot, Fig. 35, laser source, Fig. 36 with Gaussian distribution, and convective and radiative cooling in the ambient environment, Fig. 37.

**Fig. 35** Forced convective cooling with the gas spot**Fig. 36** Laser spot**Fig. 37** Convective and radiative cooling in the ambient environment.

E. The laser contour cutting simulation is performed in the "Study" module for each sample, with time parameters set in "Time Dependent" (Fig. 38) and laser scanning parameters adjusted in "Parametric Sweep" (Fig. 39).

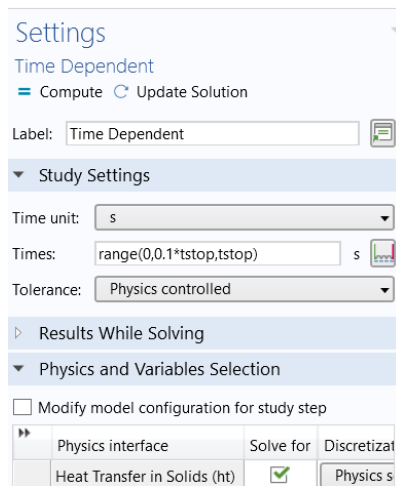


Fig. 38 Setting the time parameters

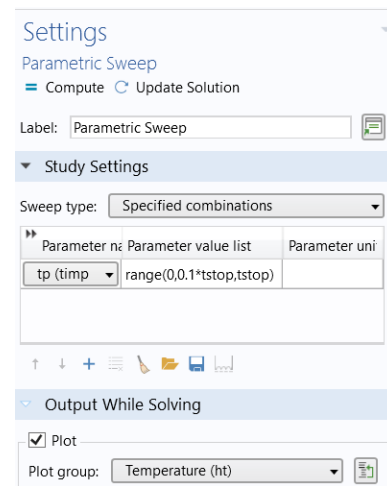


Fig. 39 Setting the spot scanning param. laser

## 6. Analysis of the Results

The results obtained from the numerical simulation of the laser contouring process of the X6Cr13 material with a thickness of  $g_p = 5$  mm are presented, approached in two stages: the first involves the surface material removal, as shown in Fig. 40, and the second involves the temperature distribution during deep material removal, as shown in Fig. 41. The second stage assumes the removal of surface material and the focusing of the laser spot inside the material.

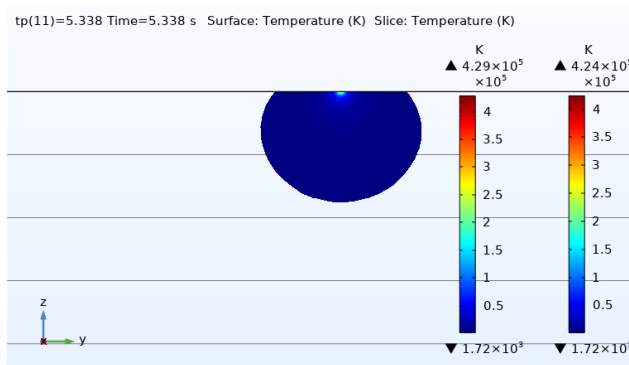


Fig. 40 Temperature Distribution during Surface Removal

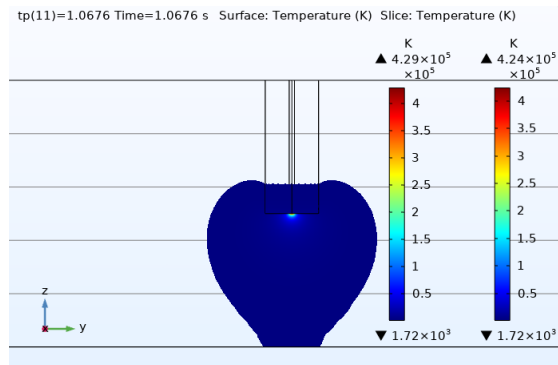
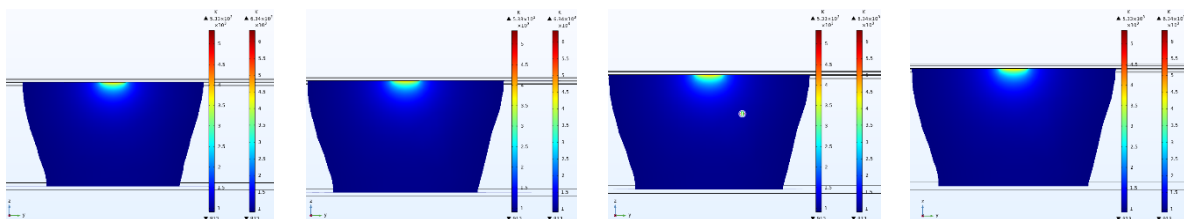


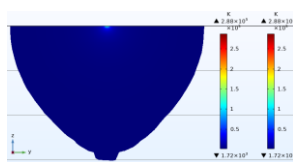
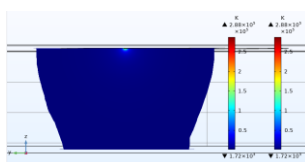
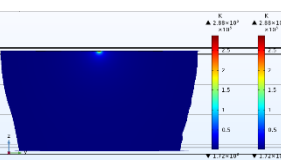
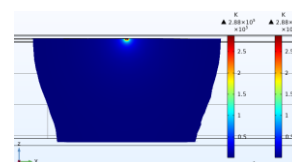
Fig. 41 Temperature Distribution during Deep Removal with Penetration

For the EN AW-1050 aluminum alloy, the temperature distribution is presented for the four power values used, as shown in Figs. 42–45. It can be observed that the material removal zone, defined by the melting isotherm of this aluminum alloy (923 K), indicates full penetration processing in all four processing regimes.



**Fig. 42** Temperature Distribution at P=300W**Fig. 43** Temperature Distribution at P=400W**Fig. 44** Temperature Distribution at P=500W**Fig. 45** Temperature Distribution at P=600W

For AISI 304 steel, the temperature distribution is presented for the four power values used, as shown in Figs. 46–49. It can be observed that the area defined by the melting isotherm (1723 K), corresponding to the removed material, shows partial penetration at a power of 700 W, while complete penetration occurs at the other power levels.

**Fig. 46** Temperature Distribution at P=700W**Fig. 47** Temperature Distribution at P=1000W**Fig. 48** Temperature Distribution at P=1500W**Fig. 49** Temperature Distribution at P=2400W

The results obtained through numerical simulation are in agreement with the experimental data shown in Figs. 14–32.

## 7. Conclusions

As a result of the contour cutting tests on the X6Cr13 part at 2000 W, as well as the tests on the four EN AW-1050 parts at powers of 300, 400, 500, and 600 W, and the four AISI 304 parts at 700, 1000, 1500, and 2400 W, small differences were observed compared to the initial dimensions specified in the technical drawing. These differences consist of variations in the initial diameters of the holes in the parts and the diameters at the corners compared to the specifications in the technical drawing.

The results obtained from the numerical simulation highlight the parameters with the greatest influence on the CNC laser cutting process, namely, the beam power, cutting speed, and assist gas pressure, which affect the heat transfer coefficient during forced convective cooling. These parameters are connected to productivity, precision, and the quality of the machined surface.

The contribution of this work consists in testing the behavior of the three materials, widely used in industry, in contour laser cutting at different processing regimes and in the numerical simulation of the processing process, which clarified the influence of the processing parameters on the material removal process.

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## RESEARCH ON THE PROCESS OF LASER MICROWELDING

**SĂRBĂTOARE Eduard, SIMION Dragoș, TOAIE Adrian,  
Prof. Liviu Daniel Ghiculescu, Drd. Ing. Sabin Mihai, Drd. Ing. Andrei  
Rusu(Conducători științifici)**

Faculty: of Industrial Engineering and Robotics, Specialization: Manufacturing Engineering,  
Year of study: IV, e-mail: eduard.sarbatoare@gmail.com

*ABSTRACT: This paper presents research on the laser microwelding of metallic materials, covering the current state of the field, experimental studies with various welding regimes, and the modeling of the process using the finite element method. Conclusions are drawn regarding the validation of the numerical simulation model and process optimization.*

*KEYWORDS: microwelding, laser, experiments, numerical simulation*

### 1. Introduction

Laser welding is widely applicable, excelling in joining materials with diverse properties and small dimensions, such as thin foils and micro-wires used in micro- and nanotechnology applications. This is enabled by the laser's ability to focus the beam to sub-micrometric dimensions, achieving a high power density commonly used in industry,  $10^{14}$  W/cm<sup>2</sup> [1].

### 2. Current State of Laser Microwelding

Laser welding of thin stainless steel sheets using nanosecond laser pulses has been investigated, analyzing the effects of process parameters (energy, frequency, scanning speed) on weld quality. Optimized parameters enable precise welds with minimal thermal impact and no defects [2].

Tests have demonstrated good mechanical strength in laser microwelding of Nitinol alloy, commonly used in cardiovascular devices due to its unique properties (superelasticity and shape memory). Compared to other methods (resistance welding and percussion arc welding), laser welding provides superior joint quality, preserving the material's structural integrity and functional properties [3].

Efforts have been made to develop a 3D numerical model for Nd:YAG laser microwelding, enabling the study of temperature distribution, weld pool formation, and material thermal behavior. Using the finite element method (FEM), the influence of parameters such as laser power, scanning speed, and focal spot size on weld quality was analyzed [4].

Authors Jiayi Xu and Qing Jiang provide an overview of the physical principles underlying ultrafast laser microwelding, including laser-material interaction mechanisms and weld zone formation.

Key process parameters, such as pulse type and characteristics, scanning speed, beam focusing, focal positioning, and pulse energy, are examined. Various welding configurations, such as edge, overlap, and dissimilar material welding (glass-metal), are also discussed [5].

Additionally, femtosecond laser welding of Siglass hybrid material has been explored, demonstrating the feasibility of strong joints between dissimilar materials, including Siglass–soda-lime glass, Siglass–fused silica, Siglass–borosilicate glass, and homogeneous Siglass–Siglass welds [6].

### 3. Experimental Data

The equipment used for experimental data collection at CETAL, Măgurele, includes the following: Laser Source: TRUMPF TruDisk 3001 Yb:YAG disk laser, shown in Figure 1, with the following specifications [7]:

Laser Power: 3000W, continuously adjustable range: 80 with active power control, laser wavelength 1030 nm, Laser Spot Diameter (with used optics): 0.8 mm



Fig. 1. TRUMPF TruDisk 3001



Fig. 2. TRUMPF TruLaser Robot 5020

Robot: TRUMPF TruLaser Robot 5020, shown in Figure 2, with technical specifications listed in Table 1 [8, 9]:

**Tabel 1. Technical Specifications**

| Robot:                      | Maximum Workpiece Dimensions: |
|-----------------------------|-------------------------------|
| Number of axes: 6           | Width: 1400 mm                |
| Repeatability: $\pm 0.1$ mm | Height: 800 mm                |
| Payload: 30 kg              | Depth: 1200 mm                |

Welded samples are shown in figures 3, 4, and 5.

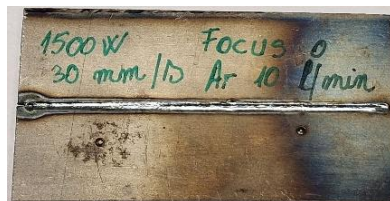


Fig. 3. Sample 1



Fig. 4. Sample 2



Fig. 5. Sample 3

Experimental data for the welded samples are presented in table 2:

**Tabel 2. Experimental Data for Welded Samples**

| Parameter             | Sample 1 | Sample 2 | Sample 3 |
|-----------------------|----------|----------|----------|
| Measurement           |          |          |          |
| Width [mm]            | 43       |          |          |
| Length [mm]           | 85       |          |          |
| Thickness [mm]        | 1.4      | 1.5      | 1.9      |
| Laser Power [W]       | 1500     | 2000     | 2500     |
| Weld Bead Length [mm] | 80       |          |          |

|                               |    |
|-------------------------------|----|
| Laser Spot Speed [mm/s]       | 30 |
| Cooling Gas Flow Rate [L/min] | 10 |

Stainless steel AISI 304 / EN 1.4301 is known for its versatility and corrosion resistance. Its main properties are presented in Tables 3, 4, and 5:

**Tabel 3. Chemical Composition [10]**

| Element        | Percentage in material | Element       | Percentage in material |
|----------------|------------------------|---------------|------------------------|
| Carbon (C)     | 0.08                   | Silicon (Si)  | 0.75                   |
| Manganese (Mn) | 2                      | Chromium (Cr) | 18-20                  |
| Phosphorus (P) | 0.045                  | Nickel (Ni)   | 8-10.5                 |
| Sulphur (S)    | 0.03                   | Iron (Fe)     | Balanced               |

**Tabel 4. Physical Properties [10], [11]**

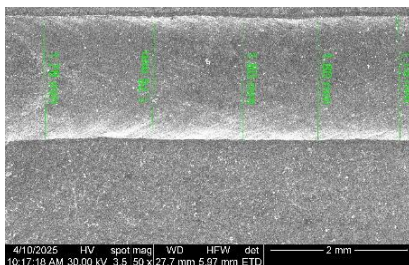
|                                                        |                                                                    |
|--------------------------------------------------------|--------------------------------------------------------------------|
| Density [g/cm <sup>3</sup> ]                           | 8                                                                  |
| Specific Heat Capacity [J/(kg · K)]                    | 502                                                                |
| Electrical Resistivity [ $\mu\Omega \cdot \text{cm}$ ] | 72                                                                 |
| Young Modulus [GPa]                                    | 193                                                                |
| Thermal Expansion [1/K (0~100°C)]                      | $17.3 \cdot 10^{-6}$                                               |
| Thermal Conductivity [W/(m · K)]                       | 16.2                                                               |
| Melting Range [°C]                                     | 1380-1450                                                          |
| Magnetism                                              | Non-magnetic in annealed state, slightly magnetic after processing |

**Tabel 5. Emissivity Data [12]**

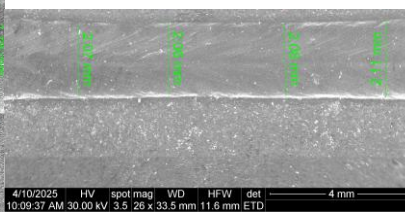
| EN 1.4301 Emissivity Data | Temperature [°C] | Emissivity  |
|---------------------------|------------------|-------------|
| After Heating             | 216-490          | 0.440-0.360 |
| After 43 hours at 527°C   | 216-527          | 0.620-0.730 |

Welded samples were analyzed using a scanning electron microscope (SEM), FEI Quanta Inspect F50M, with a resolution of 1 nm, at the National University of Science and Technology Politehnica Bucharest.

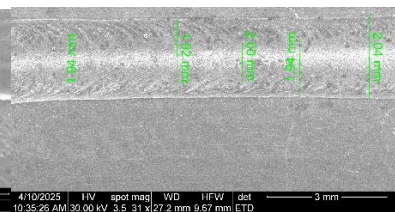
Variations in weld bead width for the three samples are shown in Figures 6, 7, and 8.



**Fig. 6. SEM Sample 1**



**Fig. 7. SEM Sample 2**



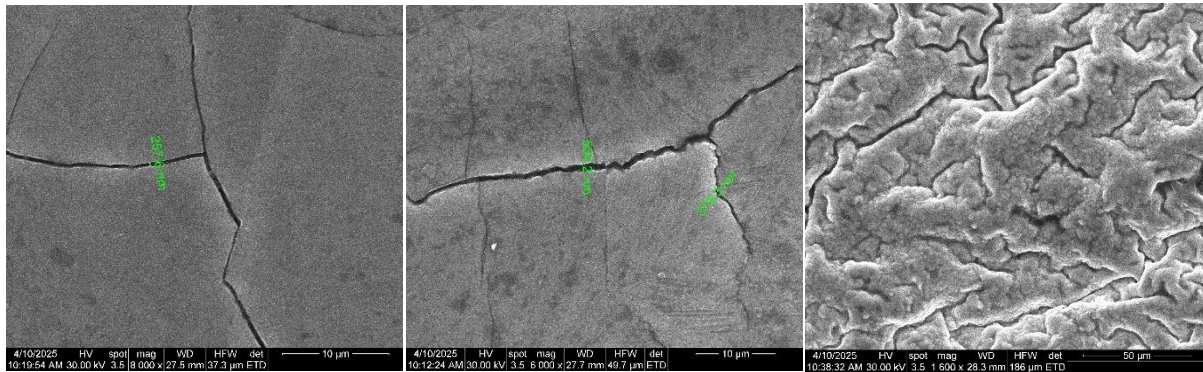
**Fig. 8. SEM Sample 3**

Weld bead microgeometry aspects are summarized in Table 6

**Tabel 6. Weld Bead Microgeometry Aspects**

| Aspect \ Parameter                             | Sample 1    | Sample 2    | Sample 3    |
|------------------------------------------------|-------------|-------------|-------------|
| Thickness [mm]                                 | 1.4         | 1.5         | 1.9         |
| Laser Power [W]                                | 1500        | 2000        | 2500        |
| Weld Bead Width [mm]                           | 1.76 – 1.80 | 2.06 – 2.11 | 1.92 – 2.04 |
| Microcrack Width [nm]                          | 170 – 260   | 380 – 530   | –           |
| Distance Between Microcracks [ $\mu\text{m}$ ] | 10 – 100    | 15 – 50     | –           |

During microwelding, the weld bead undergoes rapid heating, while the adjacent material remains at a lower temperature. This thermal gradient leads to micro-irregularities. Microcracks were observed in the weld zones of Samples 1 and 2 (Figures 9 and 10), unlike Sample 3, which exhibited spherical formations (Figure 11).



**Fig. 9.** Sample 1 Microcracks

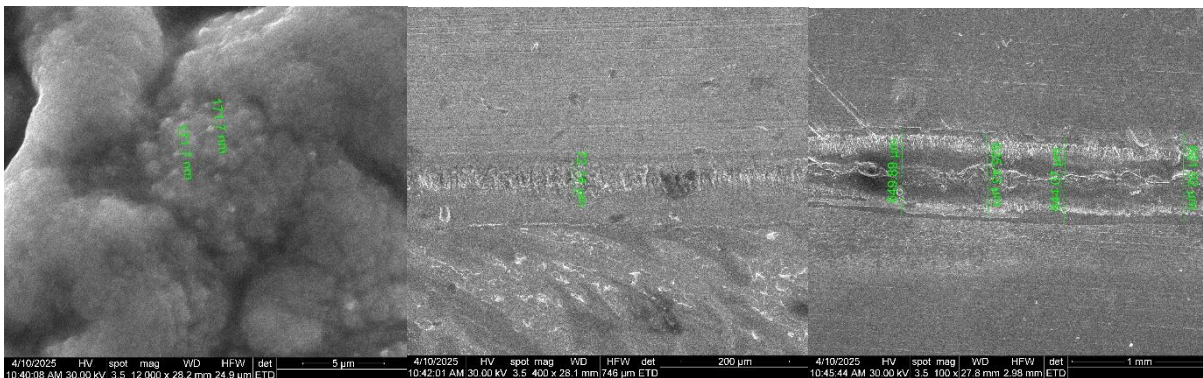
**Fig. 10.** Sample 2 Microcracks

**Fig. 11.** Sample 3 Spherical Formations

At Sample 2 ( $P = 2000 \text{ W}$ ), microcrack widths (380–530 nm) were larger than at Sample 1 ( $P = 1500 \text{ W}$ , 170–260 nm). At higher laser power with the same welding speed (30 mm/s), surface cracking intensified.

For the thickest sample (Sample 3), additional microgeometry aspects of the weld bead were observed, as shown in Figures 12, 13, and 14.

The spherical particles ( $\sim 171 \text{ nm}$ ) resulted from the surface tension of the molten material, resolidified after cooling (Figure 12). The transition zone between the weld bead and the base material, with a width of  $72 \mu\text{m}$ , showed melting marks perpendicular to the welding direction (Figure 13). The weld bead width on the bottom surface (600–700  $\mu\text{m}$ ) was smaller than on the top surface due to thermal energy dissipation within the material volume (Figure 14).



**Fig. 12.** Resolidified Spherical Particles

**Fig. 13.** Transition Zone at Weld Bead Edge

**Fig. 14.** Weld Bead Width on Bottom Surface

#### 4. Numerical Simulation of the Laser Microwelding Process

The modeling process using COMSOL Multiphysics 5.5 is described as follows:

A. The “Model Wizard” functionality was selected, choosing the 3D “Heat Transfer in Solids” module and a “Time Dependent” study.

B. Model parameterization is shown in Figures 15 and 16, with material properties (EN 1.4301) input as shown in Figure 17.

| Name    | Expression          | Value          | Description                             |
|---------|---------------------|----------------|-----------------------------------------|
| dspot   | 0.8[mm]             | 8E-4 m         | diametrul spotului laser                |
| gp      | 1.9[mm]             | 0.0019 m       | grosimea piesei                         |
| l1      | 21.5[mm]            | 0.0215 m       | latime piesa                            |
| l2      | 85[mm]              | 0.085 m        | lungime piesa                           |
| rgaz    | 2.5[mm]             | 0.0025 m       | raza spot gaz                           |
| Ttop304 | 1450+273.15         | 1723.2         | temperatura de topire inox 304 [K]      |
| P       | 2500[W]             | 2500 W         | Putere laser                            |
| sigma   | dspot/6             | 1.3333E-4 m    | abaterea medie patratica                |
| A1      | 0.45                | 0.45           | coeficient de absorbtie in otel         |
| emi     | 0.8                 | 0.8            | coeficient de emisivitate               |
| h1      | 10[W/(m^2*K)]       | 10 W/(m^2*K)   | coeficient de transfer termic           |
| Ed      | P/(pi*0.25*dspot^2) | 4.9736E9 W/m^2 | Densitatea putere pe spotul laser       |
| x0      | rgaz                | 0.0025 m       | pozitia initiala a spotului             |
| speed   | 30[mm/s]            | 0.03 m/s       | viteza spot                             |
| tstop   | (l2-2*rgaz)/speed   | 2.6667 s       | timp oprire                             |
| tp      | 0                   | 0              | timp prelucrare baleiat                 |
| xr      | x0+speed*tp         | 0.0025         | pozitia curenta a spotului              |
| h2      | 2000[W/(m^2*K)]     | 2000 W/(m^2*K) | coeficient de transfer termic forat qaz |

**Fig. 15.** Common Modeling Parameters in “Global Definitions”

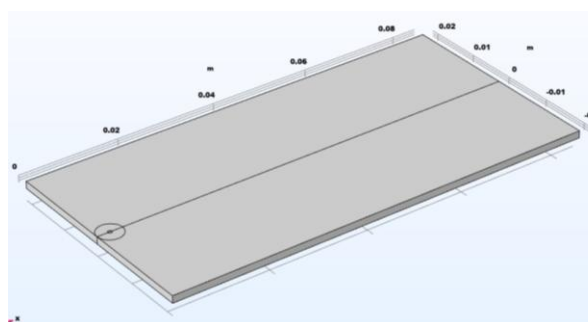
|        |    |         |          |                 |
|--------|----|---------|----------|-----------------|
| Sample | gp | 1.4[mm] | 0.0014 m | grosimea piesei |
| 1      | P  | 1500[W] | 1500 W   | Putere laser    |
| Sample | gp | 1.5[mm] | 0.0015 m | grosimea piesei |
| 2      | P  | 2000[W] | 2000 W   | Putere laser    |
| Sample | gp | 1.9[mm] | 0.0019 m | grosimea piesei |
| 3      | P  | 2500[W] | 2500 W   | Putere laser    |

**Fig.16.** Parameters Differing Between Samples

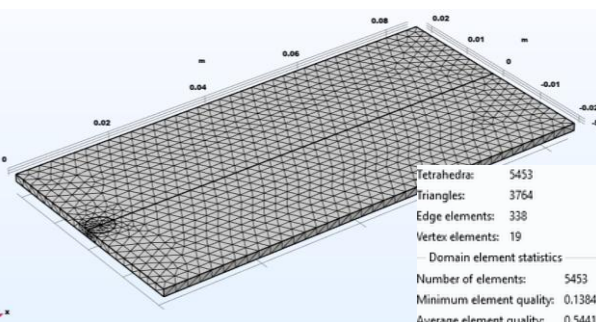
| Property                           | Variable   | Value | Unit     |
|------------------------------------|------------|-------|----------|
| Density                            | rho        | 8000  | kg/m³    |
| Thermal conductivity               | k_iso ;... | 25    | W/(m·K)  |
| Heat capacity at constant pressure | Cp         | 600   | J/(kg·K) |

**Fig. 17.** Input of Welded Material Parameters (EN 1.4301)

C. The parameterized sample geometry is shown in Figure 18, discretized using fine tetrahedral finite elements in the “Geometry” node of “Model Builder” (Figure 19).



**Fig. 18.** Sample Geometry Creation



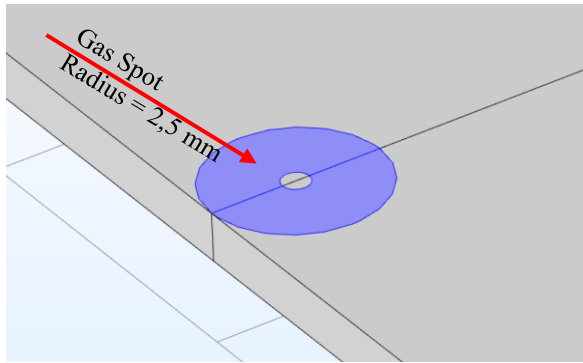
**Fig. 19.** Geometry Discretization with Finite Elements and Statistics

| Name    | Expression                      | Unit |
|---------|---------------------------------|------|
| G_space | $\exp(-(x-x_r)^2/(2*\sigma^2))$ |      |
| Plaser  | A1*Ed                           | W/m² |
| LHS     | Plaser*G_space                  | W/m² |

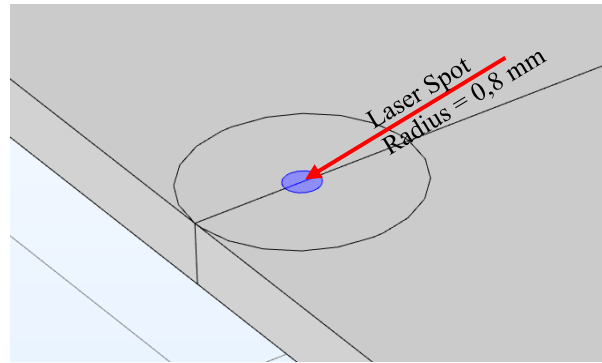
**Fig. 20.** Definition of Laser Spot Energy Distribution

In the “Variables” node, the laser spot energy distribution was defined using a Gaussian function (G-space). The absorption coefficient (A1), dependent on the laser wavelength ( $\lambda$ ), surface quality, and material state during processing, was also introduced (Figure 20).

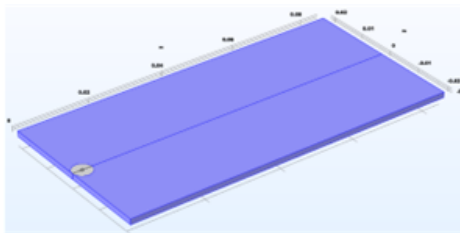
D. Boundary conditions, shown in Figures 21, 22, and 23, included forced convective cooling with a heat transfer coefficient (h2) on the assisting gas (Ar) spot and the moving laser spot for butt welding. The rest of the workpiece was cooled convectively and by ambient radiation. The forced convective cooling heat transfer coefficient was orders of magnitude higher than the ambient convective cooling coefficient.



**Fig. 21.** Convective Cooling Gas Spot

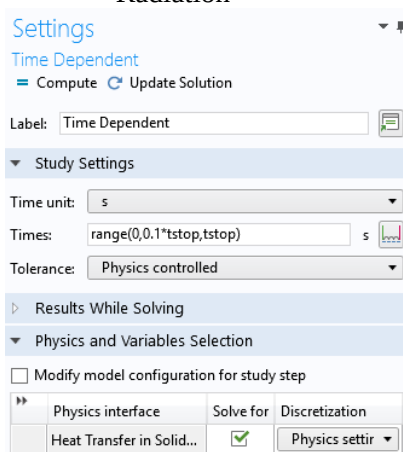


**Fig. 22.** Laser Spot

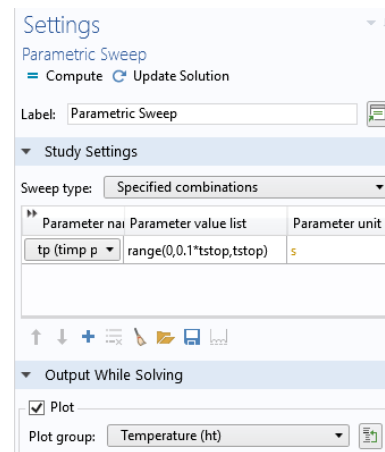


**Fig. 23.** Convective Cooling and Ambient Radiation

Simulations were performed in the “Study” module for each sample. Time parameters were set in the “Time Dependent” module (Figure 24) with the limit “tstop,” and laser spot sweep parameters were defined in the “Parametric Sweep” module (Figure 25) using the swept time “tp.”



**Fig. 24.** Time Parameter Settings



**Fig. 25.** Laser Sweep Parameter Settings

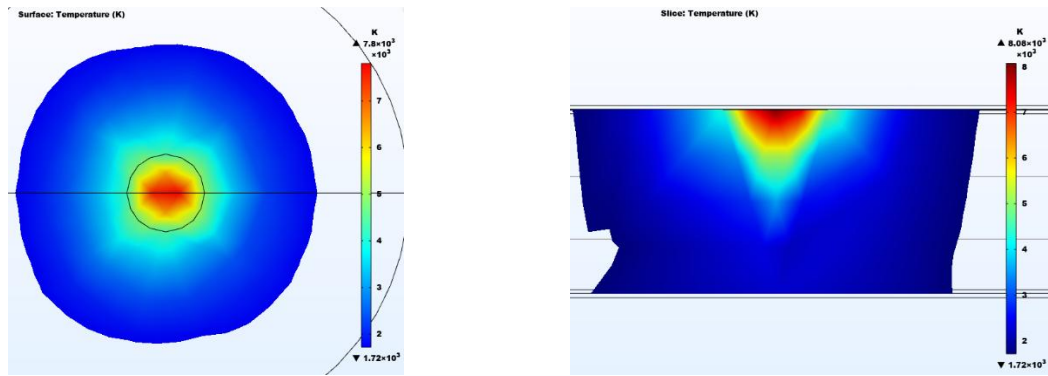
## 5. Analysis of Results

COMSOL Multiphysics simulations revealed surface and cross-sectional temperature distributions, limited by the AISI 304 melting isotherm (1450°C), for each sample with different thicknesses (gp) (Figures 26, 27, and 28).

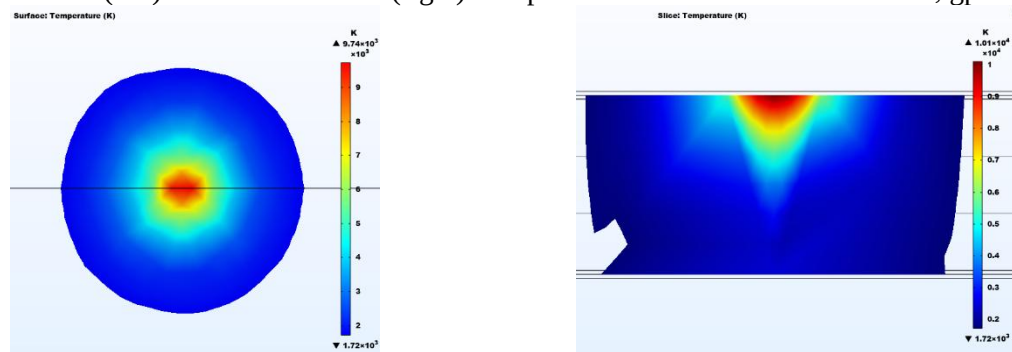
Simulated weld bead widths were comparable to experimental measurements (Table 6), validating the computational model. Simulated values were slightly higher due to energy loss from material vaporization in the molten weld pool.

The weld bead dimensions were smaller at the bottom surface, explained by energy dissipation as the laser penetrates deeper into the material, consistent with experimental data (Figure 14).

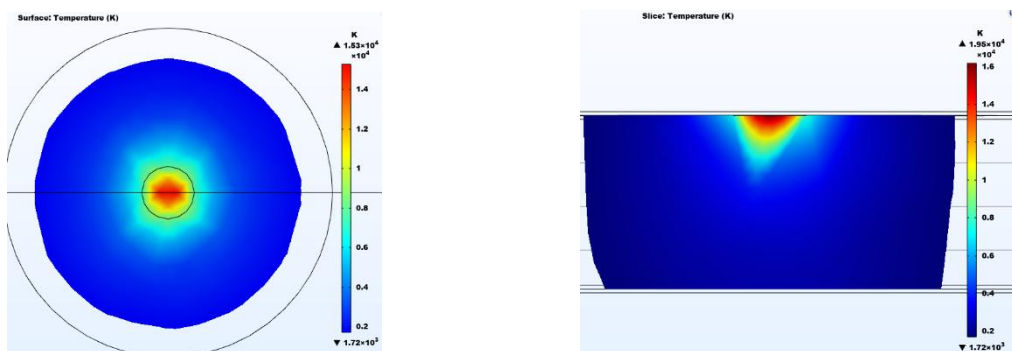
Microcracks in Sample 2 (380–530 nm, Figure 10) suggest a pronounced thermal gradient, confirmed by the cross-section in Figure 27, showing a rapid temperature drop within 1 mm of the spot. To reduce defects, a higher laser spot speed (e.g., 40 mm/s) is proposed to minimize thermal accumulation.



**Fig. 26.** Surface (left) and Cross-Section (right) Temperature Distribution at  $P=1500$  W,  $gp=1.4$  mm



**Fig. 27.** Surface (left) and Cross-Section (right) Temperature Distribution at  $P=2000$  W,  $gp=1.5$  mm



**Fig. 28.** Surface (left) and Cross-Section (right) Temperature Distribution at  $P=2500$  W,  $gp=1.9$  mm

Through the comparative analysis of simulated weld bead dimensions resulting from computer models, an increase in these dimensions is observed with the increase of laser power from 1500 W to 2500 W.

## 6. Conclusions

Laser microwelding proved effective for welding AISI 304 stainless steel due to the laser's focusing capability (0.8 mm spot) and precise thermal control. Experiments with powers of 1500 W, 2000 W, and 2500 W produced weld beads with widths of 1.76–2.11 mm, demonstrating precise joints with minimal thermal impact.

Laser power significantly affected weld bead microgeometry. At 1500 W (Sample 1), smaller microcracks (170–260 nm) and a more uniform bead were achieved compared to 2000 W (Sample 2), which exhibited larger microcracks (380–530 nm). At 2500 W and 30 mm/s spot speed, defects can be minimized, improving weld quality.

A higher welding speed (e.g., 40 mm/s) is proposed to enhance thermal energy dissipation and reduce thermal gradients, lowering the likelihood of microcracks.

Experiments on samples with varying thicknesses (1.4 mm, 1.5 mm, 1.9 mm) demonstrated the adaptability of laser microwelding to dimensional variations in AISI 304. SEM analysis showed consistent weld bead widths, but defects (microcracks in Samples 1 and 2) were influenced by thickness and power.

Simulations confirmed greater energy dissipation in thicker samples (Sample 3), resulting in a narrower bottom weld bead (600–700  $\mu\text{m}$ ), suggesting the need to adjust laser power proportional to material thickness to prevent defects.

The results highlight the potential of laser microwelding for high-precision applications, such as welding thin foils for microtechnologies or medical devices (e.g., cardiovascular).

Parameter control and numerical simulation validation provide a robust foundation for industrial implementation, offering benefits like defect reduction and energy optimization.

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# RESEARCH ON ABRASIVE FLOW MACHINING OF A CONICAL SURFACE WITHIN AN EXTRUDER COMPONENT

NIȚU Maria-Luiza, Nicolae IONESCU (Conducător științific)

Faculty: Industrial Engineering and Robotics, Specialization: Machine Manufacturing Technology

Year of Study: 4, E-mail: nituluiza1@gmail.com

**ABSTRACT:** This paper presents a specific TOP-DOWN nanomachining technology, namely Abrasive Flow Machining (AFM).

AFM is a superfinishing process through which surfaces and edges can be finished by extruding a viscous-abrasive medium, precisely directed toward the regions where material removal is required. Additionally, the AFM process can be used for polishing, deburring, and edge rounding of components with a wide range of dimensions, especially in areas that are difficult to access using conventional methods. The process is well suited for automation, enabling production rates of hundreds or even thousands of parts per hour.

**KEYWORDS:** AFM, Deburring, Conical Surface;

## 1. Introduction

Abrasive Flow Machining (AFM) involves the circulation of a semi-fluid abrasive compound – typically a polymer or gel medium embedded with abrasive particles such as silicon carbide or aluminum oxide – between two opposing chambers of a die or component. The principle diagram of the process is presented in figure 1. The reciprocating motion of this compound is hydraulically or pneumatically controlled, and the pressure exerted generates the abrasive action on the surface.

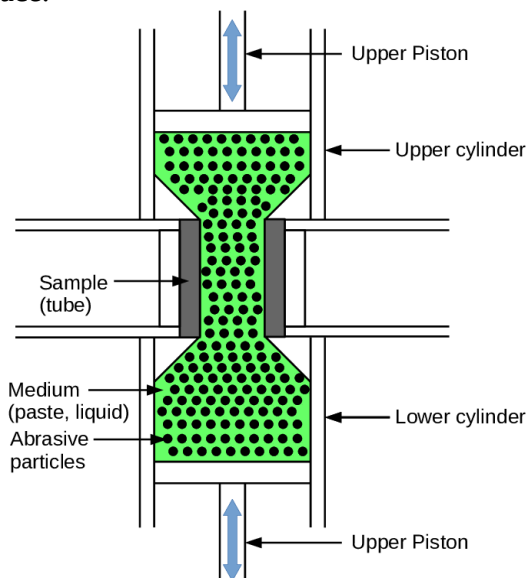


Fig 1. Principle Diagram of "Abrasive Flow Machining" [2]

Due to its ability to access complex geometries and produce uniform surface finishes without direct contact with rigid tools, AFM is widely employed in industries such as aerospace, automotive, biomedical, and die manufacturing. It is a versatile and precise process capable of significantly enhancing surface quality, performance, and the durability of critical components.

## 2. Current State of the Art

Current research in the field of Abrasive Flow Machining (AFM) focuses on refining process parameters and expanding the applicability of the method across diverse industries. A significant development direction involves the integration of artificial intelligence, particularly through the use of neural networks, to identify optimal processing conditions with the goal of increasing process efficiency and reducing machining time.

Moreover, the application domain of AFM has significantly broadened compared to its initial use cases, now encompassing the finishing of critical components in the aerospace, automotive, biomedical sectors, as well as in the machining of brittle materials. Experimental results highlight the method's capability to produce surfaces with exceptionally low roughness and to considerably enhance component performance, particularly in terms of durability and behavior under dynamic loading.

Fig 2. illustrates how the abrasive medium is forced to reciprocate through the machined regions.

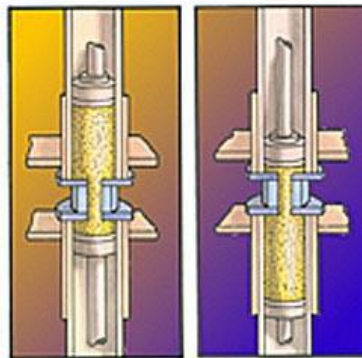


Fig 2. Machining by abrasive flow with two opposing cylinders [1]

In addition to the standard process configuration, advanced variants have been developed, such as orbital flow machining and the **AFM-Sonex** technology, which integrates ultrasonic vibrations to achieve superior surface finishes, even when processing hard-to-machine materials. In parallel, significant advancements have been made in the automation of AFM systems, which are now capable of operating autonomously within flexible manufacturing cells, delivering very short cycle times and high process repeatability.

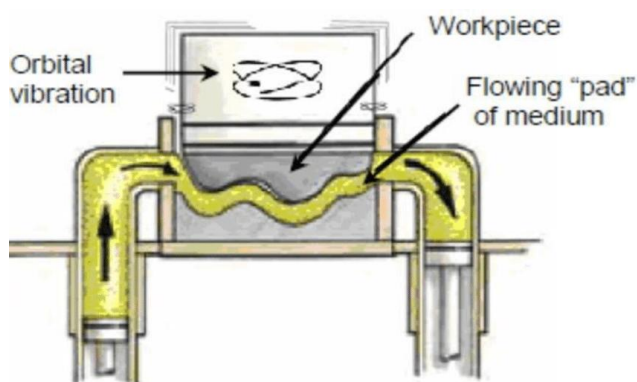


Fig 3. Orbital motion machining [3]

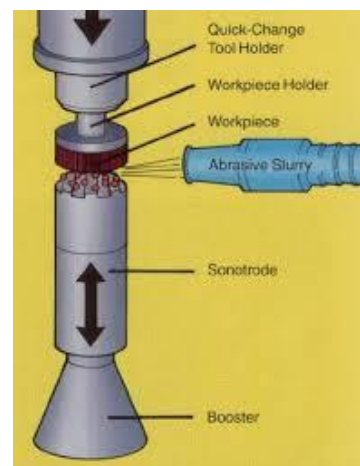


Fig 4. AFM-Sonex technology [4]

In the scientific literature, research on Abrasive Flow Machining (AFM) focuses on optimizing process parameters, testing technological variants, and expanding application domains.

Among the current experimental directions, the implementation of artificial intelligence models—such as artificial neural networks—stands out, as these are employed to determine optimal processing parameters. By applying heuristic search and selection algorithms, such models contribute to reduced machining times and increased operational efficiency.

### 3. Experimental Study

For the machining of internal surfaces with conical geometry—such as the active zone of an extrusion die used for PVC pipe production—an efficient AFM process variant involves the use of two working chambers operated in an alternating manner. In this configuration, the semi-solid abrasive medium is repeatedly forced through the machining zone, moving back and forth through the conical channel of the component.

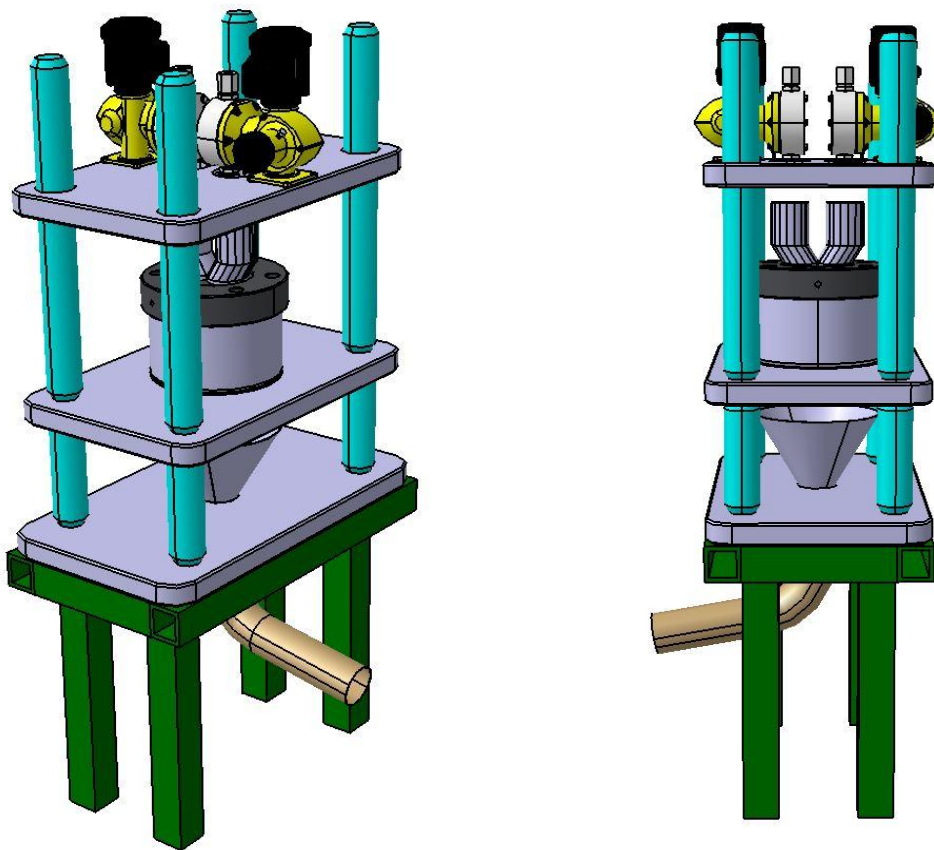


Fig 5. Prototype for machining a conical surface using the AFM method

The bidirectional flow is achieved through alternating pressure exerted by two opposing cylinders within a hydraulically controlled system. As the abrasive medium passes through the working zone, the flow becomes restricted in narrow areas, leading to a localized increase in viscosity and the temporary entrapment of abrasive particles. These particles then behave like a solid abrasive tool, acting precisely on the conical walls of the internal channel.

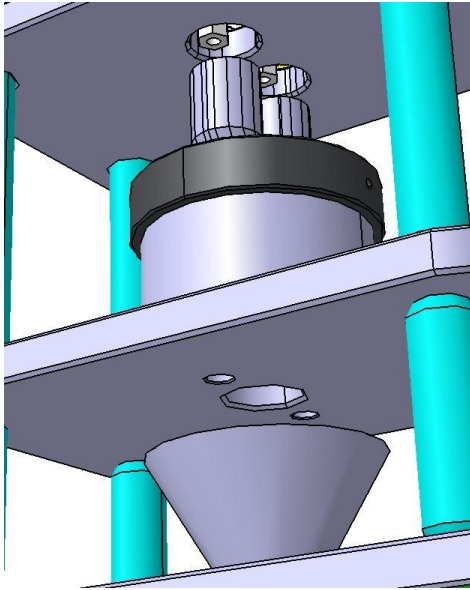


Fig 6. Visualization of the components through which the material passes from the injection pump to the discharge

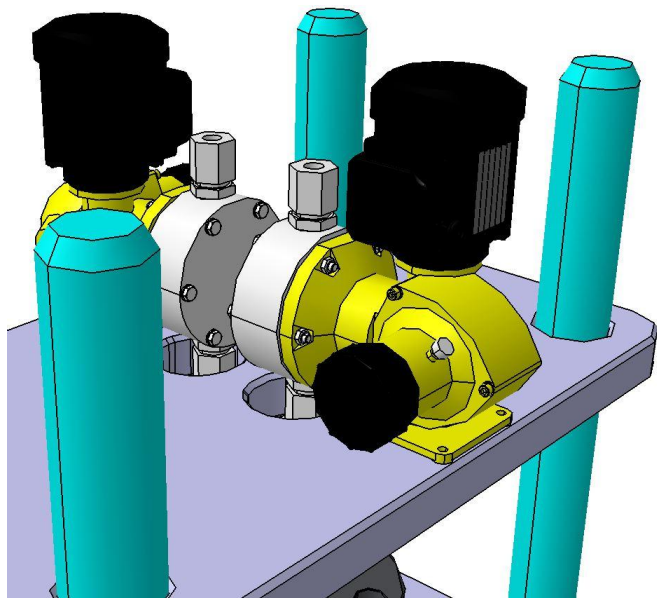


Fig 7. Injection pumps

After exiting the constriction zone, the medium returns to its initial flow state, preparing for a new abrasion phase. This alternation of flow regimes—generated by the two opposing chambers—enables uniform and controlled machining of the conical internal surfaces, ensuring the efficient removal of micro-defects and the achievement of a high-quality finish without compromising the functional geometry of the component.

The extrusion die is a critical element of the PVC pipe production line, responsible for shaping the molten material into a tubular profile with a constant diameter.

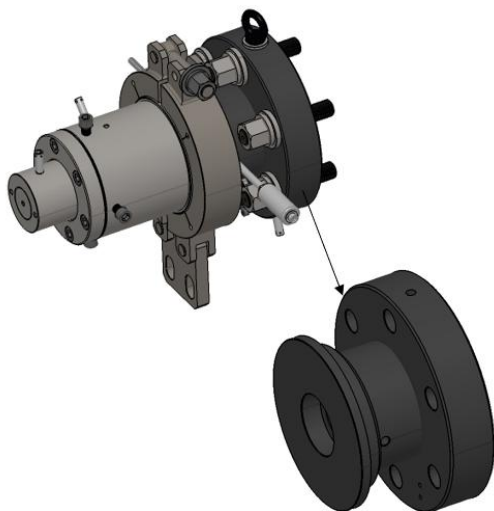


Fig 6. Extrusion flange and the "Extrusion head assembly for PVC pipes" it is part of

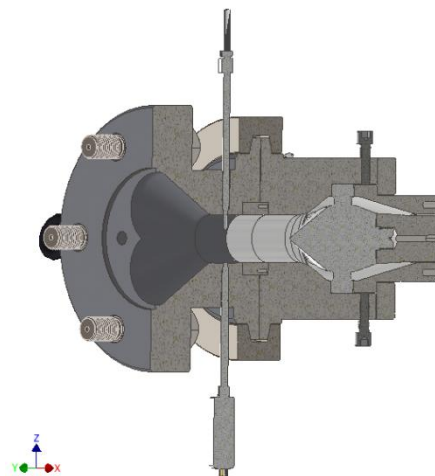


Fig 7. "Extrusion head assembly for PVC pipes" sectioned on the XZ plane in Autodesk Inventor Professional 2025

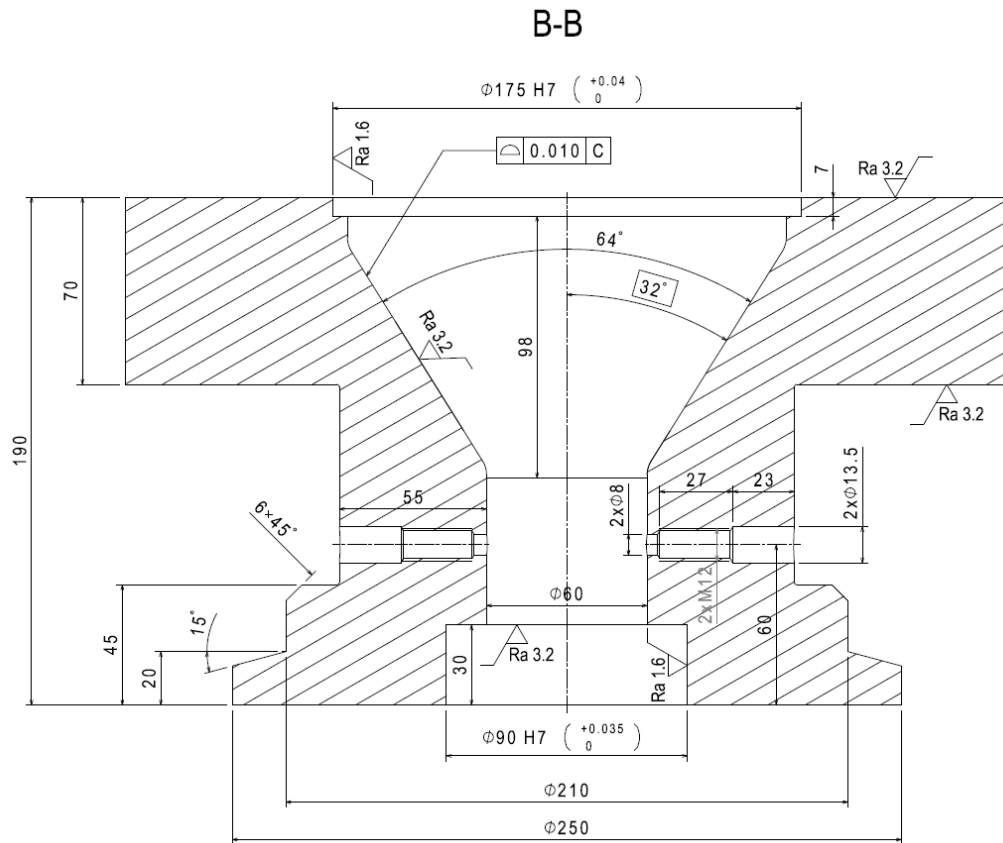


Fig 7. Section B-B of the part for visualizing the internal conical profile

Section B-B was taken from the top view of the extrusion flange

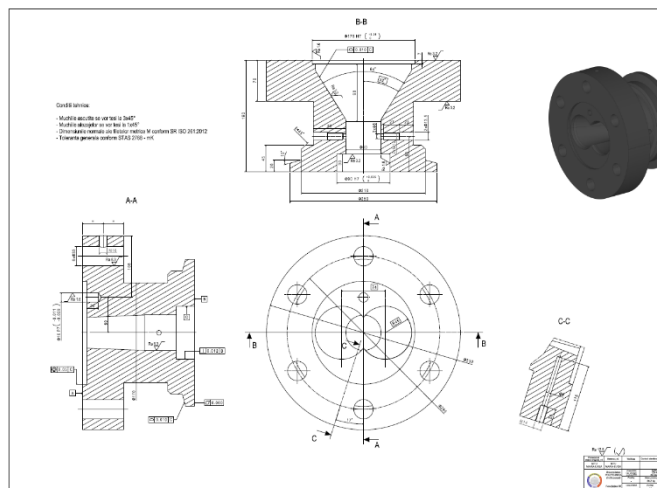


Fig 8. Execution drawing of the part

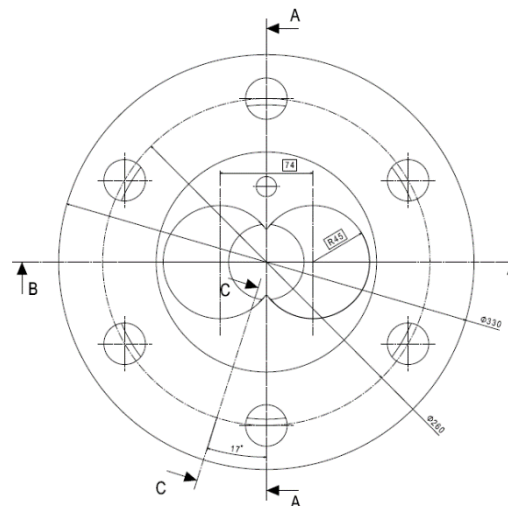


Fig 9. Execution drawing of the part

#### 4. Conclusions

The primary future development direction for equipment used in Abrasive Flow Machining (AFM) lies in the implementation of an advanced digital process simulation system, which will be detailed in a subsequent version of this research paper. In parallel, there is a clear need to optimize the structural architecture of the equipment and to conduct a series of experimental tests aimed at characterizing and validating the performance of the abrasive medium used.

Analysis of experimental and observational data clearly highlights that Abrasive Flow Machining (AFM) is emerging as a next-generation, highly efficient technology for high-precision finishing of surfaces characterized by complex or hard-to-reach geometries.

1. The AFM process has proven to be a remarkably effective method for polishing, edge rounding, and deburring operations—even in component zones with complex internal geometries that are inaccessible by conventional techniques.
2. A fundamental technological feature that gives the AFM method its uniqueness is the process's ability to generate abrasion exclusively in regions where the flow of the abrasive medium is subjected to severe geometric constraints. This characteristic allows for precise and localized material removal, ensuring that adjacent surfaces not requiring treatment remain completely unaffected—an essential advantage for maintaining dimensional accuracy and achieving superior final part quality.
3. Given the wide variety of industrial applications and the morphological diversity of the components subjected to finishing, several constructive types of AFM systems are employed in practice, each specifically adapted to the geometric configuration and technological requirements of the application.
4. The application scope of AFM technology—along with process optimization strategies, including the integration of predictive models based on artificial neural networks—is undergoing continuous expansion, driven by advancements in artificial intelligence and state-of-the-art numerical simulation techniques.

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# ALGORITHM AND APPLICATION FOR AUTOMATING MACHINING ALLOWANCES OF EXTERNAL CYLINDRICAL SURFACES

PARASCHIV Alexandru-Ionuț, Vlad GHEORGHITĂ,  
Marius-Vali LAZĂR (Conducător științific)

Faculty: of Industrial Engineering and Robotics, Departament: Manufacturing Engineering,  
Year of Study: IV, e-mail: alexparaschiv08@gmail.com

*ABSTRACT: This paper presents the design and development of an algorithm and a dedicated computer application that automates the calculation process of machining allowances of external cylindrical surfaces in accordance with international standards such as ISO 8062-4. By integrating the workpiece geometric data and various material and casting process parameters, the proposed system calculates both the nominal dimension of the moulded casting stock part and the dimensions required for machining, eliminating the human error that might appear in the process. The result of this study highlights the potential for significant improvements in both reliability and efficiency of the product manufacturing through the automation of the machining allowances calculation process.*

*KEYWORDS: machining, allowance, casting, automation.*

## 1. Introduction

In manufacturing engineering, achieving parts with the required precision and surface quality for functional conditions necessitates removing a layer of material from the stock part, known as the machining allowance. Determining the optimal dimensions of the machining allowance is of significant technical and economic importance in the design of technological processes [1]. Traditionally, this step is performed manually using tables and general standards, methods that increase the likelihood of errors, material waste, and extended machining times.

The purpose of this paper is to design an algorithm and develop a dedicated software application to automate the process of determining machining allowances for external cylindrical surfaces in casting processes. The application aims to minimize manual intervention, thereby reducing human errors, while adhering to the international standard ISO 8062-4.

To achieve these objectives, a study was conducted on the current state of automated calculation methods, and solutions from specialized literature were analyzed. Subsequently, an automated calculation algorithm was developed based on the method presented in the international standard and tested on relevant datasets. Challenges in the educational process related to machining allowance calculations in technological process design were also observed, along with the benefits this algorithm can provide. The results confirm the efficiency of the proposed method and its potential for application in both academic settings and small-to-medium-sized manufacturing enterprises.

## 2. Current state

The automation of machining allowance calculations in accordance with international standards is a developing field with emerging applications in industry and research. While dedicated software solutions are limited to spreadsheets and internal systems, with no commercial alternatives for fully automating machining allowance calculations per ISO 8062-4, some CAD/CAM applications and 3D inspection systems have begun to partially integrate these functionalities. Certain CAD/CAM platforms allow the definition and application of tolerances per ISO 8062-4, facilitating the design of stock parts with appropriate machining allowances. In 3D inspection systems, compliance with machining allowance specifications is achieved by comparing CAD models with scanned 3D models, enabling adjustments in the manufacturing process.

Research is exploring advanced methods for automating this process, such as the use of “point-cloud registration” [7] and optimization algorithms for machining allowance distribution that account for material properties, casting process parameters, and machining requirements.

### 3. General considerations

Based on the international standard ISO 8062-4, formulas can be derived to calculate the nominal dimensions of external cylindrical surfaces.

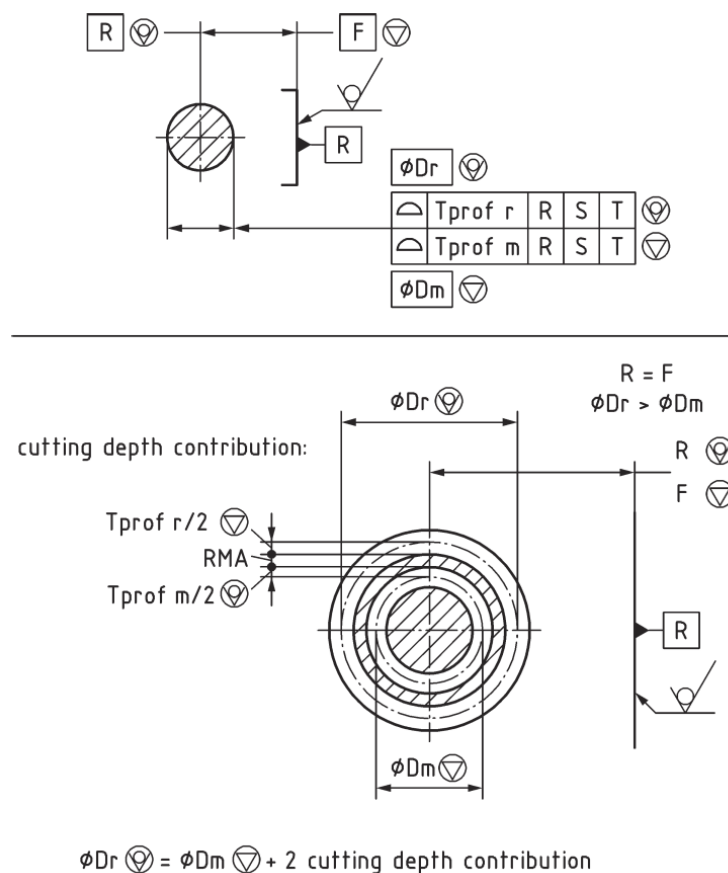


Fig. 7. Calculation of the nominal dimension of the stock part per ISO 8062-4 [3]

For understanding the calculation process and testing the algorithm, a flange-type reference part made of EN-GJL-250 (SR EN 1561:2024) is used, with the dimension for which the allowance is calculated being  $\phi 70 \times 30$  mm [11].

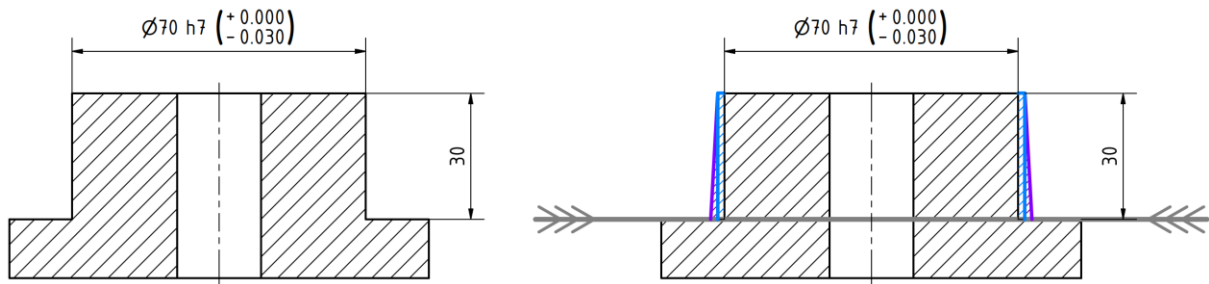


Fig. 8 Technical drawings of the reference part [5]

From Figure 1, the formula is derived:

$$R = d + (T_D)_G + 2 \cdot RMA + 2 \cdot A_i \quad (1)$$

where:  $R$  – calculated nominal dimension of the stock part;

$d$  – dimension of the diameter from the technical drawing;

$(T_D)_G$  – limit deviation extracted from ISO 2768 mK;

$RMA$  – required machining allowance;

$A_i$  – draft angle for permanent moulding casting.

For generalization, the medium tolerance class is chosen based on the diameter:

| Permissible deviations in mm for ranges in nominal lengths | Tolerance Class Designation (Description) |            |            |                 |
|------------------------------------------------------------|-------------------------------------------|------------|------------|-----------------|
|                                                            | f (fine)                                  | m (medium) | c (coarse) | v (very coarse) |
| 0.5 up to 3                                                | ±0.05                                     | ±0.1       | ±0.2       | –               |
| over 3 up to 6                                             | ±0.05                                     | ±0.1       | ±0.3       | ±0.5            |
| over 6 up to 30                                            | ±0.1                                      | ±0.2       | ±0.5       | ±1.0            |
| over 30 up to 120                                          | ±0.15                                     | ±0.3       | ±0.8       | ±1.5            |
| over 120 up to 400                                         | ±0.2                                      | ±0.5       | ±1.2       | ±2.5            |
| over 400 up to 1000                                        | ±0.3                                      | ±0.8       | ±2.0       | ±4.0            |
| over 1000 up to 2000                                       | ±0.5                                      | ±1.2       | ±3.0       | ±6.0            |
| over 2000 up to 4000                                       | –                                         | ±2.0       | ±4.0       | ±8.0            |

Fig. 9 Determination of general limit deviations [2]

$$(T_D)_m = 0.3 - (-0.3) = 0.6 \text{ [mm]} \quad (2)$$

To determine the required machining allowance (RMA), the material class of EN-GJL-250 (SR EN 1561:2024) and the casting type must be established, as shown in Figure 4. In this case, the material is gray cast iron, and the casting method considered is permanent mold casting.

|                     | Sand cast hand moulding | Sand cast machine mould and shell moulding | Metallic permanent mould | Pressure die casting | Investment casting |
|---------------------|-------------------------|--------------------------------------------|--------------------------|----------------------|--------------------|
| Steel               | G to K                  | F to H                                     | —                        | —                    | E                  |
| Grey iron           | F to H                  | E to G                                     | D to F                   | —                    | E                  |
| S. G. iron          | F to H                  | E to G                                     | D to F                   | —                    | E                  |
| Malleable iron      | F to H                  | E to G                                     | D to F                   | —                    | —                  |
| Copper alloys       | F to H                  | E to G                                     | D to F                   | B to D               | E                  |
| Zinc alloys         | F to H                  | E to G                                     | D to F                   | A to D               | —                  |
| Light metal alloys  | F to H                  | E to G                                     | D to F                   | B to D               | E                  |
| Nickel based alloys | G to K                  | F to H                                     | —                        | —                    | E                  |
| Cobalt based alloys | G to K                  | F to H                                     | —                        | —                    | —                  |

Fig. 10 Determination of the RMA class based on material and casting type [3]

Using class D, the RMA value is selected from the table in Figure 5, based on the dimension and casting class per the standard.

| Overall dimension |                  | RMA grades |     |     |     |     |     |     |     |     |    |
|-------------------|------------------|------------|-----|-----|-----|-----|-----|-----|-----|-----|----|
| in mm             |                  |            |     |     |     |     |     |     |     |     |    |
| above             | up to, including | A          | B   | C   | D   | E   | F   | G   | H   | J   | K  |
| <                 | ≤                |            |     |     |     |     |     |     |     |     |    |
| —                 | 40               | 0,1        | 0,1 | 0,2 | 0,3 | 0,4 | 0,5 | 0,5 | 0,7 | 1   | 2  |
| 40                | 63               | 0,1        | 0,2 | 0,3 | 0,3 | 0,4 | 0,5 | 0,7 | 1   | 1,4 | 3  |
| 63                | 100              | 0,2        | 0,3 | 0,4 | 0,5 | 0,7 | 1   | 1,4 | 2   | 2,8 | 4  |
| 100               | 160              | 0,3        | 0,4 | 0,5 | 0,8 | 1,1 | 1,5 | 2,2 | 3   | 4   | 6  |
| 160               | 250              | 0,3        | 0,5 | 0,7 | 1   | 1,4 | 2   | 2,8 | 4   | 5,5 | 8  |
| 250               | 400              | 0,4        | 0,7 | 0,9 | 1,3 | 1,8 | 2,5 | 3,5 | 5   | 7   | 10 |
| 400               | 630              | 0,5        | 0,8 | 1,1 | 1,5 | 2,2 | 3   | 4   | 6   | 9   | 12 |
| 630               | 1 000            | 0,6        | 0,9 | 1,2 | 1,8 | 2,5 | 3,5 | 5   | 7   | 10  | 14 |
| 1 000             | 1 600            | 0,7        | 1   | 1,4 | 2   | 2,8 | 4   | 5,5 | 8   | 11  | 16 |
| 1 600             | 3 000            | 0,8        | 1,1 | 1,6 | 2,2 | 3,2 | 4,5 | 6   | 9   | 13  | 18 |
| 3000              | 6300             | 1          | 1,4 | 2   | 2,8 | 4   | 5,5 | 8   | 11  | 16  | 22 |
| 6300              | 10000            | 1,1        | 1,5 | 2,2 | 3   | 4,5 | 6   | 9   | 12  | 17  | 24 |

Fig. 11 Determination of the required machining allowance class [3]

With the value  $RMA = 0.5$  [mm] obtained, the draft angles are determined based on the height for which the machining allowance is calculated and class B (less precise), according to the table in Figure 6. Draft angles tables vary for each casting type.

| Height range of feature for draft value<br>in mm |                  | Grade A (DA)         |                      | Grade B (DB)           |                        |
|--------------------------------------------------|------------------|----------------------|----------------------|------------------------|------------------------|
| above                                            | up to, including | External draft value | Internal draft value | External draft value 2 | Internal draft value 2 |
| <                                                | ≤                |                      |                      |                        |                        |
| —                                                | 4                | 8,5° (0,3 mm)        | 11,3° (0,4 mm)       | 11,3° (0,4 mm)         | 11,3° (0,4 mm)         |
| 4                                                | 6,3              | 3,3° (0,3 mm)        | 5,6° (0,5 mm)        | 5,6° (0,5 mm)          | 5,6° (0,5 mm)          |
| 6,3                                              | 10               | 3,5° (0,5 mm)        | 4,9° (0,7 mm)        | 4,9° (0,7 mm)          | 5,6° (0,8 mm)          |
| 10                                               | 16               | 3,1° (0,7 mm)        | 1,4° (1,0 mm)        | 3,5° (0,8 mm)          | 5,3° (1,2 mm)          |
| 16                                               | 25               | 2,8° (1,0 mm)        | 3,9° (1,4 mm)        | 3,4° (1,2 mm)          | 4,5° (1,6 mm)          |
| 25                                               | 40               | 2,5° (1,4 mm)        | 3,5° (2,0 mm)        | 3,2° (1,8 mm)          | 4,1° (2,3 mm)          |
| 40                                               | 63               | 2,2° (2,0 mm)        | 2,8° (2,5 mm)        | 2,8° (2,5 mm)          | 3,6° (3,2 mm)          |
| 63                                               | 100              | 1,8° (2,5 mm)        | 2,8° (4,0 mm)        | 2,5° (3,6 mm)          | 3,2° (4,5 mm)          |
| 100                                              | 160              | 1,8° (4,0 mm)        | 2,2° (5,0 mm)        | 1,6° (5,0 mm)          | 2,6° (6,0 mm)          |
| 160                                              | 250              | 1,7° (6,0 mm)        | 1,8° (6,5 mm)        | 2,0° (7,0 mm)          | 2,2° (8,0 mm)          |
| 250                                              | 400              | 1,4° (8,0 mm)        | 1,6° (9,0 mm)        | 1,6° (9,0 mm)          | 1,8° (10,0 mm)         |
| 400                                              | 630              | 1,2° (11,0 mm)       | 1,3° (12,0 mm)       | 1,3° (12,0 mm)         | 1,5° (13,0 mm)         |

Fig. 12 Determination of the draft angles for permanent moulding casting [3]

Applying equation (1), the result is:

$$R = \varnothing 70 + 0.6 + 2 \cdot 0.5 + 2 \cdot 1.8 \cong 75 \text{ [mm]}$$

The tolerance of the nominal dimension of the stock part is determined using the table of total casting tolerances from ISO 8062-3, as shown in Figure 7:

| Nominal dimensions related to the moulded part |          | Linear dimensional tolerance for dimensional casting tolerance grade (DCTG) <sup>a</sup> |        |        |        |        |        |        |        |        |         |         |         |         |         |         |                      |
|------------------------------------------------|----------|------------------------------------------------------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|----------------------|
|                                                |          | DCTG 1                                                                                   | DCTG 2 | DCTG 3 | DCTG 4 | DCTG 5 | DCTG 6 | DCTG 7 | DCTG 8 | DCTG 9 | DCTG 10 | DCTG 11 | DCTG 12 | DCTG 13 | DCTG 14 | DCTG 15 | DCTG 16 <sup>b</sup> |
| —                                              | ≤ 10     | 0,09                                                                                     | 0,13   | 0,18   | 0,26   | 0,36   | 0,52   | 0,74   | 1      | 1,5    | 2       | 2,8     | 4,2     | —       | —       | —       | —                    |
| > 10                                           | ≤ 16     | 0,1                                                                                      | 0,14   | 0,2    | 0,28   | 0,38   | 0,54   | 0,78   | 1,1    | 1,6    | 2,2     | 3       | 4,4     | —       | —       | —       | —                    |
| > 16                                           | ≤ 25     | 0,11                                                                                     | 0,15   | 0,22   | 0,3    | 0,42   | 0,58   | 0,82   | 1,2    | 1,7    | 2,4     | 3,2     | 4,6     | 6       | 8       | 10      | 12                   |
| > 25                                           | ≤ 40     | 0,12                                                                                     | 0,17   | 0,24   | 0,32   | 0,46   | 0,64   | 0,9    | 1,3    | 1,8    | 2,6     | 3,6     | 5       | 7       | 9       | 11      | 14                   |
| > 40                                           | ≤ 63     | 0,13                                                                                     | 0,18   | 0,26   | 0,36   | 0,5    | 0,7    | 1      | 1,4    | 2      | 2,8     | 4       | 5,6     | 8       | 10      | 12      | 16                   |
| > 63                                           | ≤ 100    | 0,14                                                                                     | 0,2    | 0,28   | 0,4    | 0,56   | 0,78   | 1,1    | 1,6    | 2,2    | 3,2     | 4,4     | 6       | 9       | 11      | 14      | 18                   |
| > 100                                          | ≤ 160    | 0,15                                                                                     | 0,22   | 0,3    | 0,44   | 0,62   | 0,88   | 1,2    | 1,8    | 2,5    | 3,6     | 5       | 7       | 10      | 12      | 16      | 20                   |
| > 160                                          | ≤ 250    | —                                                                                        | 0,24   | 0,34   | 0,5    | 0,7    | 1      | 1,4    | 2      | 2,8    | 4       | 5,6     | 8       | 11      | 14      | 18      | 22                   |
| > 250                                          | ≤ 400    | —                                                                                        | —      | 0,4    | 0,56   | 0,78   | 1,1    | 1,6    | 2,2    | 3,2    | 4,4     | 6,2     | 9       | 12      | 16      | 20      | 25                   |
| > 400                                          | ≤ 630    | —                                                                                        | —      | —      | 0,64   | 0,9    | 1,2    | 1,8    | 2,6    | 3,6    | 5       | 7       | 10      | 14      | 18      | 22      | 28                   |
| > 630                                          | ≤ 1 000  | —                                                                                        | —      | —      | —      | 1      | 1,4    | 2      | 2,8    | 4      | 6       | 8       | 11      | 16      | 20      | 25      | 32                   |
| > 1 000                                        | ≤ 1 600  | —                                                                                        | —      | —      | —      | —      | 1,6    | 2,2    | 3,2    | 4,6    | 7       | 9       | 13      | 18      | 23      | 29      | 37                   |
| > 1 600                                        | ≤ 2 500  | —                                                                                        | —      | —      | —      | —      | —      | 2,6    | 3,8    | 5,4    | 8       | 10      | 15      | 21      | 26      | 33      | 42                   |
| > 2 500                                        | ≤ 4 000  | —                                                                                        | —      | —      | —      | —      | —      | —      | 4,4    | 6,2    | 9       | 12      | 17      | 24      | 30      | 38      | 49                   |
| > 4 000                                        | ≤ 6 300  | —                                                                                        | —      | —      | —      | —      | —      | —      | —      | 7      | 10      | 14      | 20      | 28      | 35      | 44      | 56                   |
| > 6 300                                        | ≤ 10 000 | —                                                                                        | —      | —      | —      | —      | —      | —      | —      | —      | 11      | 16      | 23      | 32      | 40      | 50      | 64                   |

<sup>a</sup> For wall thicknesses in grades DCTG 1 to DCTG 15, one grade coarser applies (see Clause 7).  
<sup>b</sup> Grade DCTG 16 exists only for wall thicknesses of castings generally specified to DCTG 15.

Fig. 13 Determination of tolerances for cast parts [4]

Thus, the final dimension is obtained as:  $75 \pm 0.55 \text{ [mm]}$ .

#### 4. Technical description

The automation of these calculations involves processing data and integrating formulas into a client-server architecture typical of modern web applications, enabling real-time interaction between the user and the calculation algorithm while ensuring a user-friendly interface.

##### 4.1. General architecture of the application

The main components are:

- Frontend: Implemented in HTML5, CSS3, and JavaScript;
- Backend: Implemented in Python using the Flask framework [8] for processing HTTP requests and performing calculations;
- Hosting: Deployed on the Render cloud application platform;
- Data Persistence: Based on CSV (Comma-Separated Values) files [9], loaded at server initialization and serving as the data source.

#### 4.2. Structure of the calculation algorithm

The algorithm performs calculations based on user-input data and tables extracted from international standards, implemented as CSV files. The main steps include:

- Retrieving data from the web form;
- Mapping input values to standardized intervals using dedicated functions (*map\_to\_interval()*);
- Accessing corresponding values from CSV files using determined indices;
- Calculating the nominal dimension per equation (1) and adding the casting tolerance.

#### 4.3. Data flow

The data flow is represented as follows:

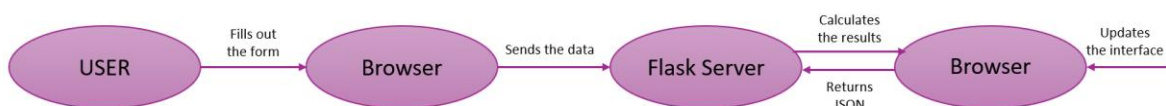


Fig. 14 Data flow [5]

#### 4.4. Web interface

The web interface consists of an HTML page styled with CSS, including numeric input fields, dropdown selectors, and explanatory tooltips.

The main functionality is the dynamic updating of displayed values based on input parameters without page reloading.

#### 4.5. Representative code snippet

The algorithm is implemented in a Python file, where the *handle\_form()* function manages HTTP POST requests:

```
def handle_form():
    number1 = float(request.form['number1'])
    number2 = float(request.form['number2'])
    tdm_value = request.form['tdm_select']
    rma_value = request.form['rma_select']
    draft_value = request.form['draft_select']
    ct_select = int(request.form['ct_select'])

    # Map classes
    tdm_row_idx = tdm_row_map.get(tdm_value.lower())
    rma_col_idx = rma_col_map.get(rma_value.upper())
    draft_col_idx = draft_col_map.get(draft_value.upper())

    # Map dimensions to intervals
    tdm_col_idx = map_to_interval(number1, tdm_intervals)
    rma_row_idx = map_to_interval(number1, rma_intervals)

    # Extract values from tables
    tdm_val = float(tdm_df.iloc[tdm_row_idx, tdm_col_idx])
    rma_val = float(rma_df.iloc[rma_row_idx, rma_col_idx])
    draft_val = float(draft_df.iloc[draft_row_idx, draft_col_idx])

    # Calculate result
    result = number1 + 2 * tdm_val + 2 * rma_val + 2 * draft_val

    return jsonify({"result": result})
```

Fig. 15 Code snippet from calc.py [5]

This snippet highlights the processing flow of raw data, accessing tables, and returning the result in JSON format [10].

#### 4.6. Usage example

For the input data  $d = 70$ ,  $h = 30$  and  $T_m = m$ ,  $RMA = D$ ,  $draft = B$  and  $CT = 7$ , extracted from the technical drawing of the reference part, the application generates  $\emptyset 75 \pm 0.55$ , identical to the result obtained manually in the previous chapter.

**alexi-p's Machining Allowance Calculator for external cylindrical surfaces**

Diametrul:  ⓘ

Înălțimea:  ⓘ

Clasa de toleranță:  ⓘ

Clasa RMA:  ⓘ

Unghiuri de înclinare:  ⓘ

Clasa dimensională:  ⓘ

**Rezultatul este:  $75 \pm 0.55$**

**Dimensiuni intermediare: ⓘ**

| Denumire prel                          | $A_k$ | Denumire finală                         | Select IT |
|----------------------------------------|-------|-----------------------------------------|-----------|
| $S_D \overline{\phi 70} \times 30$     | 1.49  | $S_D \phi 72 \pm 0.15 \times 30$        | IT12      |
| $S_{F/2} \overline{\phi 70} \times 30$ | 0.8   | $S_{F/2} \phi 70.4 \pm 0.037 \times 30$ | IT9       |
| $S_F \overline{\phi 70} \times 30$     | 0.2   | $S_F \phi 70 \times 30$                 | IT7       |

**Calculează**

Fig. 16 Example of web page usage [6]

## 5. Future developments

The primary development needed for this application is its extension to other types of surfaces, including internal cylindrical surfaces, flat surfaces, and complex (freeform) surfaces. Another significant improvement is the diversification of stock manufacturing types by introducing machining allowances for forging and various mold types (sand, metallic, etc.).

Additionally, the web interface can be enhanced with image generation to simplify visualization, automatic determination of optimal parameters based on material properties, and automation of technical drawing generation that includes calculated machining allowances. Generating compliance reports could further streamline data processing for users.

Other developments include incorporating artificial intelligence and machine learning through algorithms that automatically adjust based on real-world results, developing an adaptive system that improves accuracy as it accumulates new data, and pursuing industrial validation, database expansion, and certification in compliance with international standards.

## 6. Conclusions

This paper represents an initial step toward automating the determination of machining allowances and improving the efficiency of metal part production in accordance with the requirements of the international standard ISO 8062-4. Both theoretical aspects regarding the importance of machining allowances and practical aspects related to implementing a system capable of automatically generating required values based on relevant geometric parameters were addressed.

Through research and analysis of specialized standards and literature, a rigorous foundation for the proposed solution was established. The developed algorithm was validated

through testing on a set of cases. The results confirm that the application significantly reduces the time required for manual calculations and eliminates errors.

Moreover, the paper highlights the high potential for improvement and expansion of the proposed solution through the inclusion of additional stock manufacturing methods, generated data, and the use of artificial intelligence algorithms for dynamic optimization of machining allowances. These development directions align with current industry trends toward digitalization, automation, and integration into Industry 4.0 ecosystems.

In conclusion, the paper demonstrates the utility and feasibility of implementing a software application for determining machining allowances and opens important perspectives for continued research and development of advanced software solutions with direct applicability in modern manufacturing processes.

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# DEVELOPMENT OF AN EXPERIMENTAL EDUCATIONAL VEHICLE PROTOTYPE WITH DUAL FUNCTIONS: PREDEFINED PATH FOLLOWING AND REMOTE CONTROL

CHELU Fabian-Cătălin, COJOACĂ Cristian-Andrei-Ionuț, TRĂISTARU Andrei, VELCEA Alexandra, DUGĂEȘESCU Ileana (Conducător științific)

Faculty: Faculty of Industrial Engineering and Robotics, Specialization: Industrial Informatics, Year of Study: II,

e-mail: [alexandra.velcea@stud.fiir.upb.ro](mailto:alexandra.velcea@stud.fiir.upb.ro)

*Abstract: This paper aims to present an educational vehicle prototype meant for studying embedded programming in IoT and control algorithms. The device's architecture is detailed below, along with the graphical interfaces defined for this project. The schematic diagram, as well as components and algorithms used are described. The prototype has two built-in functional modes, and both have been tested using a handmade line following map. This work underscores the importance of practical, project-based learning and contributes to the advancement of accessible, modular platforms for control systems education.*

**KEYWORDS:** experimental prototype, ESP8266, education, PID control, line follower.

## 1. Introduction

In recent years, the use of mobile robots for educational purposes has seen significant growth, as they are increasingly integrated as tools to bridge theoretical knowledge with practical applications. This project aims to develop a small-scale autonomous vehicle prototype capable of performing two key functions: automated tracking of a predefined path and manual control via a wireless connection. Such a vehicle offers diverse practical applications, particularly for exploring concepts like sensor utilization, signal processing (e.g., identifying reference points using infrared sensors), motor operation (via an L298N H-bridge controller [1]), and embedded programming (integrating the ESP8266 [2,3,4] microcontroller). As a result, the prototype serves as a versatile educational platform in fields such as robotics and automation.

## 2. Direction Control in Line Followers

Line-follower robots are mobile systems designed and programmed to fulfill one main function which is to follow a pre-established path, depending on the user's set requirements [5].

Specialized literature describes similar mobile systems [6], used with educational and transportational purposes, developed utilizing microcontrollers like Arduino or similar modules. These systems can employ basic steering algorithms (e.g., "if-else" logic) or advanced methods like proportional-integral-derivative (PID [7,8]) control for precise path tracking.

Because of its low cost and compact size, the ESP8266 [2,3,4] module enables the creation of remotely controlled vehicles via radio or web interfaces. Some vehicles are dedicated line-followers, while others incorporate radio or Bluetooth control.

## 3. Modeling, 3D Printing of Components, and Development of the Experimental Prototype

For the experimental prototype, the casing and chassis were designed to facilitate assembling the electronic components. The casing, shown in Fig. 1(a), serves to protect the internal components of the prototype. Fig. 1(b) displays the chassis of the experimental prototype, which is modeled with holes and bores to enable proper component assembling.

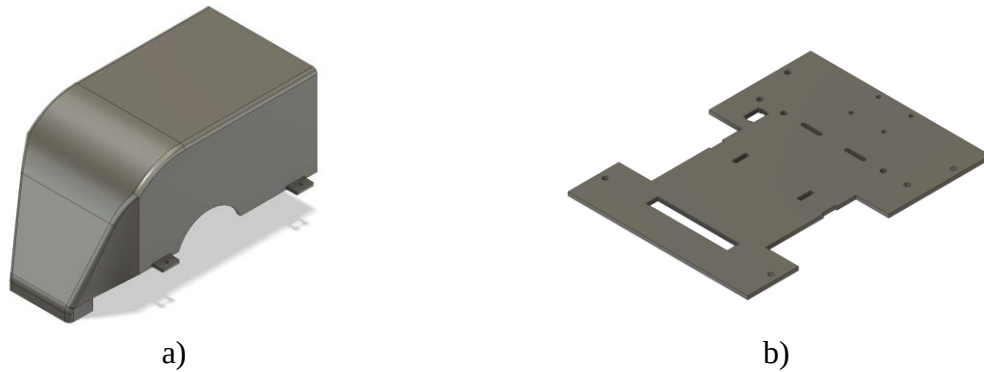
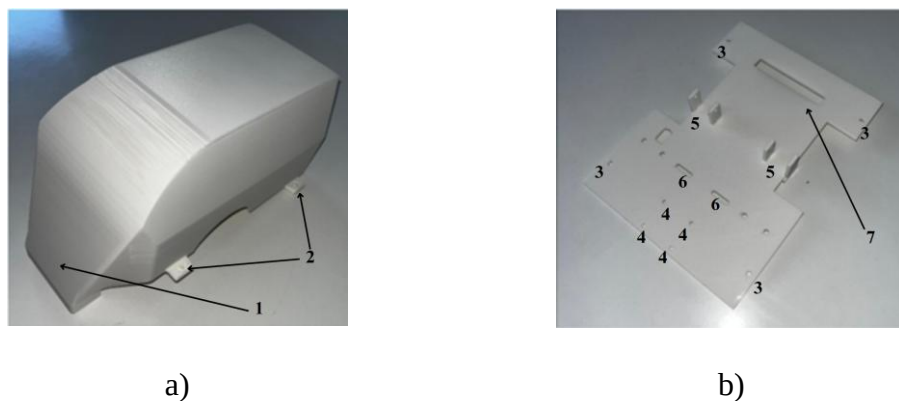


Fig. 1. Modeled components of the prototype: a) casing, b) chassis

The 3D modeling of the two components aimed to generate .stl files meant for 3D printing. Both the casing and the chassis are shown in Fig. 2, emphasizing the bores and mounts designed to secure the electronic components.



**Fig. 2. a) Casing:** 1 – Housing for the infrared sensor, 2 – Bores for assembling the enclosure to the chassis; **b) Chassis:** 3 – Bores for assembling the chassis to the enclosure, 4 – Bores for mounting the front wheel, 5 – Brackets for mounting the motors, 6 – Bores for mounting the power source, 7 – Slit for routing the infrared sensor connections. The bores that are not labeled serve the purpose of distributing and managing other connections

The assembly of the prototype began after the two 3D-printed parts were obtained. During this stage, a connection diagram (Fig. 3) showcasing the electronic components and their connections was created, among which the following can be found:

1. An ESP8266 NodeMCU [2,3,4,9]: A module based on the ESP8266 chip, featuring Wi-Fi 802.11 b/g/n interface and 17 GPIO pins. It is programmable via the Arduino IDE application [3,4];
2. An L298N motor driver module: A dual H-bridge module used to control the movement of two DC motors. It supports motor supply voltages from 5V to 35V and can handle up to 2A per channel [1,10];

3. Two DC motors: These motors operate within a supply voltage range of 3V to 6V. For instance, a typical motor in this category has a no-load speed of 7000 RPM at 3V and up to 12000 RPM at 6V [11];
4. A 3-channel infrared (IR) sensor module: This kit consists of three units, each consisting of an IR LED and a phototransistor. It operates at a supply voltage of 5V and is commonly used for line-tracking applications [12,13];
5. A power supply: The power source consists of an assembly of four 3.7V batteries connected in series, totaling 14.8V. This configuration is typical for lithium-ion battery packs, where each cell has a nominal voltage of 3.7V and a full charge voltage of 4.2V [14].

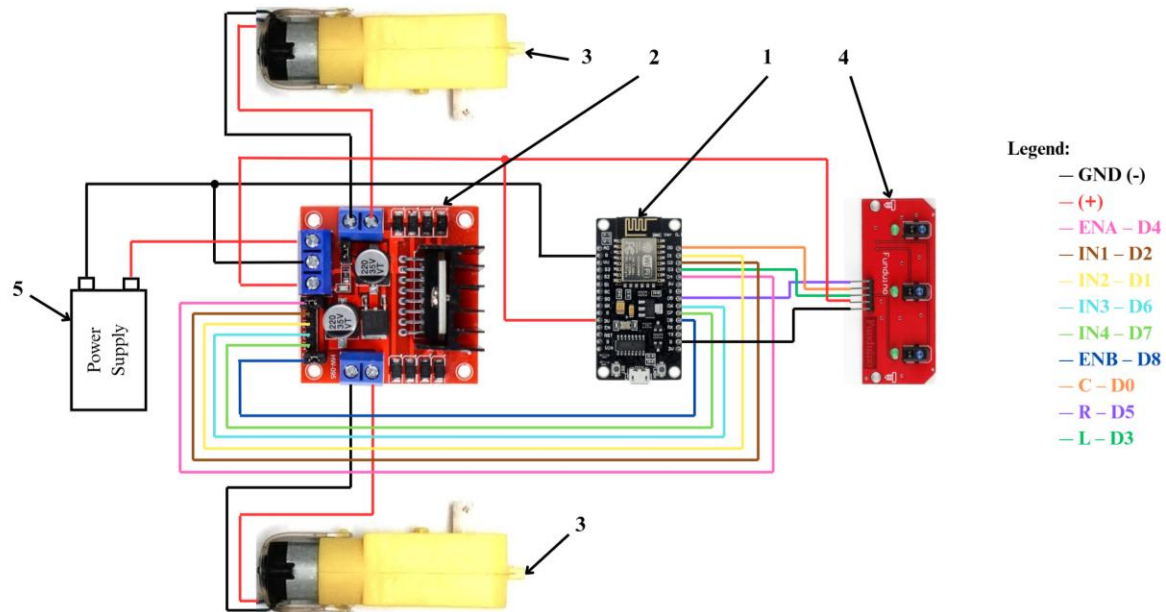


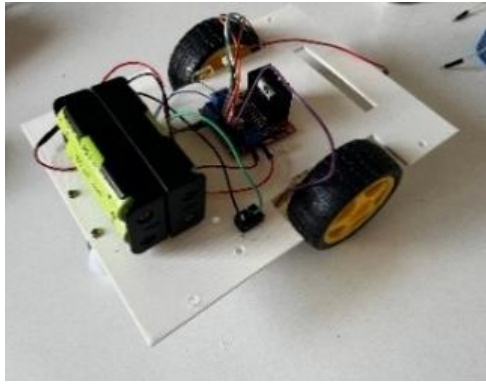
Fig. 3. Wiring diagram of the components in the experimental prototype:

- 1 – NodeMCU development board with ESP8266 [2,3,4,9], 2 – L298N motor driver [1,10], 3 – two DC motors [11], 4 – infrared sensor module with three sensors [12,13], 5 – power source.

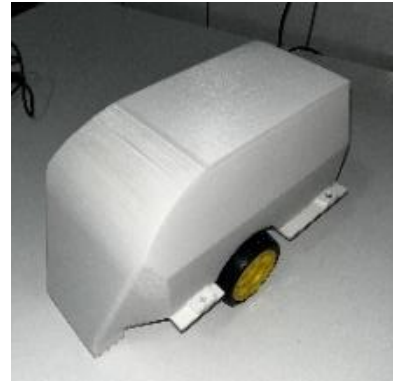
The legend on the right-hand side of the figure above showcases the connections tying the components. Thus, by following each connection according to the color used, the prototype's assembly . The colors indicate the following: black is used for ground (GND) connections, red for power supplies, pink, brown, and yellow for DC motor 1, blue, turquoise, and light green for DC motor 2, dark green, orange, and purple for the IR module.

In Fig. 4 a), the 3D-printed chassis is shown, onto which the two motors, the L298N shield, the two wheels, the power button, and the power supply have been mounted.

Fig. 4 b) displays the experimental model of the educational vehicle.



a)



b)

Fig. 4. Experimental model: a) chassis with assembled components, b) fully assembled model of the educational vehicle

#### 4. Testing the experimental model

Both the prototype and the predefined path designed for line following on which tests were performed are presented in Fig. 5.



Fig. 5. The preset route followed by the prototype

The shaft of each motor is coupled with a wheel, and the motors are controlled using the L298N driver module. In order to achieve this, the motor-enabling pins (ENA and ENB) of the H-bridge on the driver were connected to digital pins 4 and 8. The wires of the first motor (red wire – power supply, black wire – ground) are connected to the OUT1 pins, and the wires corresponding to the second motor were connected to the OUT2 pins of the L298N driver. The direction of motor rotation for each motor is determined by the input pins (IN). In the case of motor 1, the control signals are transmitted through the IN1 and IN2 pins, which are connected to digital pins 2 and 1, respectively. For motor 2, the control signals are transmitted through the IN3 and IN4 pins, connected to digital pins 6 and 7, respectively.

The pins' definition for both sending the pulse width modulation (PWM) signal and for controlling the movement (forward/backward) of the two motors is the following:

```
#define IN1 4 // (D2): control pin FORWARD left motor
#define IN2 5 // (D1): control pin BACKWARD left motor
```

```
#define IN3 12 // (D6): control pin FORWARD right motor
#define IN4 13 // (D7): control pin BACKWARD right motor
#define ENA 2 // (D4): PWM channel for speed adjustment of the left motor
#define ENB 15 // (D8): PWM channel for speed adjustment of the right motor
```

The two pins (IN1 and IN2 for the first motor, respectively IN3 and IN4 for the second motor) operate complementarily, meaning that when IN1 is active (HIGH), IN2 is inactive (LOW) and the motor rotates in a certain direction. To change the direction of motor rotation, the states of the two pins are swapped; specifically, IN1 is set to inactive (LOW), while IN2 is set to active (HIGH).

```
// Manual forward control
digitalWrite(IN1, LOW); // IN1=0: left motor direction – forward rotation
digitalWrite(IN2, HIGH); // IN2=1: complete signal for left motor forward
digitalWrite(IN3, HIGH); // IN3=1: right motor direction – forward rotation
digitalWrite(IN4, LOW); // IN4=0: complete signal for right motor forward
analogWrite(ENA, speed); // ENA=left PWM: sets the speed of the left motor
analogWrite(ENB, speed); // ENB=right PWM: sets the speed of the right motor
// Manual backward control
digitalWrite(IN1, HIGH); // IN1=1: left motor direction – backward rotation
digitalWrite(IN2, LOW); // IN2=0: complete signal for left motor backward
digitalWrite(IN3, LOW); // IN3=0: right motor direction – backward rotation
digitalWrite(IN4, HIGH); // IN4=1: complete signal for right motor backward
analogWrite(ENA, speed); // ENA=left PWM: sets the speed of the left motor
analogWrite(ENB, speed); // ENB=right PWM: sets the speed of the right motor
```

The 3-channel module (Fig. 6) is used to move the educational vehicle along the predetermined path. It connects via 5 pins as follows: GND – to ground, VCC – to power supply (5V), Left – to digital pin 3, Center – to digital pin 0, and Right – to digital pin 5.

Below is the definition of the three pins corresponding to the module used for tracking the path shown in Fig. 5:

```
#define right 14 // (D5): right IR sensor – line detection
#define center 16 // (D0): center IR sensor – line detection
#define left 0 // (D3): left IR sensor – line detection
```

The three incorporated infrared sensors detect the reflection between the track line (black strip) and the adjacent background (white sheet of paper). If the center sensor (Center) detects the line, then the experimental vehicle moves forward (Forward), and if the two side sensors (Left and Right) detect the line, then it will turn slightly to reposition itself on the track.

```
// Reading the IR sensor signals and determining the position
int calculatePosition() { // Definition of the function that returns the line position
    bool r = digitalRead(right); // Read right sensor
    bool c = digitalRead(center); // Read center sensor
    bool l = digitalRead(left); // Read left sensor
    if (l && !c && !r) return 0; // line at the far right
    if (l && c && !r) return 500; // between right sensor and center sensor
    if (!l && c && !r) return 1000; // directly under the center sensor
    if (!l && c && r) return 1500; // between center sensor and left sensor
```

```

if (!l && !c && r) return 2000; // line at the far left
if (l && !c && r) return 1000; // ambiguous situation (right and left)
return target; // If no combination matches, the target value is used
} // End of calculatePosition() function

```

In the figure below is shown the chassis onto which the following components are mounted: the line following module (1), two DC motors (2, 2') on whose shafts are the two wheels (3, 3') used for moving the experimental prototype.

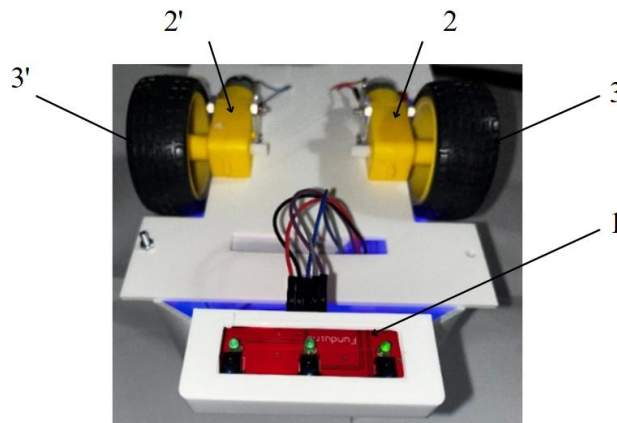


Fig. 6. Line following IR module and DC motors mounted on the chassis

For precise path following, control algorithms can be used so as to maintain a clear direction along the predetermined line. These algorithms allow for adjusting the direction and speed of the motors depending on the deviation that occurs during the movement of a line-follower type vehicle. PID control (Proportional–Integral–Derivative) [7,8] is frequently used to ensure efficient operation of such a system. In the first stage, the IR module detects the position relative to the line, after which an error is calculated, defined as the difference between the desired position and the detected one. Subsequently, the algorithm adjusts the motor speeds to correct this error, taking into account the three components of PID control. Precise adjustment of the parameters is necessary to achieve proper functioning. This process involves gradually modifying the values of the proportional ( $K_p$ ), integral ( $K_i$ ), and derivative ( $K_d$ ) constants, testing their effects on the system, and making the necessary adjustments until stable and appropriate behavior is achieved [7,8].

Fig. 7 displays the interface used for the manual control of the experimental prototype. Using this, the system allows for switching between Manual mode and Auto mode by pressing the corresponding buttons. In the first mode, direction control is performed using the W, A, S, and D keys, while speed control can be adjusted using the increase (+ Speed) and decrease (– Speed) buttons, where the speed value is predefined at 512, as shown in Fig. 7.

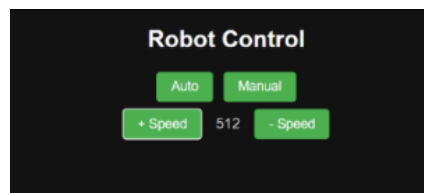


Fig. 7. The interface utilized to control the prototype

Below is a conditional structure used for detecting the press of the "W" key. In this context, the value of the "posY" variable is incremented by a step, which causes the graphical element to move along the vertical axis, thus simulating forward motion. In parallel, the "cmd" variable is set to "forward" value, used for motor control.

```
// Manual keyboard control – handling W key press
switch(key) { // Checks which key was pressed
  case 'w':    // If the key is "w" (forward)
    posY += step; // Increase Y-axis position by the value of step
    cmd = 'forward'; // Prepare the "forward" command
    break; // Stop processing other cases of the switch structure
}
```

## 5. Conclusions

The use of 3D modeling and printing provided a solution for creating the chassis and casing, facilitating the development of a prototype tailored to specific requirements. The manufacturing process allowed for customization, contributing to weight reduction and improved efficiency of the prototype. The installation of the two DC motors and the integration of the line-following module enabled testing of the experimental model. The test results highlighted the system's functionality and revealed areas for potential improvement.

In conclusion, the developed experimental prototype, with a chassis and casing designed and 3D printed, demonstrates the efficiency of using modern technologies in the design and manufacturing process. The assembly of the two motors and the line follower module enabled the realization of a functional experimental model.

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# DETECTION LOGGING SYSTEM FOR AUTONOMOUS PLATFORMS

TAMAȘ Eugen Adrian<sup>1</sup>, NĂFLIU-JOIȚA Ion-Edi<sup>2</sup>, ABAZA Bogdan Felician,  
DOICIN Cristian Vasile(Conducători științifici)

<sup>1,2</sup> Faculty of Industrial Engineering and Robotics, Specialization: Applied Informatics in Industrial Engineering,  
Year of Study: I, e-mail: [tamas.eugen.adrian@gmail.com](mailto:tamas.eugen.adrian@gmail.com)

**ABSTRACT:** This paper presents a backend subsystem for logging and configuring actions of autonomous platforms, centralizing object detection data (e.g., from YOLO) into an SQLite database. Designed for embedded systems, it manages the efficient flow and storage of images and detection data. Images are uploaded via a PHP interface and stored with timestamps, paths, and detections in a daily database. Organized by day, the system supports scalable SQL operations and includes input validation to guard against XSS attacks. It enables automated actions based on detection logs, aiding mission-critical decisions. Implementation details and performance optimizations for constrained environments are discussed.

**KEYWORDS:** databases, backend, detection logging

## 1. Introduction

This paper presents a subsystem for managing metadata associated with visually detected objects and relevant types of actions in an autonomous environment, using a simple and robust web interface built in PHP and supported by a local SQLite database. This subsystem serves to centralize, display, and verify in real time the data generated by the platform's visual components, thereby facilitating integration between perception and reaction within the system's overall architecture [7].

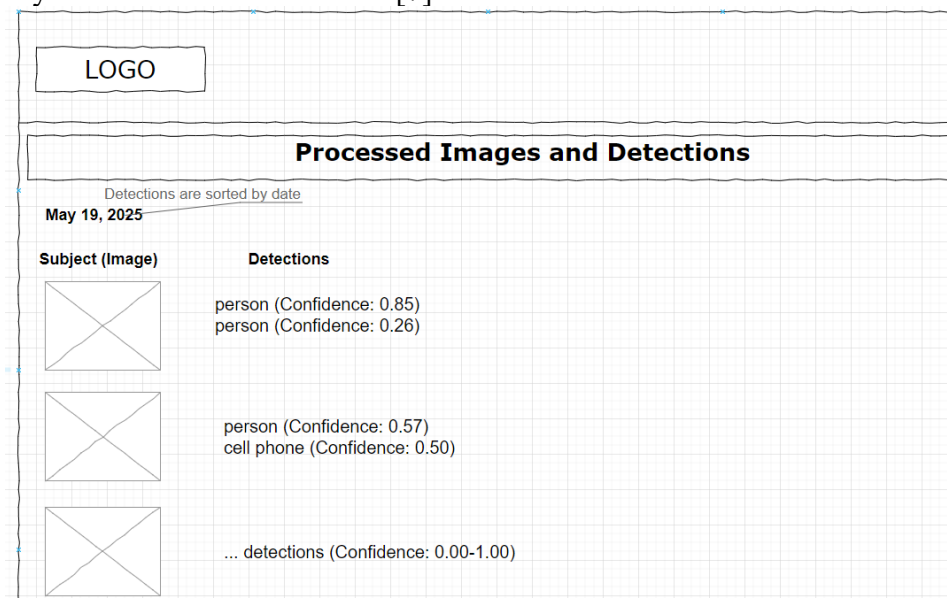


Fig. 1. front end application interface layout design

The interface allows for the display of object classes (based on COCO labels [4], see Fig. 1) and possible action types through direct database queries, while also ensuring the daily persistence of detections along with the associated images. This approach aims to achieve both

traceability of detections and a structured local database that can later be used for training decision-making systems or for post-event analysis [8].

## 2. Current state of the study

The detection, storage, and monitoring subsystem plays a critical role in the autonomous platform by ensuring that all inference outputs from the YOLO-based visual detection module are systematically recorded and managed [1]. Operating in parallel with the real-time object detection pipeline, this subsystem is responsible for capturing each analyzed video frame, storing the image and its associated metadata (predictions) in a structured, local SQLite database, and offering a lightweight user interface for system monitoring and verification.

Designed with resource-constrained hardware in mind—such as the Raspberry Pi—the system emphasizes low overhead and high reliability. The backend is developed in PHP with minimal dependencies, optimized for fast execution and low memory consumption. Such lightweight implementations of machine learning infrastructure have proven effective in similar embedded environments [9], supporting both academic and industrial use cases [2], [3].

After each inference cycle, the system serializes detection results (e.g., class labels, bounding box coordinates, confidence scores) into a JSON object. This metadata, along with the corresponding image frame, is sent to a local server via an HTTP POST request. Upon receipt, the server validates the input: the image is saved in a chronologically organized directory, while the JSON metadata is securely written to the images table of an SQLite database with an associated timestamp. This method ensures long-term data persistence and enables auditable logging of model outputs, facilitating later performance evaluation, debugging, and retraining.

To support real-time visibility and system diagnostics, a minimalist web dashboard (see Fig. 2) is available through `index.php`. This interface dynamically displays logged detections, organizes them by category and timestamp, and enables further administrative actions. Key reference data—including the object classes supported by the YOLO (COCO-based) model [8] and predefined action types (e.g., send alert, log entry)—are stored in separate tables (`coco_classes` and `actions`) and initialized via `init_db.php` and `init_actions.php` scripts.

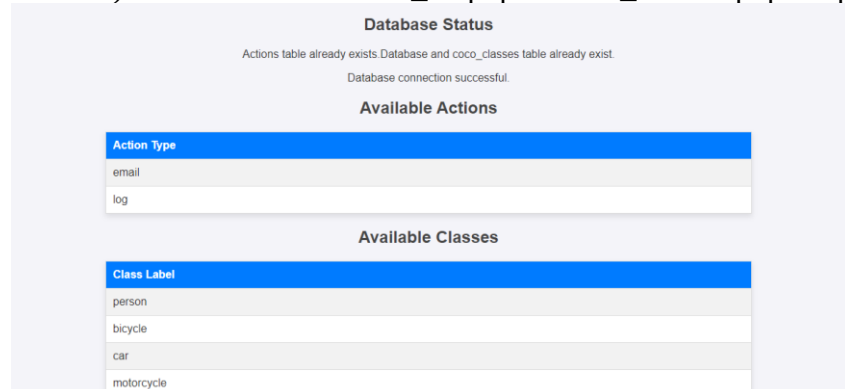


Fig. 2. Database status page

This modular and extensible architecture allows the system to evolve over time. For example, developers can easily define new action triggers based on detection results or integrate with other autonomous decision-making subsystems, such as automated navigation, user alert systems, or maintenance logs. The design ensures not only operational autonomy but also future-proof adaptability across a variety of embedded robotic platforms.

In addition to its core role in data persistence and the structured organization of raw visual detections, the subsystem incorporates a lightweight web interface accessible via

index.php. This interface offers users an intuitive, retrospective view of the system's performance and outputs.



|                                                                                   |                                                                                                                                                                 |
|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <ul style="list-style-type: none"> <li>• person (Confidence: 0.86)</li> <li>• cell phone (Confidence: 0.61)</li> </ul>                                          |
|  | <ul style="list-style-type: none"> <li>• person (Confidence: 0.87)</li> <li>• cell phone (Confidence: 0.61)</li> </ul>                                          |
|  | <ul style="list-style-type: none"> <li>• person (Confidence: 0.87)</li> <li>• cell phone (Confidence: 0.67)</li> </ul>                                          |
|  | <ul style="list-style-type: none"> <li>• person (Confidence: 0.86)</li> <li>• cell phone (Confidence: 0.40)</li> </ul>                                          |
|  | <ul style="list-style-type: none"> <li>• person (Confidence: 0.87)</li> <li>• cell phone (Confidence: 0.54)</li> </ul>                                          |
|  | <ul style="list-style-type: none"> <li>• person (Confidence: 0.85)</li> <li>• cell phone (Confidence: 0.43)</li> <li>• cell phone (Confidence: 0.30)</li> </ul> |

Fig. 3. log history

The page automatically scans all local SQLite databases—each corresponding to a day of operation—and retrieves entries from the images table, including both the analyzed video frames and their associated detection metadata (in JSON format). Results are displayed in a chronological table where each row includes a thumbnail of the processed image alongside a human-readable summary of the detected objects, including class labels and confidence scores.

This interface serves multiple critical functions: it enables rapid diagnostics of system behavior, helps identify edge cases or misclassifications, and supports the evaluation of the YOLO model's performance in real-world scenarios. Additionally, its modular design makes it a strong foundation for future enhancements, such as export tools, search and filtering capabilities, or integration with advanced analytics and reporting systems.

### 3. Implementation

The subsystem for data logging consists of 4 stages: the image and detection data, processed by the Python script for the image detection subsystem are sent to the local server, the server receives, processes and stores detection data in the database. The user then can view detection history in the browser.

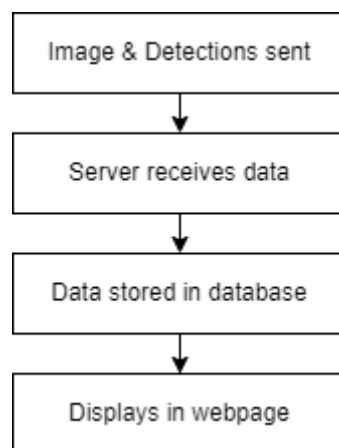


Fig. 4. Subsystem diagram

```

1. <?php
2. include('config.php');
3. $dbDir = 'data/';
4. $dbFiles = glob($dbDir . '*.db');
5. function parseDateFromFilename($filename) {
6.     $date = basename($filename, '.db');
7.     return date('F j, Y', strtotime($date));
8. }?>
9. <!DOCTYPE html>
10. <html lang="en">
11. <head>
12.     <meta charset="UTF-8">
13.     <meta name="viewport" content="width=device-width, initial-scale=1.0">
14.     <title>Processed Images and Detections</title>
15.     <style>...stylesheet used </style>
16. </head>
17. <body>
18. <h1>Processed Images and Detections</h1>
19. <?php foreach ($dbFiles as $dbFile): ?>
20.     <?php
21.         $date = parseDateFromFilename($dbFile);
22.         try {
23.             $pdo = new PDO("sqlite:$dbFile");
24.             $pdo->setAttribute(PDO::ATTR_ERRMODE,
PDO::ERRMODE_EXCEPTION);
25.             $query = "SELECT * FROM images";
26.             $stmt = $pdo->query($query);
27.             $images = $stmt->fetchAll(PDO::FETCH_ASSOC);
28.         } catch (PDOException $e) {
29.             die("<p>Database error: " . htmlspecialchars($e->getMessage()) . "</p>");
30.         } ?>
31.     <h2><?= htmlspecialchars($date) ?></h2>
32.     <table>
33.         <thead>
34.             <tr>
35.                 <th>Subject (Image)</th>
36.                 <th>Detections</th>
37.             </tr></thead>
38.             <tbody>
39.                 <?php foreach ($images as $image): ?>
40.                     <tr><td>
41.                         <?php
42.                             $image_path = str_replace("C:\\xampp\\htdocs", "",
$image['image_path']);
43.                             $image_url = $site_url . "/data/images/" . basename($image_path);
44.                             ?>
45.                             
46.                         </td><td>
47.                             <ul>
48.                                 <?php

```

```

49.         $detections =
    json_decode(htmlspecialchars_decode($image['detections']), true);
50.         if (is_array($detections)) {
51.             foreach ($detections as $detection):
52.                 ?>
53.                     <li>
54.                         <strong><?= htmlspecialchars($detection['class'])
    ?></strong> (Confidence: <?= number_format($detection['confidence'], 2) ?>)
55.                     </li>
56.                 <?php
    endforeach;
57.             } else {
58.                 echo "<li>No detections available</li>";
59.             }
60.         }
61.     ?>
62. </ul>
63. </td>
64. </tr>
65. <?php endforeach; ?>
66. </tbody>
67. </table>
68. <?php endforeach; ?>
69. </body></html>

```

This PHP script is used to display the data recorded by the detection subsystem. It begins by scanning the data/ directory for SQLite database files, each named according to the day it was created (e.g., 2025-06-09.db). These files are processed one by one, and the corresponding dates are extracted and formatted for display. This structure allows users to view detection results grouped by day.

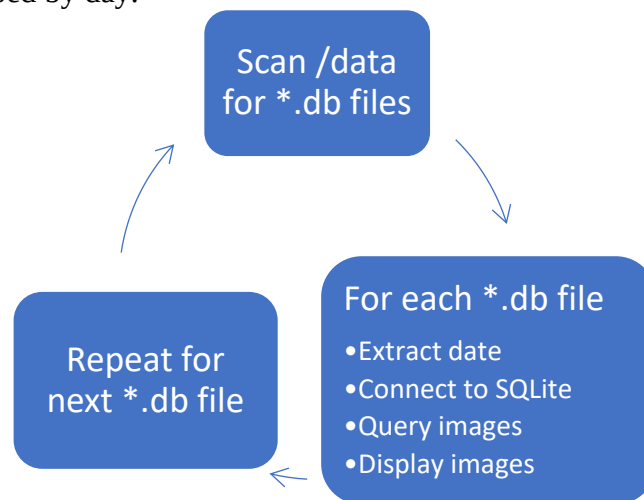


Fig. 5. Frontend diagram

For each database, the script connects using PDO and retrieves all records from the images table. Each record includes the path to an image file and a text field containing the detection results, stored in JSON format. The image path is adjusted so that it can be accessed from the browser, and the image is displayed as a thumbnail in the interface. The detection data are decoded and shown as a list below the corresponding image. Each detected object is shown with its class label and associated confidence score.

The interface is built as a simple HTML page and organized by date. It uses basic table formatting to show the image and the detections side by side. If a detection record cannot be decoded correctly, a message is displayed to indicate that no data are available. All output is passed through sanitation functions to reduce the risk of displaying malformed or unsafe content in the browser.

This viewer allows for the manual inspection of previously recorded detection results and supports checking whether the system captured and logged data correctly. It complements the automatic storage functions of the backend by offering a straightforward way to access and interpret the stored information.

Code snippet required for validating and centrally storing information to be used by other subsystems:

```

1. <?php
2. define("DATA_DIR", __DIR__ . "/data");
3. define("IMAGE_DIR", DATA_DIR . "/images");
4. if (!file_exists(IMAGE_DIR)) {
5.     mkdir(IMAGE_DIR, 0777, true);}
6. if (!file_exists(DATA_DIR)) {
7.     mkdir(DATA_DIR, 0777, true);}
8. $date = date("Y-m-d");
9. $dbFile = DATA_DIR . "/" . $date . ".db";
10. try {
11.     $pdo = new PDO("sqlite:$dbFile");
12.     $pdo->setAttribute(PDO::ATTR_ERRMODE, PDO::ERRMODE_EXCEPTION);
13.     $createTableQuery = "
14. CREATE TABLE IF NOT EXISTS images (
15.     id INTEGER PRIMARY KEY AUTOINCREMENT,
16.     timestamp INTEGER NOT NULL,
17.     image_path TEXT NOT NULL,
18.     detections TEXT NOT NULL
19. );";
20. $pdo->exec($createTableQuery);
21. } catch (PDOException $e) {
22.     die("Database error: " . $e->getMessage());
23. }
24. if (
25.     $_SERVER["REQUEST_METHOD"] == "POST" &&
26.     isset($_FILES["image"]) &&
27.     isset($_POST["detections"])
28. ) {
29.     $image = $_FILES["image"];
30.     $detections = $_POST["detections"];
31.     if (empty($detections)) {
32.         die("Error: Detections data is missing.");
33.     }
34.     $detections = htmlspecialchars($detections);
35.     if ($image["error"] !== UPLOAD_ERR_OK) {
36.         die("Error: Failed to upload image.");
37.     }
38.     $fileExtension = pathinfo($image["name"], PATHINFO_EXTENSION);
39.     $timestamp = time();

```

```

40. $imageFilename = $timestamp . "." . $fileExtension;
41. $imagePath = IMAGE_DIR . "/" . $imageFilename;
42. if (!move_uploaded_file($image["tmp_name"], $imagePath)) {
43.     die("Error: Failed to save the image.");
44. }
45. try {
46.     $insertQuery = "
47.     INSERT INTO images (timestamp, image_path, detections)
48.     VALUES (:timestamp, :image_path, :detections);";
49.     $stmt = $pdo->prepare($insertQuery);
50.     $stmt->bindParam(":timestamp", $timestamp, PDO::PARAM_INT);
51.     $stmt->bindParam(":image_path", $imagePath, PDO::PARAM_STR);
52.     $stmt->bindParam(":detections", $detections, PDO::PARAM_STR);
53.     $stmt->execute();
54.     echo "Data saved successfully.";
55. } catch (PDOException $e) {
56.     die("Error saving data: " . $e->getMessage());
57. } } else {
58.     die("Invalid request. Make sure the image is uploaded and detections are
    provided."
59. ); }?>

```

As part of the backend logging subsystem, the PHP script is responsible for receiving and storing detection data and associated image files. It begins by defining two constants for the storage paths: one for image files and another for SQLite database files. These directories are checked for existence and created if missing, ensuring the necessary file structure is in place before processing begins. This initialization step supports reliability in long-term deployments, where automatic recovery from missing folders is required.

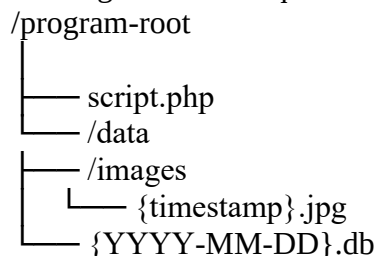


Fig. 6. subsystem filesystem structure

Each incoming data packet—consisting of a POST request with an image and its corresponding detection output—is stored in a database file named after the current date (e.g., 2025-06-09.db). This naming convention enables efficient chronological indexing of data and simplifies batch processing or later retrieval. If the database file does not exist, the script creates it and initializes an images table to store the detection log. Each entry includes a UNIX timestamp, the path to the saved image, and a JSON-formatted string of detection results.

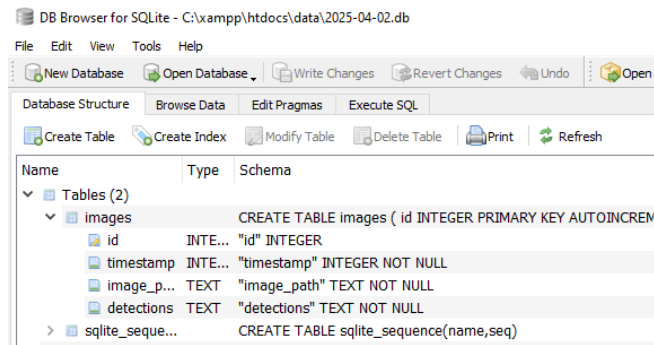


Fig. 7. SQL schema for the generated databases

The upload process includes input validation to ensure both the image and its associated detection data are present and correctly formatted. The image is renamed using the current timestamp to avoid conflicts and is moved to a dedicated /images subdirectory. Simultaneously, the detection string is sanitized to prevent injection or cross-site scripting (XSS) vulnerabilities. Once stored, the metadata is inserted into the images table via a parameterized query, ensuring safe database interaction.

This mechanism supports the core function of the subsystem: to create a persistent, verifiable, and easily queryable log of detected objects. By enforcing input checks and maintaining a predictable file structure, it contributes to the system's reliability, particularly in embedded environments with limited manual oversight.

#### 4. Conclusions

The proposed system efficiently archives images and their associated detections, generating a daily log organized chronologically, useful for both manual inspection and automated analysis. The logs include timestamps and file paths, providing complete traceability of visual perception.

In the future, the system will be extended with automated actions triggered based on detected objects, and rewriting it in Rust will bring increased performance [5]. Other directions include WebSocket support for real-time detections, dynamic classifier selection, binary storage (e.g., Protocol Buffers), distributed synchronization (e.g., rqlite), a graphical interface for re-labeling, and the inclusion of advanced scoring in detections.

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## RESEARCH ON THE DEVELOPMENT OF A ROBOTIC EXOSKELETON MANUFACTURED VIA 3D PRINTING

ENACHE Nicoleta<sup>1</sup>, MARCU George-Gabriel, MINĂ Theodora-Andra, ORGHIDEAN Rareș-Vasile, TOMA Andreea- Gabriela, ZODI Rama, Ileana DUGĂEȘESCU, Asist. Angela Miruna NEACȘU-PAVEL (Conducători științifici)

<sup>1</sup>Faculty Industrial Engineering and Robotics, Specialization: Economic Engineering and Business Management, Year of Study: I, e-mail: [nicoleta.botez@stud.fiir.upb.ro](mailto:nicoleta.botez@stud.fiir.upb.ro)

*ABSTRACT: This work investigates the development of a 3D-printed robotic exoskeleton for the construction industry, focusing on optimizing strength, ergonomics and adaptability to difficult tasks. The main objective is to design a device that will reduce the physical effort of workers, prevent injuries and increase productivity. The study identifies essential user needs, including fatigue reduction, freedom of movement, increased comfort, and durability in harsh environments. The conceptual design proposes a modular structure made of lightweight materials (PETG) fabricated by FDM 3D printing, with passive joints and adjustable fastening systems. The research highlights the technology's potential to improve working conditions in construction through accessible innovation.*

*KEYWORDS: 3D Printing, prototyping, exoskeleton, design, research.*

### 1. Introduction

Robotic exoskeletons are gaining ground not only in the medical field, but also in the construction and mechanical industries, where they help increase productivity, reduce worker fatigue and prevent accidents. This research paper investigates the development of a robotic exoskeleton, fabricated via 3D printing, for construction or mechanical applications, focusing on strength, ergonomics and adaptability to difficult tasks.

Objective of the research paper: to investigate the design, manufacturing and testing process of a 3D printed robotic exoskeleton intended to assist construction and mechanical workers, with a focus on optimizing weight, strength and functionality. [1] [2]

The importance of 3D printing: This technology enables rapid prototyping and the production of parts with complex geometry, reducing costs and development time, and allowing customization for specific users. [1] [2]

### 2. Competition analysis

Competitor analysis for an exoskeleton for the construction industry is essential for understanding the current market and identifying opportunities for differentiation. In a sector dominated by intense physical effort, multiple risks and challenges, industrial exoskeletons are becoming increasingly necessary to increase productivity and reduce workplace accidents.

To create an exoskeleton, three key competitors in the field will be analyzed: SuitX (USA) – IX Shoulder Air [3], German Bionic Cray X (Apogee+) [4] and Ottobock (Germany) – Paexo Series [5] and the main features, price, benefits and technical details will be compared.

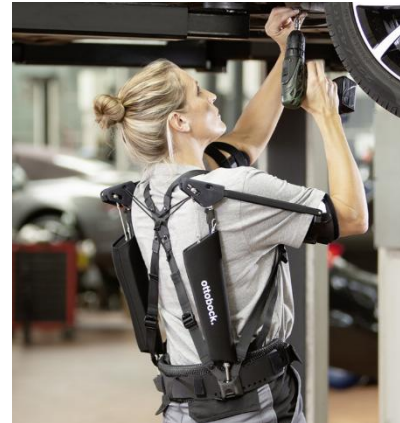
The three competing products are presented in Figure 1.



a) SuitX (SUA) – IX Shoulder Air [3]



b) German Bionic Cray X (Apogee+) [4]



c) Ottobock (Germany) – Paexo Series [5]

Fig. 1. Competing products

The analysis of the characteristics of the three competing products can be seen in Table 1:

Table 1. Characteristics of competing products

| No. | Size/ feature                  | Units         | Competing products                    |                                    |                                       |
|-----|--------------------------------|---------------|---------------------------------------|------------------------------------|---------------------------------------|
|     |                                |               | SuitX (SUA) – IX Shoulder Air [3]     | German Bionic Cray X (Apogee+) [4] | Ottobock (Germany) – Paexo Series [5] |
| 1   | Weight                         | kg            | ~1.9                                  | ~5.8                               | ~1.8                                  |
| 2   | Materials                      | Type material | resistant fibers, aluminum components | carbon fiber, aluminum             | plastic, aluminum                     |
| 3   | Equipping time                 | seconds       | < 20                                  | 60-120                             | < 15                                  |
| 4   | Available sizes                | cm            | 160–190                               | 160–200                            | 160–195                               |
| 5   | Wear duration                  | hours         | <8                                    | <8                                 | < 8                                   |
| 6   | Freedom of movement            | Yes/No        | Yes                                   | Yes                                | Yes                                   |
| 7   | Sensors                        | Yes/No        | No                                    | Yes                                | No                                    |
| 8   | Electric power                 | Yes/No        | No                                    | Yes                                | No                                    |
| 9   | Support capacity               | kg            | ≤40                                   | ≤30                                | ≤50                                   |
| 10  | Worn over protective equipment | Yes/No        | Yes                                   | No                                 | Yes                                   |
| 11  | Selling price                  | Euro          | 2.000-4.000                           | 15.000-25.000                      | 4.000-6.000                           |

After analyzing the characteristics of the competing products shown in Table 1, the following conclusions were drawn::

- **SuitX (SUA) – IX Shoulder Air** [3] is a lightweight, quick-fitting exoskeleton that is ideal for moderate tasks and has a low cost.
- **German Bionic Cray X (Apogee+)** [4] is an exoskeleton that offers intelligent sensor and motorization assistance, but is heavy, expensive and slower to equip.
- **Ottobock (Germany) – Paexo Series** [5] is the lightest and best performing exoskeleton in terms of support capacity (50 kg), but is more expensive than the first exoskeleton presented.

### 3. EXO-LIFT exoskeleton concept

The EXO-LIFT will be an industrial exoskeleton, designed to assist users in tasks involving frequent lifting of the arms or holding them in raised positions while working. This exoskeleton will offer a balance between weight, efficiency and cost. The device will be easy to use and wear throughout the workday.

In order to realize the concept for the EXO-LIFT exoskeleton the following benefits can be considered:

- Reduces fatigue in the upper body, ideal for repetitive activities;
- Ventilated and comfortable design for extended wear;
- Compatible with multiple industries including automotive, construction, maintenance and logistics;
- Manufactured using 3D printing technology;
- No electrical components, easy to maintain and use in various work environments.

**Table 2. EXO-LIFT exoskeleton prototype characteristics**

| No. | Size/ feature                  | Units         | Exoskeleton EXO-LIFT |
|-----|--------------------------------|---------------|----------------------|
| 1   | Weight                         | kg            | ~2.5                 |
| 2   | Materials                      | Type material | To be determined     |
| 3   | Equipping time                 | seconds       | <120                 |
| 4   | Available sizes                | cm            | 150-200              |
| 5   | Wear duration                  | hours         | <8                   |
| 6   | Freedom of movement            | Yes/No        | Yes                  |
| 7   | Sensors                        | Yes/No        | No                   |
| 8   | Electric power                 | Yes/No        | No                   |
| 9   | Support capacity               | kg            | ≤20                  |
| 10  | Worn over protective equipment | Yes/No        | No                   |
| 11  | Selling price                  | Euro          | 2.000-3.500          |

EXO-LIFT will be an efficient, affordable exoskeleton that will have a lower support capacity (20 kg) than the SuitX (SUA) – IX Shoulder Air [3], but at a competitive price. It will also have a lower selling price than the German Bionic Cray X (Apogee+) [4] and may offer a better balance between quality and price than the Ottobock (Germany) – Paexo Series [5].

### 4. Specification Definition

Identifying user needs: to design an effective exoskeleton, it is necessary to consider the real needs of end users, namely construction and mechanical workers.

#### 4.1. Identified User Needs:

- Reduced fatigue and risk of injury:

Users want mechanical support that reduces strain on arms, shoulders and back while handling difficult tasks.

The exoskeleton helps prevent muscle and joint injuries caused by overuse.

- Freedom of movement:

The exoskeleton facilitates the user's natural movements, allowing activities such as lifting objects, stretching and bending.

- More comfort while wearing:

Ergonomic design requirement: even pressure distribution on the body for increased comfort.

Ventilation and materials that reduce heat accumulation and sweating.

- Easy mounting and adjustment:

Workers need a quick mounting and dismounting system.

- Durability and strength:

The exoskeleton to be resistant to mechanical shocks, dust, humidity and temperature variations characteristic of construction work environments.

- Easy maintenance:

The exoskeleton allows for cleaning, repair, and replacement of components in a short time and at low cost.

In conclusion, users need an exoskeleton that is lightweight, comfortable, durable and high-performance, which increases their strength and reducing fatigue levels in daily construction activities.

The development of a robotic exoskeleton for use in the construction industry requires the clear definition of functional, ergonomic and technological specifications to meet the real requirements of users.

#### **4.2. Main objectives of the exoskeleton:**

The EXO-LIFT exoskeleton aims to reduce the physical effort associated with lifting, supporting and weight handling tasks, while helping to prevent injuries caused by muscle overuse and unfavorable work postures, adapting to a wide range of body morphologies and professional activities such as masonry, welding or assembly.

#### **4.3. Target specifications:**

Product specifications will be presented in Table 3:

**Table 3. EXO-LIFT exoskeleton prototype target specifications**

| <b>Functional specifications</b>                                                | <b>Ergonomic specifications</b>                                                       | <b>Technological specifications</b>                                          |
|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| 1. Repetitive weight lifting.                                                   | 1. Easy to use.                                                                       | 1. Materials used: high-resistance filaments.                                |
| 2. Capacity to support loads of up to 20 kg distributed across the upper limbs. | 2. Compatibility with protective equipment.                                           | 2. Primary manufacturing method: 3D printing.                                |
| 3. Interaction with tools and machinery (without blocking natural movements).   | 3. Total weight not to exceed 10 kg.                                                  | 3. Modular fastening elements with quick systems (Velcro, adjustable clips). |
| 4. Reducing muscle fatigue in the back and shoulders.                           | 4. Possibility of quick adjustment and mounting.                                      | 4. Autonomy: 8+ hours.                                                       |
| 5. High mobility to allow workers to work in tight spaces or on scaffolding.    | 5. The pressure on the body should be distributed evenly, for increased user comfort. | 5. Fast charging in less than two hours.                                     |
| 6. Resistance to dust, humidity                                                 | 6. Uneven surfaces (construction sites, unstable platforms).                          | 6. Support capacity: 20 kg.                                                  |

### **5. Conceptual design**

Starting from the specifications established in the previous chapter, the conceptual design aims to define the basic architecture and constructive solutions for the robotic exoskeleton.

### **General structure:**

The proposed exoskeleton has a modular structure composed of a main frame made of lightweight materials, passive joints with steel springs for repetitive loads, limb support systems including passive or active mechanisms and fastening system with adjustable straps and anchor points for equipment. There are also auxiliary components such as shock absorbers, springs and position sensors.

In order to materialize the proposed concept, an exoskeleton prototype is desired. It will be manufactured using additive manufacturing technology, but in order to determine the optimal parameters it is necessary to test several cases in which they are varied for the following types of materials: PLA and PETG, for the Ender 3 S1 PLUS printer, G-code being generated using Ultimaker Cura software.

Testing the extrusion temperature is a necessary step in the calibration of a 3D printer, as it directly influences the adhesion of the layers as well as the strength and surface quality of the print. One of the most common test methods is Temp Tower, a structure printed with segments using different extrusion temperatures. In this chapter, we analyze the results obtained from printing a Temp Tower using both PLA and PETG, noting anomalies and discussing possible causes.



Fig. 2 – Samples tested by varying the temperature of the two materials:

a) PLA – Tested temperatures: 180°C, 185°C, 190°C, 195°C, 200°C, 205°C, 210°C, 215°C, 220°C;

b) PETG – Tested temperatures: 220°C, 225°C, 230°C, 235°C, 240°C, 245°C, 250°C

The optimum printing temperature for PLA is 190-210°C, which provides an ideal balance between fluidity and precision. From testing, it was observed that the ideal temperature is 195°C, providing the optimal ratio between fluidity and precision, while avoiding the problems associated with too high temperatures, such as over-extrusion or unwanted deformations of the printed part.

For PETG, a printing temperature of 220°C has proven to be optimal, ensuring good clarity of the printed object and minimizing defects. Although PETG is typically recommended for temperatures between 220°C and 260°C, certain high-quality or low-viscosity filaments can be processed even at the lower end of this range. Printing at 220°C brings important advantages: it reduces stringing, improves detail accuracy and ensures efficient interlayer adhesion without the risk of over-extrusion which could compromise the surface finish.

The NANO All In One 3D Printer Test [6] was conducted to quickly evaluate the printer's accuracy, alignment, and detail capabilities.

These conclusions emphasize the importance of practical testing, as filament properties may vary depending on manufacturer and batch. Lower temperatures, especially for PETG, can improve surface quality and minimize issues such as filaments or over-extrusion. For consistent results, it is recommended to periodically check the settings and adapt them to the specific characteristics of the material used.

Table 4. Results obtained

| Test version no. | Material | Parameters            | Preview Printing    | Obtained model                                                                        |
|------------------|----------|-----------------------|---------------------|---------------------------------------------------------------------------------------|
| 1                | PLA      | 0.10 mm, 40 mm/s, 25% | 2h 8m, 1.40m (4.2g) |    |
| 2                | PLA      | 0.20 mm, 60 mm/s, 50% | 1h 2m, 1.45m (4.3g) |   |
| 3                | PLA      | 0.30 mm, 80 mm/s, 75% | 41m, 1.48m (4.4g)   |  |
| 4                | PET-G    | 0.10 mm, 40 mm/s, 25% | 2h 6m, 1.42m (4.4g) |  |
| 5                | PET-G    | 0.20 mm, 60 mm/s, 50% | 1h 1m, 1.49m (4.5g) |  |

|   |       |                       |                   |                                                                                     |
|---|-------|-----------------------|-------------------|-------------------------------------------------------------------------------------|
| 6 | PET-G | 0.30 mm, 80 mm/s, 75% | 41m, 1.49m (4.6g) |  |
|---|-------|-----------------------|-------------------|-------------------------------------------------------------------------------------|

Tolerance testing is critical for the design of 3D parts that require mechanical interaction, such as: gears, hinges or assemblable components. Clearance Tolerance Test [7] is a useful tool for determining the minimum clearance required between two parts to ensure smooth movement without jamming or excessive play. Tolerances of 0.1 mm, 0.15 mm, 0.2 mm, 0.25 mm, 0.3 mm, and 0.35 mm were tested to identify optimal values for both PLA and PETG, using previously established extrusion temperatures (195°C for PLA, 220°C for PETG).

#### PLA testing (195°C)



a) PLA tolerance test



b) Results obtained

Fig. 3 - PLA testing (195°C)

For PLA, the parts separated properly to tolerances of up to 0.2 mm, indicating good printer accuracy; the results can be seen above in Figure number 3.

#### PETG testing (220°C)



a) PETG tolerance test



b) Results obtained

Fig. 4 - PETG testing (220°C)

For PETG, the parts remained functional and separated correctly to a tolerance of 0.15 mm, demonstrating good dimensional accuracy; the results can be seen above in Figure number 4.

Tests have shown that optimal tolerances depend largely on the material used and the accuracy of the printer. For PLA, a tolerance of 0.25 mm ensures functionality without high material consumption, while PETG requires slightly lower values, 0.2-0.25 mm, due to its thermal behavior and layer adhesion. These results emphasize the importance of material- and application-specific calibration, especially in designs involving mechanical components. Future research will include tolerance testing for ABS and optimization of slicer parameters.

In the development of the exoskeleton prototype, one of the components for the physical interface with the user is the forearm fixation bracelet. Its role is to ensure the stability of the mechanical assembly on the user's arm, facilitating motion transfer and reducing the mechanical play between the active structure and the human body. The component was designed in a semicircular shape, adapted to the contour of the forearm.



a) PLA printing



b) PETG printing

Fig. 5 - Bracelet to fix on the forearm

PLA printing was achieved without difficulty, resulting in a part with good dimensional accuracy, a smooth surface and a rigid structure, suitable for applications with moderate mechanical stresses; interlayer adhesion was satisfactory and the curved shape was reproduced. Therefore, from the testing carried out, PLA was found to be a suitable material for visual prototyping and component assembly verification.

In the case of PETG printing, the resulting part exhibited superior mechanical strength and easy flexibility, qualities that make it more stress tolerant, and the combination of elasticity and durability recommends this material for functional or semi-structural applications.

## 6. Conclusions

In conclusion, this research has outlined initial conceptual ideas for the development of an exoskeleton for construction workers, with the aim of reducing muscle fatigue in activities involving arm lifting and increasing safety in the workplace. Following a detailed analysis of the three competing products on the market, the relevant specifications for the target users were selected in order to create an efficient and accessible prototype.

The characteristics of the EXO-LIFT exoskeleton are: light weight (~2.5 kg), support capacity up to 20 kg allowing freedom of movement, durability and easy maintenance. These have been improved after comparing competing products, changing as follows: ventilated design and adaptable fastening system for superior comfort.

In the conceptual design, PETG was chosen as the main material as it was found to be lightweight, offering a balance between strength, flexibility, cost and ease of 3D printing, as well as durability in industrial environments (dust, UV and oil resistant).

A future research direction is the realization of a motion study using dedicated 3D modeling software. The development stages related to obtaining a functional prototype are also being pursued: CAD prototyping in SolidWorks of component parts, 3D simulation of functional and structural elements, printing components using PETG materials and creating a functional prototype.

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# LAMELLAR TOOL-ELECTRODE GUIDE AND INTERSTICE- FLUSHING DEVICE FOR ELECTROCHEMICAL MICROMACHINING

ALBINA Alexandru, BURUIANA Roxana Andreea, IANCU Nikolaos, MINDRU Ioana, STOICA Alexandru, GHICULESCU Liviu-Daniel (Conducător științific)

Faculty of Industrial Engineering and Robotics, Master's program: Engineering of Nanostructures and Unconventional Processes

Year of study: I, e-mail: alexandrustoica66@gmail.com

*ABSTRACT: This paper presents a self-centering guiding device for lamellar tool-electrodes in electrochemical micromachining (ECM). The device achieves  $\pm 4 \mu\text{m}$  positioning accuracy and reduces electrode change-over time to under 60 seconds, boosting productivity compared to conventional fixtures. A worm-wheel mechanism ensures precise, repeatable alignment, while corrosion-resistant materials and seals provide durability under 0.3 MPa electrolyte pressure with a clamping force of 2 kN per jaw. A scaled prototype was manufactured and tested, validating the concept and highlighting necessary refinements. Market analysis shows a strong need for compact, fast, and ergonomic solutions that combine accuracy, resistance, and ease of use. With demonstrated advantages over existing alternatives, the proposed device has high potential for adoption in aerospace, medical, and micro-mould industries, advancing the efficiency and reliability of ECM micro-manufacturing processes.*

*KEYWORDS: electrochemical micromachining, device, accuracy, electrode*

## 1. Introduction

The paper introduces a compact self-centring guide that precisely aligns lamellar tool-electrodes for electro-chemical micromachining (ECM). A worm-wheel mechanism limits deviation to  $\pm 4 \mu\text{m}$  and enables electrode change-over in under 60 s, cutting set-up time by half.

Materials and seals tolerate 0.3 MPa electrolyte; endurance tests confirmed a 2 kN clamping force per jaw and no corrosion after 72 h.

The projected manufacturing cost is below 4 000 RON, highlighting strong potential for rapid industrial adoption.

## 2. Project topic

The work proposes the design, development, and validation of a self-centering guiding device for lamellar electrodes used in electrochemical machining (ECM). The topic addresses a real industrial need: improving positioning accuracy and reducing setup times in ECM micro-machining processes.

The main objectives are:

- identifying the technical requirements;
- conceiving an ergonomic, reliable solution;
- manufacturing a functional prototype;
- testing it under real operating conditions; and

- carrying out an economic analysis of implementation.

The project integrates aspects of mechanical engineering, research-and-development, technology marketing, and sustainability.

### 3. Scope

The goal of the project is to develop a self-centering device for the precise clamping of lamellar electrodes in ECM. The need arises from the absence in industry of compact, fast, and durable solutions. The device must provide a positioning accuracy of  $\pm 4 \mu\text{m}$ , rapid electrode changeover, and resistance to corrosive environments.

## 4. Strategic Marketing for the Self-Centering Lamellar-Electrode Guiding Device in ECM

### 4.1 Identification of Market Opportunities

**Table 1**

| Need Code | Customer Need (specification)                                                     | Underlying Reason                                         | Product/Feature That Addresses Need | Target Customers                               |
|-----------|-----------------------------------------------------------------------------------|-----------------------------------------------------------|-------------------------------------|------------------------------------------------|
| N1        | Increase positioning accuracy of lamellar electrodes ( $\leq \pm 4 \mu\text{m}$ ) | Geometric deviations that distort machined micro-profiles | Self-centering device (P1)          | ECM laboratories, micro-mould manufacturers    |
| N2        | Shorten setup and change-over time ( $\leq 60$ s per electrode)                   | High costs caused by downtime                             | Device with fine manual adjustment  | Small- to medium-batch production, pilot lines |
| N3        | High resistance to electrolyte and wear                                           | Corrosive environment, vibration, 0.3 MPa pressures       | Device made of resistant materials  | ECM machine OEMs, research centres             |

#### Patents

- <https://patents.google.com/patent/EP0259691A2/en>
- <https://www.freepatentsonline.com/8912466.pdf>

At present there is no compact device on the market that combines self-centering, fine adjustment, and electrolyte-resistant materials in a single ergonomic, fast solution.

### 4.2 Current State of the Project Topic

Analysis of existing solutions shows that conventional vises or dedicated fixtures suffer from[1]:

- complex mechanisms that are hard to clean and adjust;
- long alignment or squaring times;
- expensive materials (special alloys) that drive up the final price;
- poor ergonomics in the electrolyte's wet environment.

The concept selected for this dissertation, a self-centering vise with synchronised jaws, overcomes these limitations, delivering a centring error below  $\pm 4 \mu\text{m}$  over a 200 mm stroke and allowing an electrode change in under 60 s.

### 4.3 Selection of Potential Customers

**Table 2 – Segments and Level of Interest**

| Segment  | Students | Professors<br>Research | / R&D<br>Laboratories | SMEs | Large<br>Enterprises | ECM-Machine<br>Manufacturers |
|----------|----------|------------------------|-----------------------|------|----------------------|------------------------------|
| Interest | ☉        | ①                      | ●                     | ●    | ●                    | ●●                           |

#### 4.4 Data Gathered from Potential Customers (Summary)

**Table 3 – Voice of the Customer**

| No. | Client Name    | Field of Activity | Product Requirements                                                | Interpreted Need                                                      |
|-----|----------------|-------------------|---------------------------------------------------------------------|-----------------------------------------------------------------------|
| 1   | SC Mecano SRL  | Automotive        | Precise clamping of the lamellar electrode and rapid re-positioning | A repeatable clamping system that is easy to adjust and Z-axis-stable |
| 2   | TechForm SA    | Aeronautics       | High rigidity and short electrode-change time                       | A stiff fixture combined with a quick-change mechanism                |
| 3   | MicroParts SRL | Medical devices   | Secure grip without deformation                                     | A fine-adjustment clamp with micrometric control                      |

#### 4.5 Competing Equipment

**Table 4 – Existing Solutions and Their Limitations**

| Manufacturer  | Product                             | Current Solution                         | Limitations                               |
|---------------|-------------------------------------|------------------------------------------|-------------------------------------------|
| JTR Machine   | Universal stainless-steel vises     | One-sided tightening; setup time > 5 min | Low accuracy; no self-centering           |
| HWACHEON      | Fixtures with prismatic jaws        | Poor ergonomics; not rated for 3–5 kA    | Deformation and rapid wear                |
| ESD Equipment | Dedicated OEM systems (per patents) | Price > €8 000                           | Complex mechanisms; difficult maintenance |

### 5. SPECIFICATION DEFINITION

#### 5.1 Requirements–Quality–Characteristics Matrix

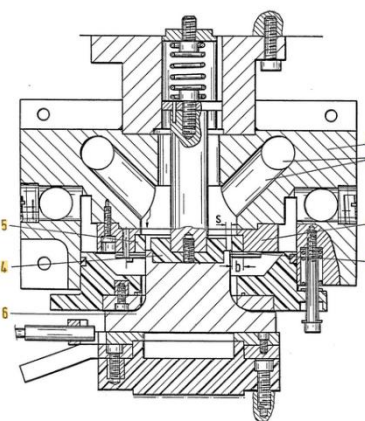


Fig. 1 HWACHEON

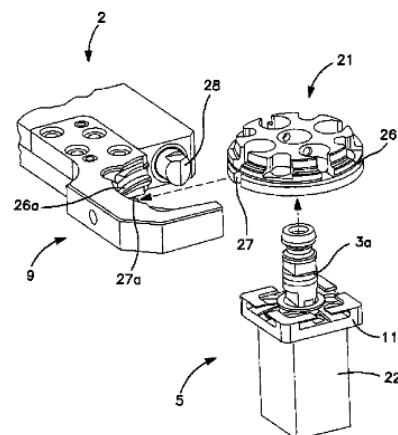


Fig. 2 ESD Equipment

### 5.1 Key Value Dimensions and Mandatory Parameters

Thus, centring deviation, change-over time, and clamping force are the customer's three key value dimensions. The mandatory parameters are derived from the market study and existing ECM standards[1].

#### 5.2 Performance of Competing Products

Analysis of current devices [1] (simple vise, articulated clamp, and patented variants) shows:

- long adjustment times (2–4 min);
- centring tolerance greater than  $\pm 15 \mu\text{m}$ ;
- low resistance to aggressive environments and corrosion;
- limited ergonomics (require wrenches or screwdrivers).

In contrast, the proposed self-centring device delivers a centring error of  $\pm 4 \mu\text{m}$  over a 200 mm stroke and changes an electrode in under 60 s, clearly surpassing the alternatives.

#### 5.3 Target and Limit Values – Design Specifications

Table 5

| No. | Characteristic                    | Rel. Imp. | Units            | Limit Value   | Target (Ideal) |
|-----|-----------------------------------|-----------|------------------|---------------|----------------|
| 1   | Centering deviation               | 5         | $\mu\text{m}$    | $\leq 6$      | $\leq 4$       |
| 2   | Electrode change-over time        | 5         | s                | $\leq 90$     | $\leq 60$      |
| 3   | Clamping force                    | 4         | kN               | 1.5 – 2.5     | 2.0            |
| 4   | Electrolyte-pressure resistance   | 4         | MPa              | $\geq 0.3$    | 0.3            |
| 5   | MTBF (mean time between failures) | 4         | h                | $\geq 5\,000$ | $\geq 8\,000$  |
| 6   | Electrical contact resistance     | 3         | $\text{m}\Omega$ | $\leq 0.2$    | $\leq 0.15$    |
| 7   | Device mass                       | 3         | kg               | $\leq 12$     | $\leq 10$      |
| 8   | Manufacturing cost                | 3         | lei              | $\leq 5\,000$ | $\leq 4\,000$  |

#### 5.4 Customer Matrix(determining characteristics, perceived value, relative weights)

Target segment: ECM micro-machining workshops and maintenance departments that seek high precision at a low cost.

Weights established through questionnaires:

- Centering accuracy – 35 %
- Change-over time – 25 %
- Reliability / MTBF – 15 %
- Corrosion resistance – 15 %
- Cost – 10 %

Starting from the overall function of holding the lamellar electrode in a precise and stable position during electrochemical machining, a prerequisite for the dimensional accuracy of the work-pieces, the primary user requirements (PUR) were identified and matched with the measurable product characteristics.

**Table 6. Customer-Requirements ↔ Technical-Characteristics Matrix**

| Need                          | Guidance accuracy [μm] | Self-locking worm-gear system | Corrosion-resistant materials (plated steel) | Self-centering jaws (symmetric) | Rigid cast-iron / steel structure | Hand-wheel lever (anti-slip) | Quick-change mechanism | Heat-treated & ground components | Dielectric seals & passivated zones | Design simplicity |
|-------------------------------|------------------------|-------------------------------|----------------------------------------------|---------------------------------|-----------------------------------|------------------------------|------------------------|----------------------------------|-------------------------------------|-------------------|
| Precision                     | •                      |                               |                                              |                                 |                                   |                              |                        |                                  |                                     |                   |
| Manual adjustment             |                        | •                             |                                              |                                 |                                   |                              |                        |                                  |                                     |                   |
| Environmental resistance      |                        |                               | •                                            |                                 |                                   |                              |                        |                                  |                                     |                   |
| Clamping                      |                        | •                             |                                              | •                               |                                   |                              |                        |                                  |                                     |                   |
| Easy access                   |                        |                               |                                              |                                 |                                   | •                            |                        |                                  |                                     |                   |
| Increased productivity        |                        |                               |                                              |                                 | •                                 |                              | •                      |                                  |                                     |                   |
| Reliability                   |                        |                               |                                              |                                 |                                   |                              |                        | •                                |                                     |                   |
| Reasonable manufacturing cost |                        |                               |                                              |                                 |                                   |                              |                        |                                  |                                     | •                 |

• = strong relationship between customer need and technical characteristic

## 6. Conceptual design

### 6.1 Overall Function and Sub-functions

The proposed device provides precise guidance of lamellar electrodes in ECM, thereby reducing dimensional errors and improving product quality. The main sub-functions are:

- Alignment and stabilisation under the mechanical and electrolyte forces of the process.
- Rapid manual adjustment adaptable to various set-ups.
- Vibration suppression through the use of resistant materials and a rigid structure.

## 6.2 External Research

A review of existing solutions (literature, patents, commercial products, and interviews) revealed the information presented in Table 7.

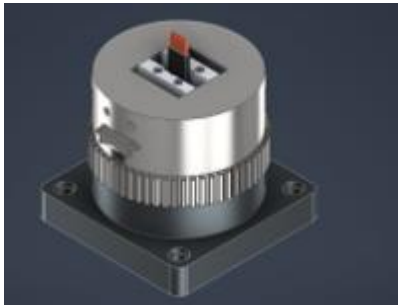
**Table 7**

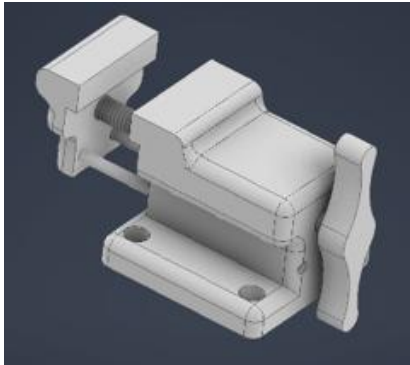
| Observation                                                   | Source / Example                                                                                                                                                                                                                              |
|---------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Current fixtures are complex and difficult to adjust          | <a href="https://data.epo.org/publication-server/rest/v1.2/publication-dates/20160928/patents/EP3072622NWA1/document.pdf">https://data.epo.org/publication-server/rest/v1.2/publication-dates/20160928/patents/EP3072622NWA1/document.pdf</a> |
| Materials are corrosion-protected alloys and stainless steels | <a href="https://patents.google.com/patent/EP0259691A2/en">https://patents.google.com/patent/EP0259691A2/en</a>                                                                                                                               |
| Manual adjustment mechanisms have poor ergonomics             | Field interviews & product data                                                                                                                                                                                                               |

## 6.3 Internal Research

*Individual concept ideas:*

**Table 8**

| Name                | Advantage                    | Picture                                                                              |
|---------------------|------------------------------|--------------------------------------------------------------------------------------|
| Self-centering vise | Precision and self-centering |  |

|                  |                        |                                                                                     |
|------------------|------------------------|-------------------------------------------------------------------------------------|
| Simple vise      | Robust, cheap          |   |
| Articulated claw | ergonomic,<br>flexible |  |

### Group Concepts

Two hybrid models were generated; the “self-centering vise” was chosen for further development:

- Centering deviation:  $\pm 4 \mu\text{m}$  over 200 mm
- Change-over time:  $< 60 \text{ s}$

## 7. Detailed design (*assembly drawing, bill of components, results of Chap. 6*)

### 7.1 Sizing, Shapes, Tolerances

A compact unit with smooth electrolyte-flow channels. The guide pads move symmetrically, driven by a worm-and-wheel mechanism. All parts are finely machined to eliminate play and ensure stability under high pressure.

### 7.2 Ergonomics and Access

Adjustment is performed with a non-slip hand-wheel that actuates a self-locking system. The layout offers

- access from every direction;

- easy reading of settings via an engraved scale;
- thrust bearings that reduce turning effort.

### 7.3 Structure and Interactions

1. Base – rigid anchoring, absorbs loads
2. Worm wheel – fine adjustment, forced rotation
3. Upper body – guidance and protection
4. Jaws – accurate centring, large contact surface
5. Links (“fins”) – transform rotation into linear motion

Operation: the operator turns the hand-wheel; the jaws close symmetrically, clamping the electrode quickly and precisely.

### 7.4 Materials and Electrical Path

- Components: ABS/PLA plastic
- Electrical path: voltage drop  $< 0.75$  V at 3–5 kA, fully insulated

Strength calculations

- Clamping force: 2 kN per jaw
- Stresses  $< 70$  % of yield strength
- Deflection  $< 5$   $\mu$ m

The device meets ECM requirements for strength, stability, and conductivity.

## 8. Manufacturing and prototype testing

The product was 3-D printed at 1 : 2 scale and then tested to see how the worm wheel engages with the “fins” that actuate the electrode-clamping element.

The first print revealed several issues:

- The body could not be assembled  $\rightarrow$  a redesign is required.
- The jaw-guide elements break easily  $\rightarrow$  they need to be replaced with steel.



Figure 3



Figure 4

## 9. Homologation, use, commercialisation and recycling of the self-centring guide device for ecm

### 9.1 Definition of Homologation

Homologation comprises the full range of activities, tests, inspections and assessments, by which a homologation committee issues a written statement that the self-centring guide device meets the requirements of the relevant product standards and technical specifications, i.e. the minimum accepted level of quality and operational safety[2].

### 9.2 The Homologation Committee

The committee is formed through an internal procedure and includes representatives of:

- the device manufacturer;
- industrial end-users (ECM operators);
- the research-and-design units involved;
- accredited laboratories for mechanical, electrical and chemical-compatibility testing;
- public authorities/regulators, as applicable.

### 9.3 Homologation Criteria and Test Programme

Because the device is not listed among equipment subject to mandatory homologation, evaluation is carried out on the manufacturer's premises, with the following main benchmarks:

**Table 9**

| Domain                 | Parameter Checked                                         | Reference Requirement                       | Test Method / Equipment                  |
|------------------------|-----------------------------------------------------------|---------------------------------------------|------------------------------------------|
| Functional             | Autocentring error                                        | $\leq \pm 4 \mu\text{m}$ over 200 mm stroke | Laser comparators & gauge block          |
|                        | Electrode change-over time                                | $< 60 \text{ s}$                            | Industrial stopwatch                     |
|                        | Clamping force per jaw                                    | $\geq 2 \text{ kN}$                         | Load cells (strain gauges)               |
| Reliability            | Safety factor of loaded parts                             | $> 2$                                       | Strain-gauge measurements & FEA analysis |
| Chemical compatibility | Resistance to electrolyte (0.3 MPa / 40 °C)               | No visible corrosion after 72 h             | Climatic chamber + microscope            |
| Ergonomics             | Maximum torque on hand-wheel                              | $\leq 5 \text{ N}\cdot\text{m}$             | Torque wrench                            |
| Electro-conductivity   | Electrical resistance (cast-iron $\rightarrow$ jaws path) | $< 0.15 \text{ m}\Omega$                    | Micro-ohmmeter                           |

Once the measurements are processed digitally, homologation is granted only if every result falls within the specified tolerances.

### 9.4 Detailed Test Procedure

1. Dimensional inspection – overall envelope and interface points are checked for compatibility with the ECM-machine table and with standard lamellar-electrode geometries.

2. Centring test – the jaws clamp a reference cylinder; deviation is measured with a digital comparator at 0°, 90°, 180°, 270°.
3. Clamping test under electrolyte pressure – the device operates for 30 min at 0.3 MPa electrolyte flow while maximum jaw displacement is monitored.
4. Rapid-cycle endurance – at least 1 000 open/close cycles to verify worm-wheel durability.
5. Guide-surface roughness check – after testing, Ra must not rise above 0.2 μm.
6. Ergonomic audit – three operators, with and without gloves, assess access to the hand-wheel and readability of the circular scale.

The committee draws up a homologation report and forwards it to the faculty / end-user management; the annex lists the committee members and their signatures.

### 9.5 Operating and Maintenance Instructions

- Mount the device on the flat ECM table using grade-10.8 M12 bolts.
- Clamp the electrode by turning the hand-wheel; the self-locking mechanism eliminates the need for spanners.
- After each shift, rinse with de-ionised water and apply a thin inhibitor film to the steel parts.
- Service interval: every 6 months or 10 000 cycles; inspect worm gear for wear.

### 9.6 Commercialisation

Target sectors where ECM offers clear benefits, aerospace, medical implants, precision dies. Key selling points:

- 40–60 % reduction in setup time versus classical fixtures;
- repeatable  $\pm 4 \mu\text{m}$  accuracy with no re-adjustment;
- service life > 5 years in three-shift operation.

#### 8.7 Recycling and End-of-Life

- Designed for quick disassembly.
- Components can be produced from PLA, a biodegradable plastic recyclable at any plastics centre.
- The product label clearly states material codes and disassembly instructions.
- The manufacturer offers a buy-back option at disposal.

## 10. Conclusion

The work proposes and validates an innovative self-centring device for guiding lamellar electrodes in electrochemical machining (ECM), addressing real industrial needs for precision, fast setup, and resistance to aggressive environments. Through an integrated approach that combined engineering, marketing, and project management, a functional prototype was conceived, tested, and analysed. It delivers performance that surpasses existing solutions and shows strong potential for commercial and industrial adoption.

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# AUTONOMOUS SYSTEM FEATURING OBJECT DETECTION, CLASSIFICATION AND VOICE CONTROL WITH FEEDBACK

TAMAȘ Eugen Adrian<sup>1</sup>, NĂFLIU-JOÎȚA Ion-Edi<sup>2</sup>,  
ABAZA Bogdan Felician, DOICIN Cristian Vasile(Conducători științifici)

<sup>1,2</sup> Faculty of Industrial Engineering and Robotics, Applied Informatics in Industrial Engineering,  
Year of study: I, e-mail: [tamas.eugen.adrian@gmail.com](mailto:tamas.eugen.adrian@gmail.com)

**ABSTRACT:** The paper introduces an integrated, modular system comprising multiple subsystems designed to support autonomous operation in resource-constrained environments. It encompasses computer vision for object detection and classification, a real-time 2D LIDAR simulation for navigational testing, and an offline voice interaction interface for natural human-machine communication. Object recognition is powered by a convolutional neural network trained on a custom dataset. The LIDAR simulation component enables virtual obstacle detection and autonomous path planning. Voice interaction is achieved through a lightweight speech pipeline, including keyword spotting, transcription (Whisper-small), and intent recognition (DistilGPT2), all processed locally without reliance on cloud services. This architecture ensures low latency, energy efficiency, and full autonomy in embedded applications.

**KEYWORDS:** Object Detection, Convolutional Neural Networks, LIDAR Simulation, Voice Command Recognition, Embedded Systems, Human-Robot Interaction

## 1. Introduction

The study presents the development of a high-performance visual subsystem, designed for real-time object detection, localization, and classification in real-world environments, such as the system shown in Figure 1, tailored for autonomous mobile platforms. The core model is based on the YOLOv8 architecture, selected for its efficiency and accuracy in transforming object detection into a regression task.

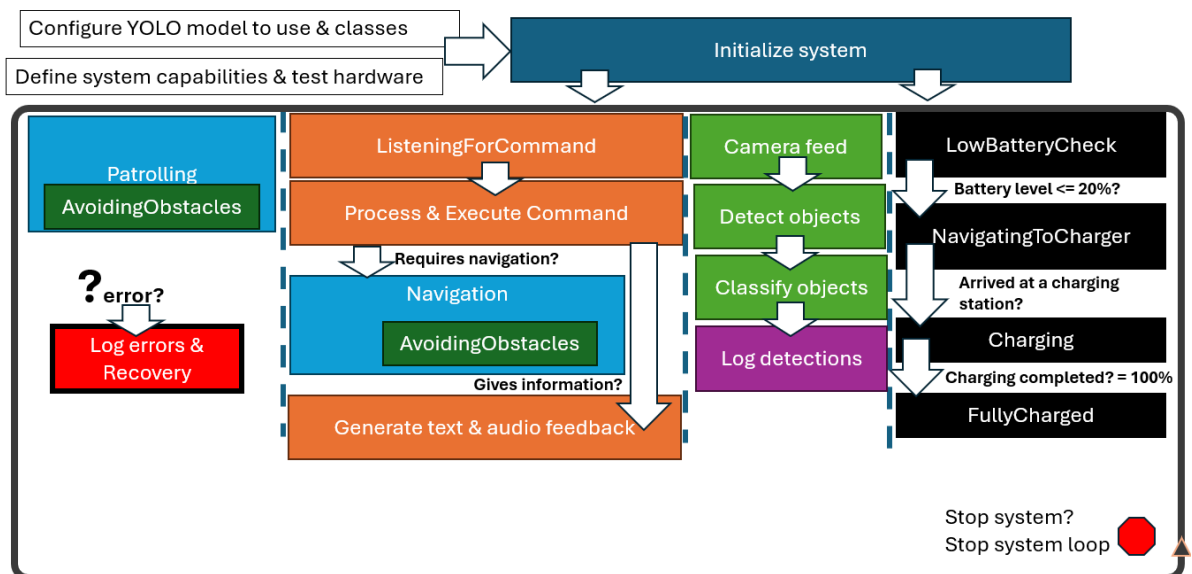


Fig. 1. System function diagram

A complementary vocal interface ensures seamless human–robot interaction, enabling natural, bidirectional communication through voice commands. It features proactive confirmation mechanisms and multimodal feedback (audio + text), improving operational safety and clarity in command execution. The TTS engine is based on pyttsx3, ensuring offline functionality and low-latency response.

These subsystems form a cohesive and scalable framework for autonomous platforms, emphasizing reliability, low latency, and full offline operability in both perceptual and interaction tasks.

This system is designed for deployment on autonomous mobile platforms with real-world applications in both educational and industrial settings. One primary use case is guiding students across a university campus—providing directions, answering common queries through vocal and visual interfaces, and enhancing accessibility for visitors. The same platform can be repurposed in industrial environments to assist personnel by detecting and classifying objects, reporting relevant information, and eventually generating automated reports. Future expansions may integrate environmental sensing (temperature, humidity, sound levels) for situational awareness and research applications in human–robot interaction.

## **2. Current State of the System**

The visual subsystem is designed for real-time object detection, localization, and classification on autonomous mobile platforms (Figure 1). It is built on the YOLOv8 architecture [4, 7], selected for its accuracy and efficiency in regression-based detection tasks. Training was conducted on NVIDIA RTX 4050 and Quadro P500 GPUs to evaluate efficiency and portability across different hardware profiles [8]. The dataset was adapted from COCO [16] and enhanced with manually annotated real-world images using Label Studio (Figure 2) [3]. Data augmentation techniques (such as flipping, blurring, and brightness adjustments) were applied to improve generalization [2]. Data augmentation keeps the same coordinates for most transformations of the input images, except for flipping, which also flips the coordinates. The recommended pixel coordinates of bounding boxes for training YOLO models is percentage of image width, thus making computations for flipping the bounding boxes of labeled regions easier (see formula 1).



Fig. 2. Data augmentation example

$$x' = 1 - x, y' = y, \text{ for horizontal flipping} \quad (1)$$

$$x' = x, y' = 1 - y, \text{ for vertical flipping}$$

$$x' = 1 - x, y' = 1 - y, \text{ for both horizontal and vertical flipping}$$

Where  $x'$  is the new X coordinate,  $x$  is the original image X coordinate

$y'$  is the new Y coordinate,  $y$  is the original image Y coordinate

$w'$  is the new image

The visual processing pipeline comprises four main stages: image acquisition, preprocessing, AI-based inference, and result transmission to centralized storage (Figure 6). Images are captured in real time using RGB cameras via OpenCV [5], resized to  $640 \times 480$ , and normalized before being passed into the inference model. Two models were tested: YOLOv8-nano and a custom-trained variant [4, 8]. Detection results (class labels, confidence scores, and bounding boxes) are serialized to JSON and transmitted via HTTP to a local server using Python APIs. The custom model achieved high performance: mAP@0.5 of 0.995, precision of 1.00 at 0.988 confidence, F1-score of 0.99, and perfect recall [1].

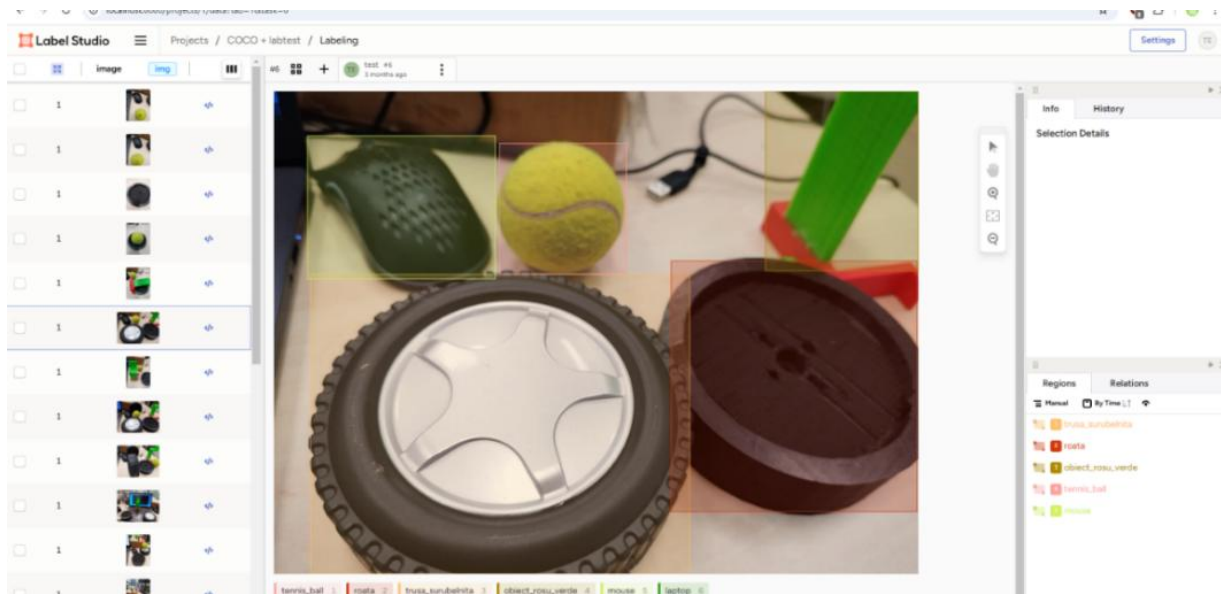


Figure 3: Labelling objects in an image using Label Studio

To support spatial awareness and navigation, a custom 2D LIDAR simulation was developed in C# (Figure 5)[9]. It emulates obstacle detection, environment mapping, and trajectory planning through raycasting [11] and A\* pathfinding [12]. The simulation runs at 60 FPS on a 640×480 grid, updating a dynamic map with real-time visualization using color-coded bitmaps rendered via the System.Drawing namespace [10]. This provides a low-cost, rapid testing environment for evaluating autonomous navigation strategies before deployment on physical platforms.

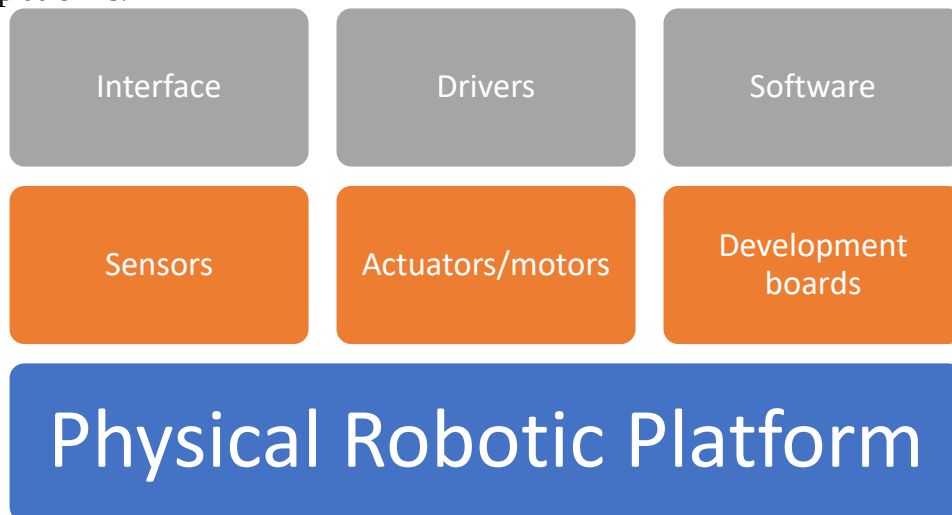


Fig. 4. Simplified system structure

A complementary vocal interface enables natural, offline human–robot interaction through voice commands. Text-to-speech output is handled using pyttsx3 [13], allowing for low-latency feedback without cloud services (Figure 4).

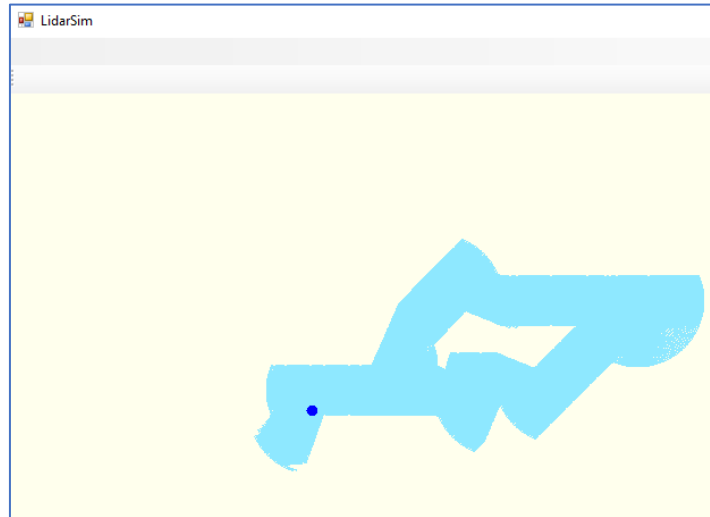


Fig. 5. Custom LIDAR simulation tool

Voice command processing is implemented via an entirely offline pipeline (Figure 5). It begins with keyword spotting and speech recognition using Whisper-small [15], followed by intent classification using a fine-tuned DistilGPT-2 model. Recognized intents fall into three categories: NAV (navigation commands), INFO (information queries), or FAIL (unrecognized input). These intents are serialized and sent to a central controller for processing. This pipeline is optimized for resource-constrained hardware like the Raspberry Pi [14].

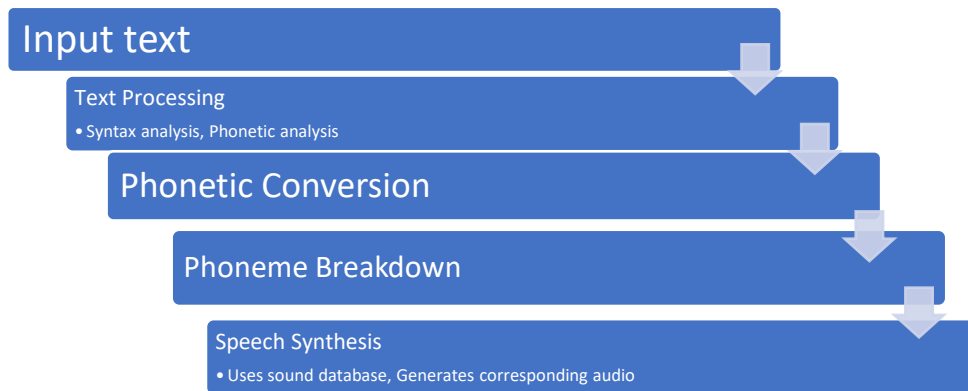


Fig. 6. Text to Speech subsystem diagram

The visual, spatial, and vocal subsystems form a cohesive, fully offline framework optimized for autonomous platforms. The system prioritizes modularity, low latency, and real-time responsiveness across perception and interaction task.



Fig. 7. Speech to text subsystem diagram

These subsystems form a cohesive and scalable framework for autonomous platforms, emphasizing reliability, low latency, and full offline operability in both perceptual and interaction tasks.



Fig. 8. Vision system architecture

The visual subsystem of the autonomous mobile platform follows a modular design with a real-time processing pipeline consisting of four main stages: image acquisition, preprocessing, AI-based inference, and result transmission to a centralized storage system. This pipeline is optimized to run on low-resource devices (e.g., Raspberry Pi), while remaining scalable and integrable with other control or decision subsystems.

To meet the demands of the use scenarios shown in (Figure 7), the system integrates a high-performance visual pipeline based on YOLOv8 for object detection and recognition, ensuring accurate classification in varied lighting and spatial contexts. The offline speech interaction subsystem allows intuitive user engagement even in environments with no internet connectivity, a key requirement for both campus-wide deployment and industrial resilience. Navigation is handled via a custom LIDAR simulator with real-time raycasting and path planning, enabling obstacle avoidance and autonomous movement. Together, these modules support dynamic tasks like answering student questions, guiding users to buildings, detecting unauthorized objects in restricted zones, and logging visual data for analysis. The modular design ensures scalability across platforms and use cases, allowing for integration of future sensors and intelligent behaviors.

### 3. Implementation

The subsystem performs real-time visual detection and transmits the results to a local server. Video frames are analyzed using a custom-trained object detection model based on YOLOv8n, adapted to the system's requirements. For each frame, detected objects are identified along with their class and confidence score. The results are formatted as JSON and sent to the server. Error handling ensures reliable data transmission, and system resources are properly released after execution.

Code sequence required to validate and store information centrally for use by other subsystems:



Fig. 9. Data endpoint architecture

The subsystem responsible for storage and preview of visual detections handles incoming data from an AI-based detection system. It follows a modular structure where captured images and associated metadata (in JSON format) are sent via HTTP POST requests. Upon receiving the data, the system automatically verifies and creates the necessary directories for storing images and database files, ensuring long-term data persistence.

The detections are stored in a daily-organized SQLite database, where each entry records the capture timestamp, image path, and associated detections. Data is securely inserted using parameterized queries to prevent SQL injection and ensure robust error handling. This design enables a clear separation between raw data acquisition and structured management within a distributed cyber-physical system.

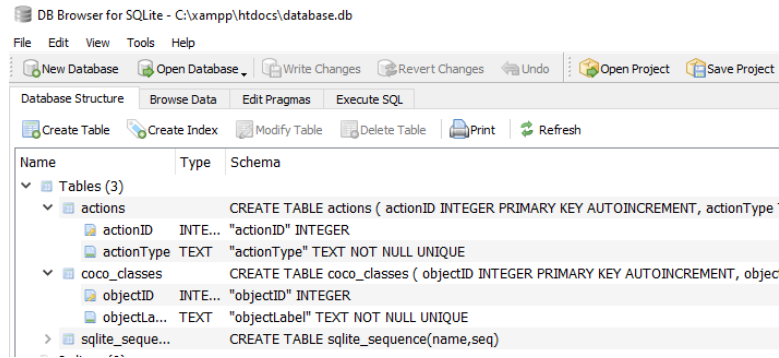


Fig. 10. SQL schema for the backend database

The database file is generated dynamically based on the current date (Y-m-d), resulting in daily segmentation of data. SQLite connections are handled using a secure and robust interface, with error handling enabled for controlled exception management. If the images table does not exist, it is automatically created with fields for timestamp, image path, and serialized JSON detections. When the server receives a POST request, it checks for both an image file and a detections field. If either is missing or invalid, execution is halted. Detection data is sanitized to prevent XSS and special character injection, while the image is renamed using a UNIX timestamp to avoid filename collisions and safely moved to permanent storage.

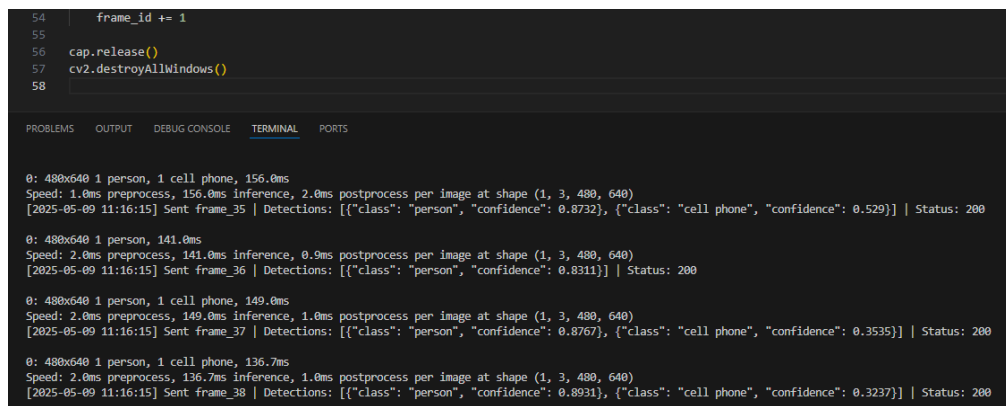


Fig. 11. Data logging, identifies in video feed 0, sends JSON, receives response 200 – OK

Finally, the metadata—comprising the timestamp, relative image path, and JSON string of detections—is inserted into the database using a prepared statement, preventing SQL injection and ensuring data integrity. This design enables robust integration between the visual inference system and downstream storage or analysis subsystems, providing a standardized interface for interprocess communication between AI modules and the backend. For the 2D LIDAR simulation tool built with WinForms and System.Drawing, the study demonstrates a simple tool to simulate environmental sensing and autonomous navigation. The system employs raycasting within a 45° cone to detect obstacles and map discovered areas on a discretized 2D grid. Navigation is guided by an A\* algorithm that dynamically computes optimal paths to unexplored targets while avoiding obstacles.

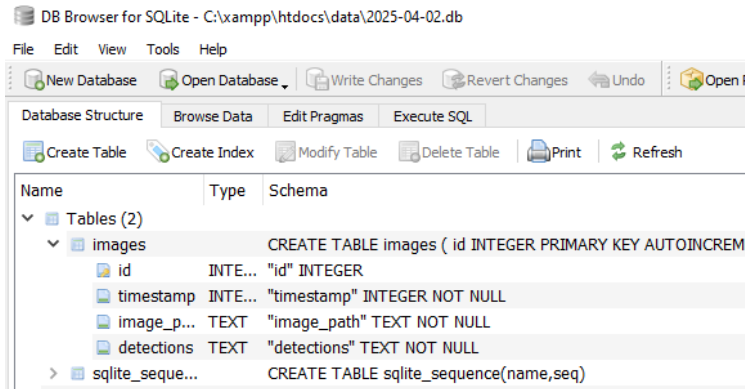


Fig. 12. SQL schema for the generated databases

Running at 60 FPS through a timer mechanism, the simulation ensures smooth updates, supported by caching strategies to optimize rendering and minimize latency. Manual keyboard controls enable interactive testing. This work highlights how basic graphical frameworks can effectively support real-time LIDAR simulations without relying on complex external dependencies.

The screenshot shows a log file named 'benchmark\_log.txt' with the following content:

```

1 2025-05-09 12:28:04,503 [INFO] === BENCHMARK MODE ===
2 2025-05-09 12:28:06,943 [INFO] [2025-05-09 12:28:05] Sent frame_0 | Detections: [{"class": "person", "confidence": 0.8663}] | Status: 200
3 2025-05-09 12:28:06,998 [INFO] Resolution | # Detections | Inf. Time (ms) | Classes
4 2025-05-09 12:28:06,998 [INFO] -----
5 2025-05-09 12:28:06,998 [INFO] 640x480 | 1 | 1502.33 | person
6 2025-05-09 12:28:07,002 [INFO] 320x240 | 1 | 125.79 | person
7 2025-05-09 12:28:07,002 [INFO] 160x120 | 1 | 121.9 | person
8 2025-05-09 12:28:07,002 [INFO] 80x60 | 2 | 126.83 | person
9 2025-05-09 12:28:07,002 [INFO] -----
10 2025-05-09 12:28:07,515 [INFO] [2025-05-09 12:28:07] Sent frame_1 | Detections: [{"class": "person", "confidence": 0.8244}] | Status: 200
11 2025-05-09 12:28:07,520 [INFO] Resolution | # Detections | Inf. Time (ms) | Classes
12 2025-05-09 12:28:07,520 [INFO] -----
13 2025-05-09 12:28:07,521 [INFO] 640x480 | 1 | 130.06 | person
14 2025-05-09 12:28:07,521 [INFO] 320x240 | 1 | 123.52 | person
15 2025-05-09 12:28:07,521 [INFO] 160x120 | 1 | 128.28 | person
16 2025-05-09 12:28:07,522 [INFO] 80x60 | 2 | 121.45 | person
17 2025-05-09 12:28:07,522 [INFO] -----
18 2025-05-09 12:28:08,023 [INFO] [2025-05-09 12:28:07] Sent frame_2 | Detections: [{"class": "person", "confidence": 0.7911}] | Status: 200
19 2025-05-09 12:28:08,029 [INFO] Resolution | # Detections | Inf. Time (ms) | Classes
20 2025-05-09 12:28:08,029 [INFO] -----
21 2025-05-09 12:28:08,029 [INFO] 640x480 | 1 | 124.57 | person
22 2025-05-09 12:28:08,030 [INFO] 320x240 | 3 | 122.34 | surfboard, person
23 2025-05-09 12:28:08,030 [INFO] 160x120 | 1 | 119.83 | person
24 2025-05-09 12:28:08,030 [INFO] 80x60 | 1 | 125.4 | person
25 2025-05-09 12:28:08,030 [INFO] -----
26 2025-05-09 12:28:08,528 [INFO] [2025-05-09 12:28:08] Sent frame_3 | Detections: [{"class": "person", "confidence": 0.8066}] | Status: 200
27 2025-05-09 12:28:08,533 [INFO] Resolution | # Detections | Inf. Time (ms) | Classes
28 2025-05-09 12:28:08,533 [INFO] -----
29 2025-05-09 12:28:08,533 [INFO] 640x480 | 1 | 121.69 | person
30 2025-05-09 12:28:08,534 [INFO] 320x240 | 2 | 121.31 | surfboard, person
31 2025-05-09 12:28:08,534 [INFO] 160x120 | 1 | 120.75 | person

```

Figure 13. Benchmark results for multi-resolution tests

Reducing image resolution in neural network-based detection (e.g., YOLOv8) aims to lower latency and energy consumption. However, tests show that inference time differences between 640×480 and 80×60 resolutions are minimal (~130–150 ms), indicating that the bottleneck lies in the model architecture and CPU rather than image size. Consequently, very low resolutions degrade accuracy without offering clear performance gains. Nonetheless, small cameras can be valuable in applications with privacy, size, or cost constraints—such as home healthcare, discreet surveillance, or wearable devices—where simple presence or motion detection is sufficient.

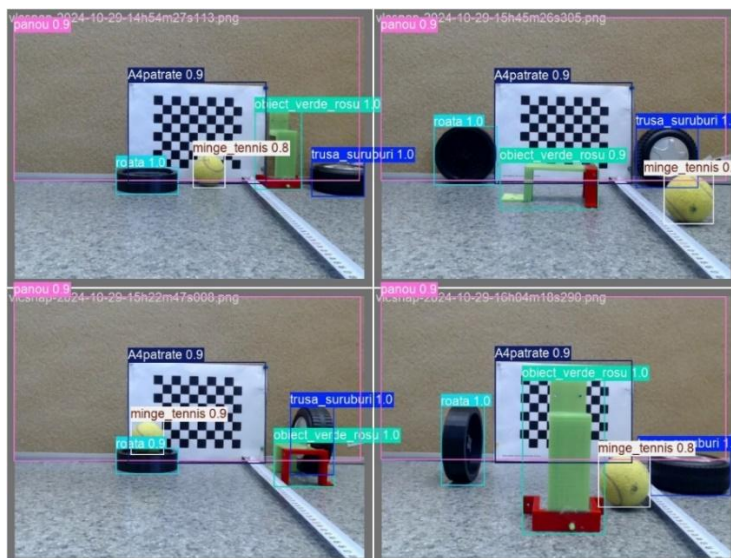


Figure 14. YOLO training results with new classes (A4patrate, roata, minge\_tennis, trusa\_suruburi)

#### 4. Conclusions

The paper presents an efficient real-time object detection and classification subsystem, optimized for resource-constrained autonomous platforms. The YOLOv8-nano architecture strikes a balance between accuracy and speed, making it suitable for low-power devices such as the Raspberry Pi. Manual labeling and augmentation of a custom dataset significantly improved accuracy, while ONNX export enabled optimizations for embedded deployment.

Future research directions include developing self-supervised techniques for data labeling and integrating the subsystem into a complete platform for autonomous navigation and contextual interactions.

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## INJECTION MOULDS POLYMERIC PRODUCTS WITH ELEMENTS STRUCTURAL PARTS MANUFACTURED BY ADDITIVE TECHNOLOGIES

**TUDORACHE Victor-Bogdan<sup>1</sup>, NECHITA Marilena-Iuliana<sup>1</sup>, STOICA Eduard<sup>1</sup> OPRAN Constantin  
Gheorghe<sup>2</sup>, PETA Luigi-Madalin<sup>3</sup>,  
BUZATU Iulian-Marian<sup>3</sup> (Conducători științifici)**

<sup>1</sup>Faculty of Industrial Engineering and Robotics, Specialization: Product design and manufacturing engineering,  
Year of studies: 1, email: [victor.tudorache2001@gmail.com](mailto:victor.tudorache2001@gmail.com)

<sup>2</sup>Faculty of Industrial Engineering and Robotics, Manufacturing Engineering Department,

<sup>3</sup>Doctoral School of Industrial Engineering and Robotics, POLITEHNICA Bucharest

**ABSTRACT:** *This research paper explores the use of additive technologies for the manufacturing of injection molds designed for polymer products. Existing solutions are analyzed, and innovative methods for integrating additively manufactured structural elements are proposed, aiming at optimizing design, reducing costs, and improving performance. A key aspect of the study is the design of a mold with a "conformal cooling channel," which enables optimized thermal flow distribution and significantly reduces cycle time. The objective is to validate efficient and sustainable solutions applicable to industrial production.*

**KEYWORDS:** *injection molds, additive technologies, polymers, advanced manufacturing, sustainability, conformal cooling.*

### 1. Introduction

The tooling and fixture industry plays a key role in supporting the mass production of components using die-based processes such as sheet metal stamping and polymer injection molding. In polymer injection molding, the cooling step dominates the manufacturing cycle, accounting for 70–80% of the total time [1-4]. Even a modest reduction in cooling time can lead to significant improvements in production efficiency, which is particularly important in high-volume manufacturing [5-8].

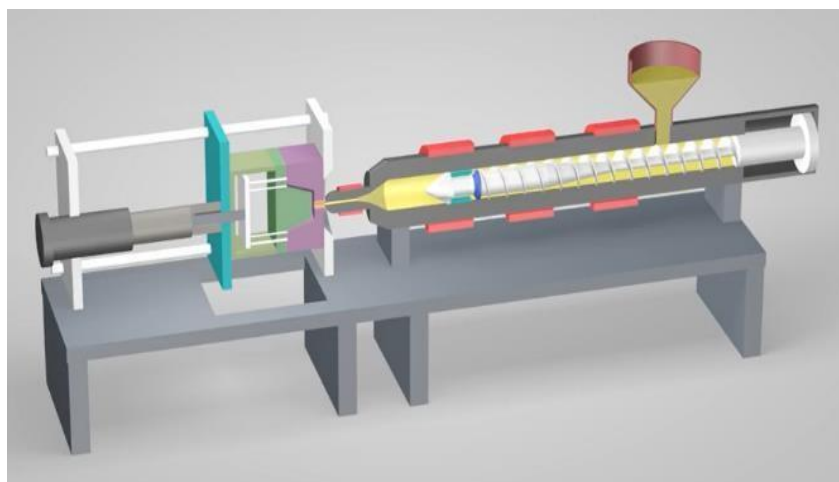


Fig. 1. The process of injecting polymeric materials into the mold [9]

The dies used in these processes are typically fabricated from blocks of material using traditional machining techniques such as milling, drilling and grinding. The cooling channels are conventionally made by straight drilling, which limits the ability to create complex internal geometries without affecting the mold structure. The limitations of traditional machining are the difficulty of making complex channels and the high cost of the drilling tools required.

Conformal cooling is an advanced solution in which the cooling channels follow the contour of the mold cavity, maintaining a constant distance from the surface. This type of design reduces the heat transfer distance, increases the uniformity of temperature distribution in the mold, and shortens the cooling time. Benefits include reduced part distortion and improved final product quality.



Fig. 2. Mold with internal conformal cooling channels [10]

The design of conformal cooling channels has become possible thanks to additive technologies such as “selective laser sintering” (SLS). These technologies allow the creation of complex geometries, such as curved or serpentine channels, impossible to obtain using traditional methods. The use of conformal channels can reduce cooling time by up to 40% compared to classic solutions.

The paper aims to develop and validate a methodology for designing molds with conformal cooling using SLS technology, evaluating thermal performance and demonstrating the advantages under real production conditions, with the aim of increasing manufacturing efficiency and sustainability.

## 2. State of the art

Molds are traditionally manufactured by milling, grinding and drilling, using equipment that allows the creation of precise and complex shapes. CNC milling machines, especially 5-axis ones, can quickly process complicated surfaces without the need to reposition the part. The cooling channels are made by deep drilling, but their shape is limited by the accessibility of the tools, which makes it difficult to achieve effective cooling. Milling machines, lathes, CNCs and drilling machines are used in the manufacture of molds, and the chosen materials, such as H13 and P20 steels, offer high strength and good thermal conductivity.

SLS (Selective Laser Sintering) technology brings a modern solution: it uses a laser to melt powder layer by layer, creating complex shapes directly from the material, which allows the creation of molds with cooling geometries impossible with traditional methods.



Fig. 3. Selective Laser Sintering (SLS) technology [11]

Normal cooling, based on straight channels, has a lower efficiency due to geometric limitations, which affects the quality of the products. In contrast, conformal cooling, achieved through additive technologies such as SLS, allows the creation of channels that follow the contour of the part, ensuring uniform cooling, reducing cooling time by 40-50% and increasing the durability of the molds. Although it involves a higher initial cost, conformal cooling offers important long-term benefits in terms of efficiency and quality.

Integrating SLS technology into mold manufacturing optimizes the cooling process, improves part quality and reduces internal stress. It also shortens the total manufacturing time and allows the use of high-performance materials, which leads to stronger and more efficient molds.).

### **3. Personal development**

#### **3.1. Project management-planning for mold making development**

The creation of an injection mold is a complex process, involving rigorous planning and efficient coordination of activities, resources and actors involved. In the context of using additive technologies to obtain molds with conformal cooling channels, the importance of well-structured project management becomes essential for respecting technical requirements, delivery deadlines and the established budget.

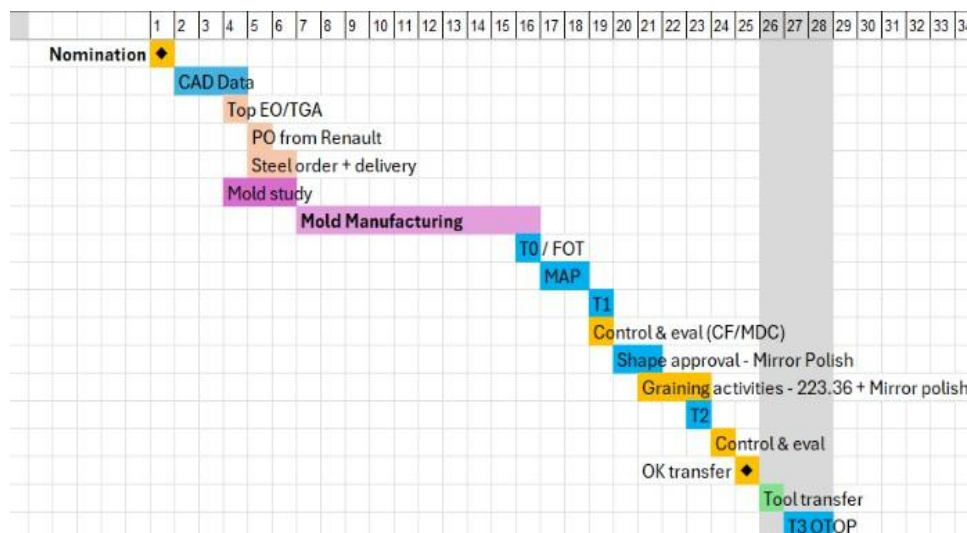


Fig. 3.1. Mold execution planning

The process begins with the nomination of the project, at which point the client selects the responsible moldmaker, based on his technical capabilities and experience. There are

The initial requirements, the desired part and any constraints are presented. The customer then submits the first version of the CAD file, representing the preliminary 3D model of the part. This serves as the basis for feasibility and moldflow analyses.

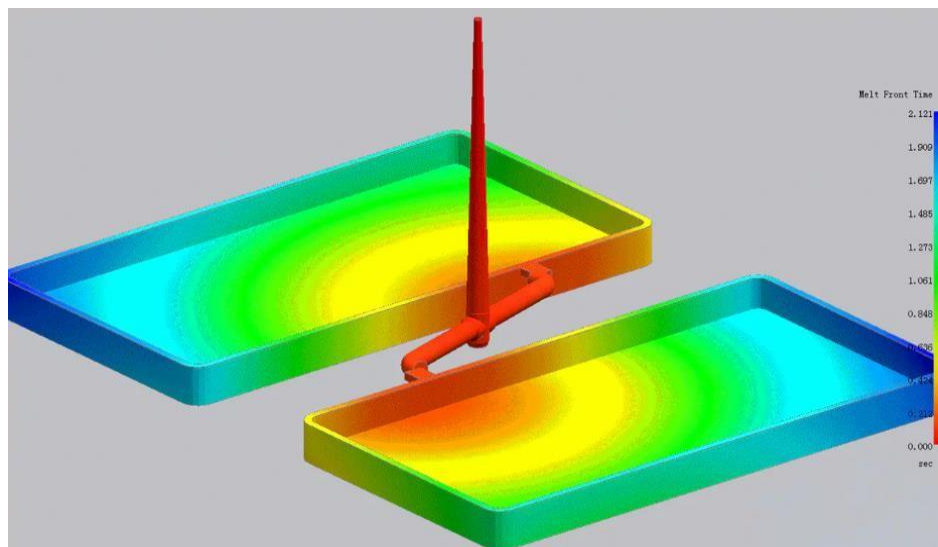


Fig. 3.2. Analysis by Moldflow [12]

After the formal validation of the geometry – “freezing” the CAD design – the mold can be designed. At this point, the customer assumes that any subsequent changes will generate additional costs. Preliminary analyses are then performed: moldflow, technological feasibility and design start. These studies establish the optimal configuration of the cooling channels and the mold geometry.

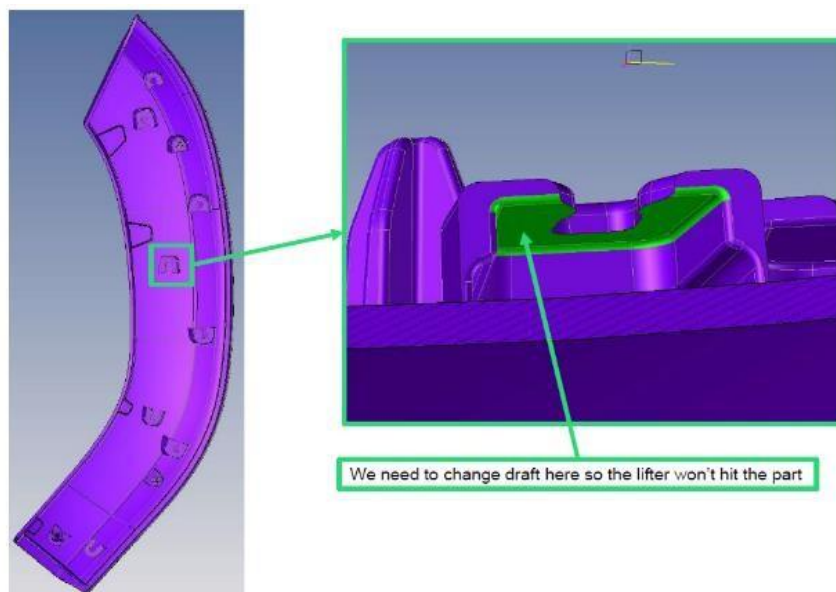


Fig. 3.3. Feasibility analysis

The client issues a firm order (PO – Purchase Order), which provides the contractual and financial framework for the start of activities. Based on the project, the necessary steel blocks are ordered, a purchase that coincides with the actual start of the manufacturing process.

The execution of the mold has an extended duration and includes all the stages of processing, assembly, and finishing, culminating in the final assembly. The first test (T0/FOT – First of Tool) is carried out, after which the resulting parts are analyzed by the customer, mainly from the point of view of assemblyability. Depending on the results obtained, retouches and optimizations are made both to the mold and to the process parameters. A new test (T1) is organized to validate the parts from a dimensional point of view. These are measured with control equipment, and reports are sent to the customer for shape and appearance analysis. If the part requires texture, its application is carried out only after obtaining the customer's agreement. The texture is engraved on the cavities under strictly controlled conditions. After testing the textured parts, the mold is transferred to the final production location, where the customer makes the final approvals for entry into production.

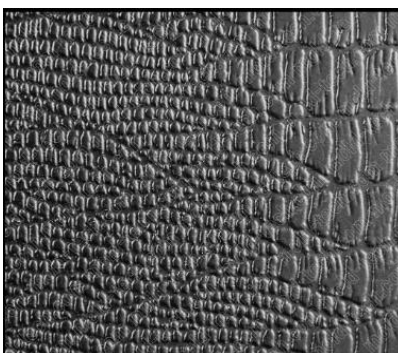


Fig. 3.4. Textured plastic part [13]

Risks encountered in this process include delays in material delivery, design errors, defects in parts from initial tests or delays in customer approvals. To minimize these risks, constant and

transparent communication, the existence of clear protocols for change management and the implementation of intermediate checks, such as design reviews or DFM analyses, are essential.

### 3.2. Product design and production

We have conducted a comparative analysis between straight channel and conformal channel cooling systems for injection molds. The study highlighted the clear advantages of using conformal channels, made by additive technologies such as Selective Laser Sintering (SLS). Unlike conventional cooling, which is limited by the geometry of the perforated straight channel, conformal cooling allows for a more uniform heat transfer due to following the contour of the part, which significantly reduces local heat accumulation.

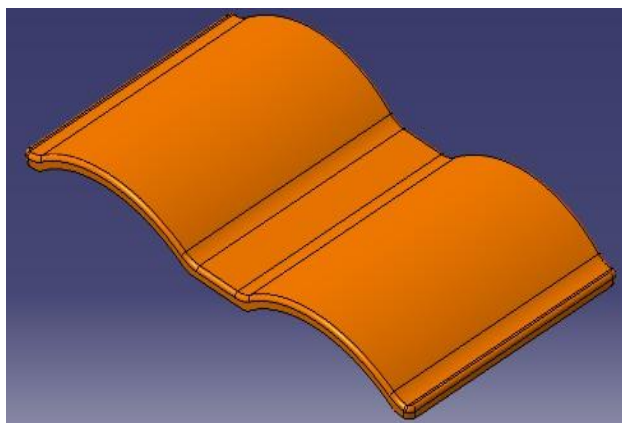


Fig.4. The product for which the study was conducted.

To perform this comparative analysis, a fictitious mold prototype was designed and modeled, with simplified geometry, to highlight the differences in thermal behavior between conventional and conformal cooling channels. In this model, two distinct channel configurations were integrated, respecting the same dimensional conditions, to ensure a fair comparison of the cooling system efficiency.

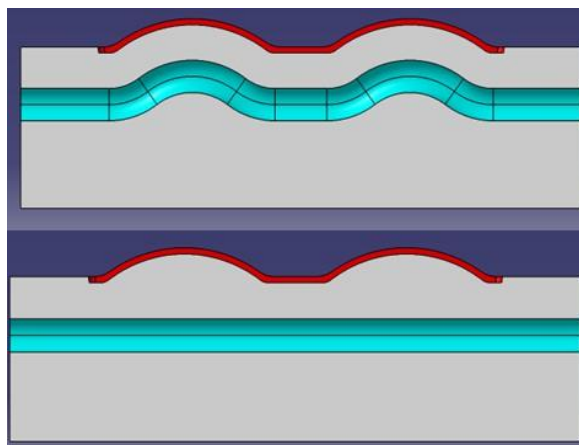


Fig.5. Conformal cooling vs. conventional cooling

The results of thermal simulations, shown in the figure below, highlight the differences in temperature distribution between molds with conventional cooling channels and those with conformal cooling channels. In the case of conventional cooling (left), heat accumulation zones appear, while conformal cooling (right) ensures more efficient cooling of the ends of the part. This improvement allows for a reduction in cooling time by up to 40–50%, increasing the quality of the injected parts and extending the life of the mold. In addition, thermal uniformity minimizes the occurrence of internal stresses and deformations.

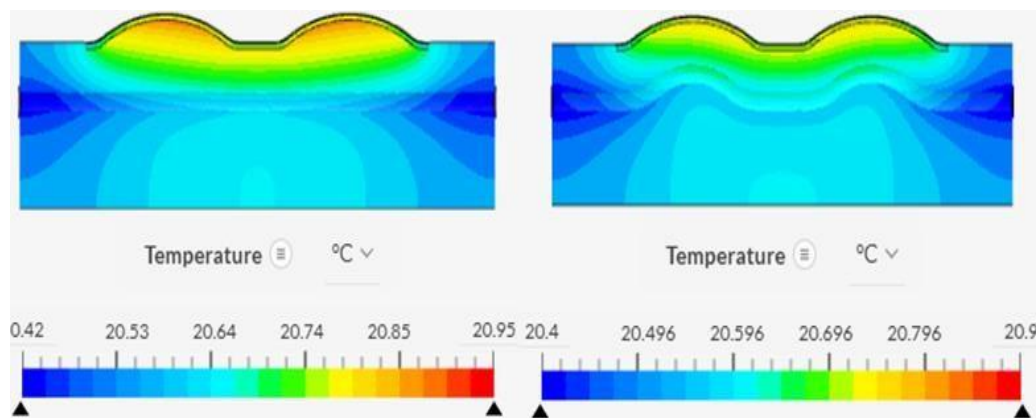


Fig.6. Conformal cooling vs. conventional cooling

### 3.3. Product approval, use, marketing and recycling

In the process of homologating a polymer product made with injection molds manufactured using additive technologies, rigorous testing and validation steps are required. First, the dimensional compliance of the injected parts must be demonstrated, using methods such as 3D measurements and visual inspections in accordance with the standards in force for injected polymer components. It is also necessary to validate the functional performance of the part, including its behavior under mechanical stress (tensile strength, impact, wear) and dimensional stability over time. Homologating molds manufactured using additive technologies also involves verifying the mold's resistance to repeated injection cycles and variable temperatures, an essential aspect for ensuring durability in series production [14].

In the process of homologating a polymer product made with injection molds manufactured using additive technologies, rigorous testing and validation steps are required. First, the dimensional compliance of the injected parts must be demonstrated, using methods such as 3D measurements and visual inspections, according to standards in force for injected polymer components. It is also necessary to validate the functional performance of the part, including its behavior under mechanical stress (tensile strength, impact, wear) and dimensional stability over time. The approval of molds made using additive technologies also involves verifying their resistance to repeated injection cycles and temperature variations, an essential aspect for guaranteeing durability in continuous production.

Testing conformal cooling channels is essential, as it directly influences the quality of the injected parts. CFD simulations and thermal tests confirm the cooling efficiency, allowing the product to be certified according to European regulations. Additive molds are increasingly used in

industries such as automotive, electronics and medical, due to optimized geometry, precise thermal control and reduced production times.

On the one hand, additive molds allow for flexibility, precision and customization.

The free design allows for the integration of conformal cooling channels and internal structures that are impossible to achieve conventionally, which leads to reduced cycle times and increased service life. Repairs are easier and faster.

On the other hand, the products obtained with these molds have dimensional accuracy and superior surface quality. Uniform cooling reduces defects, improving part consistency and reliability. It also allows for rapid customization without high costs, ideal for flexible production and small series.

## **6. Conclusions**

Integration of additive technologies, such as SLS, in the manufacture of injection molds allows the creation of conformal cooling channels, which leads to a significant reduction in cooling time and improving the quality of injected parts.

Compared to traditional solutions, conformal cooling ensures uniform thermal distribution, reduces internal stresses and increases the life of the mold, thus contributing to efficiency and sustainability of the manufacturing process.

The implementation of simulation-assisted design methodologies (e.g. Moldflow, CFD) has allowed optimization of mold geometry and thermal performance, reducing typical defects in injected products.

## **5. Future research directions**

Optimizing the topology of conformal cooling channels through generative algorithms and artificial intelligence methods to maximize thermal and mechanical efficiency.

Study of the behavior over time of additive molds subjected to cycles repeated injection cycles, variable temperatures and mechanical stresses, to validate long-term durability.

Research into the use of beryllium copper inserts in critical areas of the mold, for improving heat dissipation and local temperature reduction, in order to increase the efficiency of the cooling system.

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