

Design and Additive Manufacturing of a Scalable, Low-Cost Educational Robotic Gripper

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Abstract: This paper presents the development and prototyping of an educational robotic gripper designed for a professional mechatronics study program. The research connects key learning outcomes of the mechatronics curriculum with the design, prototyping, testing, and integration of the gripper system into robotic applications. Key parameters and components were selected during the design phase, followed by the construction of system assembly parts. A parametric design for the mechanism, suitable for additive manufacturing, is outlined in alignment with educational objectives. The scalable design and cost-effectiveness of fused deposition modeling (FDM) make the presented gripper adaptable to various robotic systems. The prototyping process includes selecting printing parameters in the case of FDM and executing the manufacturing process. Three different sizes of robotic grippers are manufactured, with plans for integration into robotic systems to support hands-on engineering education.

Keywords: additive manufacturing; low-cost production; mechatronics engineering education; parallel mechanism gripper; scalable robotic gripper

1 INTRODUCTION

To address the demands of mechatronics engineering education, hands-on training with experimental setups of mechatronic systems is essential. Robotics plays a significant role as an interdisciplinary field encompassing various technologies related to industry 4.0 [1], design, control, planning, and more. Robotic systems can generally be categorized into industrial and mobile robots. Within robotics, the end-effector (gripper) is a crucial system component [2]. For instance, the integration of different end-effectors with a three degrees-of-freedom (DoF) open-source robotic arm is explored in the paper [3]. Additionally, the paper [4] demonstrates the integration of an underactuated gripper with a heterogeneous robotic system comprising a robotic arm and a ground robot [4]. Grippers are also applied in aerial robotics, as shown in the paper [5].

In the context of research and engineering education, robotic end-effectors can be explored from multiple perspectives. A crucial aspect is the control of end-effectors, as shown in the paper [6] offering an overview of various control methods. End-effector (gripper) control systems can be categorized into open-loop and closed-loop systems. Closed-loop systems require the integration of sensors to effectively perform tasks. The paper [7] discusses a grasp controller designed for a sensorized parallel jaw gripper, enabling it to gently pick up and place down unknown objects. The control scheme draws inspiration from human actions, which rely on tactile feedback. On the hardware side, extensive research has been dedicated to the design and manufacturing of mechanical systems for robotic grippers. Additionally, significant efforts have been made in engineering education, as demonstrated by research such as design of a single-DOF gripper mechanism [8]. Gripper designs vary based on their intended purpose, with some mechanical systems being multifunctional [9], and specialized for tasks such as grasping thin objects [10]. In addition to mechanical grippers combined with electric actuators for grasping functions, soft grippers have been extensively researched, as demonstrated in paper [11].

The advancement of rapid prototyping technologies has significantly accelerated the development of mechatronic systems, with additive manufacturing (AM) playing a pivotal role. This technology is versatile, finding applications across various fields, especially in robotics, from creating educational low-cost robotic platforms [12] to manufacturing specialized multirotor UAV airframe parts [13]. Moreover, AM technologies have proven effective in producing robotic components, such as the open-source 3D-printed underactuated gripper presented in the paper [14]. In papers [15, 16], a low-cost, open-source, 3D-printed three-finger gripper platform for research and educational purposes is presented, featuring a design with minimal 3D-printed components and an off-the-shelf servo actuator. Additionally, research [17] offers a comparative study on the impact of different 3D-printed fingertips in robotic gripper jaws, focusing on the pulling force exerted on various shaped objects. Furthermore, the paper [18] emphasizes the optimization of AM techniques for constructing a new gripper design capable of handling a wide range of parts with varying sizes and shapes. Beyond gripper development, AM has also been applied to optimizing robotic structures, as demonstrated in a comparative analysis of topology optimization platforms [19].

This paper presents the design and development of a scalable educational robotic gripper. The concept is examined in the context of the professional mechatronics study program that is being conducted in Croatia. A scalable design for a robotic gripper utilizing a parallel mechanism is proposed, emphasizing low-cost production and ease of manufacturing. The paper outlines the entire process, from the initial sketch to the final prototype or product. The prototyping phase involved fused deposition modeling (FDM) AM technology, with three prototypes of varying sizes and capabilities tested. The concept of the robotic gripper can be used in different aspects of the process of hands-on engineering education. Still, it can also be used in the broader context of STEM education at lower levels. Future work will focus on integrating presented robotic grippers with robotic systems.

2 UNDERGRADUATE PROFESSIONAL MECHATRONICS STUDY PROGRAM IN CROATIA

This research examines the integration of a robotic gripper into the practical education curriculum of the mechatronics undergraduate professional study program in Croatia. In 2021, the program was developed to align with the HKO register [20]. The curriculum totals 180 ECTS credits, with 114 ECTS derived from mandatory learning outcomes and 66 ECTS from optional learning outcomes. The study learning outcomes are divided into general outcomes (IUP1 - IUP10), which focus on soft skills, and professional outcomes (IUP11 - IUP27). Table 1 lists the study learning outcomes that can be partially or fully related to the robotic gripper in the areas of modeling, control, design, and manufacturing.

Table 1 Undergraduate professional mechatronics study program learning outcomes related to robotic gripper [20].

Learning outcome code	Learning Outcomes of the Undergraduate professional study of Mechatronics in Croatia
IUP1	Apply mathematical and physical laws to engineering problems
IUP6	Identify, model, and solve engineering problems
IUP9	Use techniques, skills, and modern tools necessary for engineering practice
IUP11	Recognize and propose adequate types of materials and machining procedures for the production of mechatronic systems
IUP12	Dimensioning and selecting standardized elements of precision mechanics, machine elements, and assemblies in the process of manufacturing various mechanisms
IUP14	To know the principles of operation of electronic and electromechanical converters
IUP17	Create 2D technical documentation and construct a 3D model of mechatronic systems
IUP21	Select and connect sensors, actuators, microcomputers, programmable logic controllers, and accompanying equipment for the automation of production processes
IUP25	Integrate the computer with software support in the process of data collection, measurement and data display on the computer
IUP27	Plan, monitor and control the production of mechatronic system elements

Regarding the mentioned mechatronics study program aligned with the HKO register, there are mechatronics studies in Croatia that are either fully aligned or in the process of alignment to meet the learning outcomes of the professional mechatronics curriculum. At the Karlovac University of Applied Sciences, the study of mechatronics is currently in the process of revision and alignment. From the aspect of hands-on training, and this research topic, low-cost robotic gripper prototypes, made using entry-level components, are currently being integrated with robotic arm models, as shown in Fig. 1, and used in hands-on laboratory exercises for the Robotics course. The use of a robotic gripper in robotics classes aligns with IUP9 and IUP21. Additionally, DC servo motors used to drive the robotic gripper are covered in Actuators course aligned with IUP14. From a system design perspective, students work on case studies involving the construction of robotic grippers, including modeling parts and assemblies, which aligns with IUP17 and IUP9.

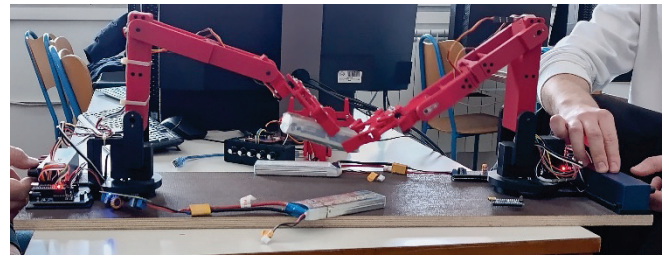


Figure 1 Low-cost robotic gripper prototypes integrated with robotic arm models, utilized in hands-on laboratory exercises for the Robotics course

This study is part of the internal project at Karlovac University of Applied Sciences, titled "Development of Innovative Educational Robotic Modules - iEduBot". As part of the project, the necessary equipment, components, and materials will be procured to develop educational robotic modules, including robotic grippers. Integrating these modules into the undergraduate professional mechatronics program will enhance hands-on learning through practical and team-based activities for students. After completing the design and production phases of the robotic gripper kits, integration into the educational process will proceed through exercises (theoretical, laboratory, and design-based), aligned with the mechatronics learning outcomes (Tab. 1).

3 DESIGN OF A SCALABLE AND MODULAR EDUCATIONAL ROBOTIC GRIPPER

From the hardware aspect, the main goal is to design a scalable and modular mechanism of a parallel robotic gripper that can be applied in the engineering education of an undergraduate professional mechatronics study. Another goal is to design a system that consists of readily available and relatively inexpensive components and parts that can be produced at low cost and with inexpensive equipment. The assembly of the parallel mechanism, which is actuated using an electric servo motor, is considered. The designed system is connected with the learning outcomes of the undergraduate professional study of mechatronics.

3.1 Mechanical Overview of a Robotic Gripper with Parallel Mechanism

Robotic grippers are an integral part of the robotic system and differ in mechanical configurations, drive type, power, precision, and other specifics. Robotic grippers with a parallel mechanism have a simple design and are suitable as a tool in engineering education. The parallel gripper shown in this paper consists of the central part of the assembly on which the electric servo motor is mounted, and the left and right sides of the gripper mechanism. Each side consists of two parallel links where the torque is transmitted via a geared link and the jaw to which the links are connected. Versions where each side has a separate motor or versions with one motor and a mechanism through which the torque is transmitted from the motor to both sides of the gripper are possible. The mechanism of the parallel gripper with one motor will be considered, as shown in Fig. 2.

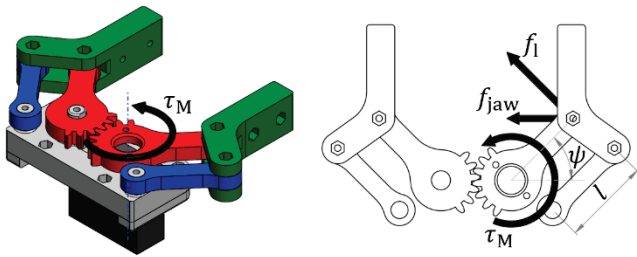


Figure 2 Schematic representation of a robotic gripper parallel mechanism

The motor torque is transmitted to the left and right jaws of the gripper via a mechanism consisting of two gear elements. The two main parameters of the mechanism that were considered in the design of the scalable gripper are the motor torque and the length of the link of the gripper parallel mechanism. Assuming that there are no losses in the mechanism and no misalignment, the amount of force in the link is given with following expression

$$f_1 = \frac{\tau_M}{2l}, \quad (1)$$

where τ_M is the torque of the motor divided between the left and right sides of the mechanism, and l is the length of the link of the parallel gripper. Therefore, the force component acting in the direction of the parallel mechanism depends on the jaw angle, and is given with following expression

$$f_{\text{jaw}} = f_1 \cdot \sin \psi = \frac{\tau_M}{2l} \cdot \sin \psi, \quad (2)$$

where the total force exerted by the left and right side of the jaw is equal

$$f_{\text{tot}} = 2f_{\text{jaw}} = \frac{\tau_M}{l} \cdot \sin \psi. \quad (3)$$

The paper will consider 3 sizes of servo motors, according to which structural elements and assembly will be selected and dimensioned with the aim of producing parts of a low cost gripper, which is aligned with IUP12.

3.2 Electric Servo Motor Drive Units of the Low-Cost Robotic Gripper

DC servo motors were chosen for the drive of the low-cost educational robotic gripper because of their price, but especially because of the simple integration with the mechanical and control system. Such motors are typically used in applications that require precise control of position, speed, or torque. The DC servo motor assembly has a compact design, considering that the motor housing contains the driver, DC motor, and gearbox, and comes in a wide range of sizes and powers. The characteristic of such motors is that there is a feedback connection using an encoder or potentiometer, which forms a control circuit with the motor driver. The feedback system constantly monitors the motor's

output and adjusts its input to match the desired position or speed. A DC servo motor is usually controlled by a PWM (Pulse Width Modulation) signal, where the pulse width determines the position, speed, or torque of the motor. This enables precise control in a various robotics, automation, and manufacturing applications, due to their fast response and efficiency. In addition to conventional motor designs, there are also digital servo motors that have a high accuracy. Three standard sizes of servo motors were considered and their characteristics are listed in Tab. 2. This aspect of the robotic gripper is aligned with the learning outcome IUP14.

Table 2 Considered DC servo motors manufacturer specifications

Servo motor	Size (mm)	Weight (grams)	Operating voltage (V)	Stall torque (kg-cm) @ 6V
FEETECH FS90MG	23.2 × 12.5 × 22	9	4.8 - 6	1.5
FEETECH FT1117M	30 × 12 × 31.7	20	4.8 - 6	3.5
FEETECH FS5115M	40.8 × 20.1 × 39	62	4.8 - 6	15.5

3.3 Design of a Scalable, Modular Robotic Gripper Mechanism

The goal of this project is to develop a scalable, modular, and cost-effective prototype of a robotic gripper mechanism. Given that there are different needs for the use of varying motor performance, a parametric design of the parts of the parallel gripper assembly is shown, which, integrated with the servo motor, forms the mechanical system of the gripper. During the design phase, the SOLIDWORKS software package was used to construct 3D models. Fig. 3 shows three sizes of the robotic gripper whose performance depends on the motor torque and the length of the link of the parallel mechanism. In addition to scalability, the assembly can be integrated with different types of robotic systems, for example with rotational or translational degrees of freedom. The scalable modular robotic gripper prototype will be used as a construction example in courses that include the construction of 3D models, aligned with IUP17.

In addition to the parametric design approach, the technological feasibility of the construction was considered given in mind that the parts are planned to be manufactured using AM technology. From that follows the economical process in terms of material costs and production time. In the design process, the mechanism assembly that will be produced by FDM AM technology is shown. From a hardware perspective, this work contributes with a scalable, modular robotic gripper that, in combination with a motor, forms a low-cost prototype suitable for integration into the curriculum of an undergraduate mechatronics study.

Further research will focus on analyzing the mechanism's structure using finite element method (FEM), addressing the challenges posed by the anisotropic mechanical properties of FDM-manufactured parts due to their layer-by-layer deposition. Additionally, error analysis will be conducted to evaluate dimensional deviations in the

gripper links and their impact on the parallelism of the gripper's fingers.

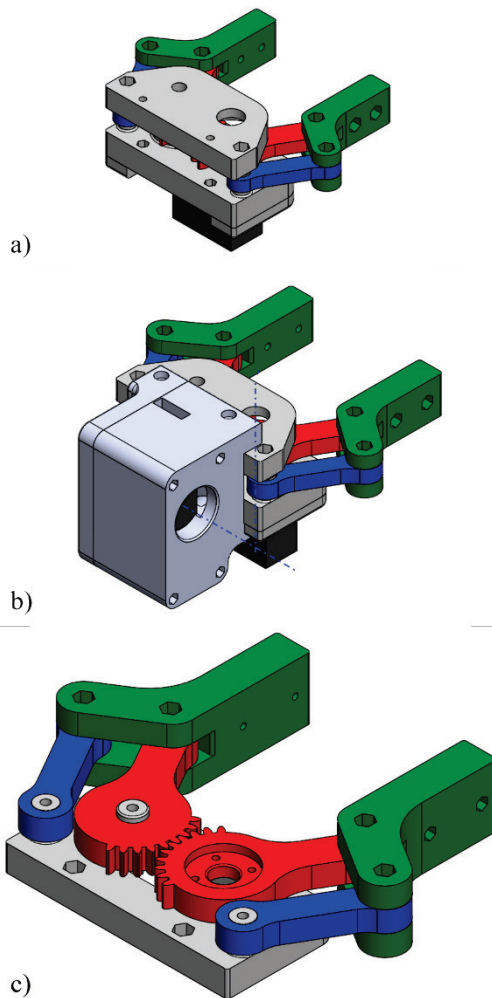


Figure 3 3D models of a parallel gripper mechanism parametric design: (a) Link length $l = 24$ mm with FS90MG motor, (b) Link length $l = 28$ mm with FT1117M motor and rotational DoF, (c) Link length $l = 40$ mm with FS5115M motor

4 PROTOTYPING A LOW-COST ROBOTIC GRIPPER USING ADDITIVE MANUFACTURING

After completing the design phase of the robotic gripper, the prototype production phase begins. For this purpose, it is necessary to create 2D technical documentation that aligns with IUP17. Fig. 4 shows a gripper assembly 3D model with associated parts that will be produced by AM technology. Given that the goal is to create a cheap educational gripper, FDM technology was chosen, which works by extruding thermoplastic material layer by layer to make a part or several parts. The material, which is in the form of a plastic filament, is heated to a semi-liquid state and deposited through a nozzle onto the fabrication platform. The nozzle follows a programmed path, controlled by computer-aided design (CAD) data. FDM technology is known for its affordability, both in terms of machinery and materials used, which makes it available for prototyping and small series production. It is easy to handle, widely available, and supports a range of

thermoplastics, making it ideal for educational and research purposes.

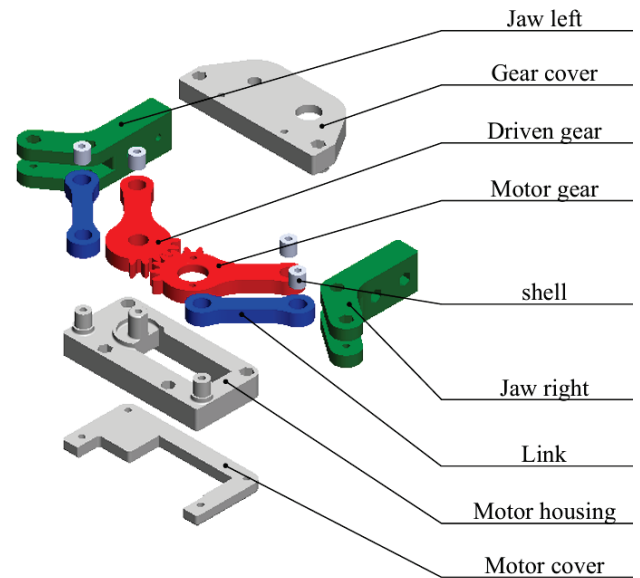


Figure 4 3D model exploded view of the gripper assembly with associated parts designed for production using AM technology

4.1 Preparation of Robotic Gripper Parts for Additive Manufacturing

Due to the combination of simplicity, cost-effectiveness, and flexibility of materials, FDM technology was chosen to produce prototypes of educational robot grippers. The initial step in preparing a 3D print, independent of the AM technology, involves saving the 3D model in .stl format. This format captures the geometry of the object by representing its surface with a mesh of triangles, facilitating accurate conversion from digital design to physical models. Next, the .stl files are loaded into a slicing software specific to the AM technology being used. For this research, an FDM 3D printer by Bambu Lab was used along with the Bambu Studio software. Adjusting the parameters of the 3D print depends on the geometry and purpose of the part and the used material. In this case, PETG material was chosen for producing educational robot grippers due to its superior durability, UV resistance, and heat tolerance, making it a better option than PLA for demanding applications. FDM technology also offers extensive parameter adjustability, which is valuable for addressing specific learning outcomes (IUP11).

Several parameters related to FDM printing technology were considered, particularly wall thickness and part infill. The thickness of the walls, base, and roof of the printed part, along with the percentage and type of infill, play a crucial role in determining its mechanical properties. Previous research [21] explored how the number of walls and the percentage of infill affect tensile strength. These findings were taken into account when configuring the parameters for the educational robot grippers in this research. For the production of a series of prototypes for teaching purposes, a

three-wall loop and a gyroid sparse infill pattern with 15% density were selected.

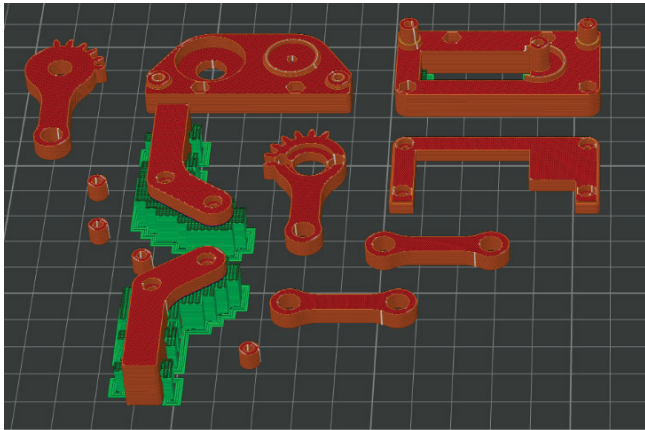


Figure 5 Slicer view of gripper parts in Bambu Studio

In the first phase of prototyping, several construction iterations were tested, with parts being printed separately, one by one. Once the final parametric design was established, it became more efficient to group the parts for 3D printing. A single prototype with identical print parameters for all parts can be produced within a single run, as shown in Fig. 5 for the gripper with the FT1117M servo motor using Bambu Studio. Printing multiple parts at once offers a significant time-saving advantage compared to printing each part individually. Although the model printing time remains similar, grouping the parts significantly reduces both preparation and post-processing times.

Each print cycle involves heating the 3D printer components (nozzle and print bed), and after completion, the nozzle and bed must cool down. For example, with PETG material on the Bambu Lab A1 Mini 3D printer, it takes approximately 8 minutes for the bed to cool below 50 °C, allowing the printed parts to be safely removed. This cooling process must be repeated for each new print. By printing all parts together, the prepare time and post-processing steps only occur once, reducing time considerably. When prototyping a series of robotic grippers, printing grouped parts offers flexibility, as the parameters for individual components can be adjusted independently, particularly in terms of mechanical properties. As the production volume increases, it becomes necessary to plan, monitor, and control the production of gripper components, but in general mechatronic systems, which is aligned with IUP27.

4.2 Additive Manufacturing and Assembly of a Gripper Mechanical System

After preparing the model in the slicer software and generating the G-code, the software provides estimates for total filament consumption, preparation time, and model printing time. During the preparation phase for PETG material, the nozzle is heated to 255 °C, and the print bed reaches 70 °C. Fig. 6 shows the 3D-printed parts of the gripper (FT1117M) produced using the Bambu Lab P1S 3D

printer. Post-processing, such as removing support material, is often necessary, particularly for parts like the gripper jaws.

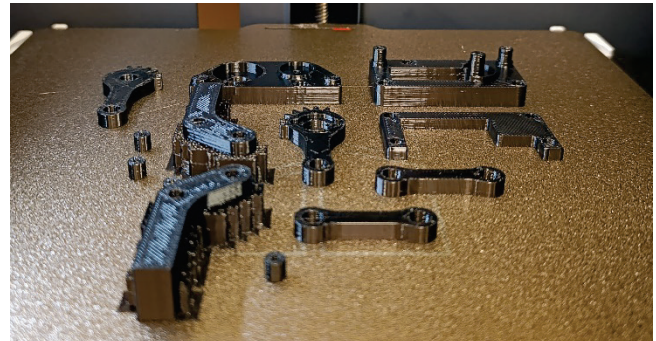


Figure 6 3D-printed gripper parts made from PETG material using the Bambu Lab P1S printer

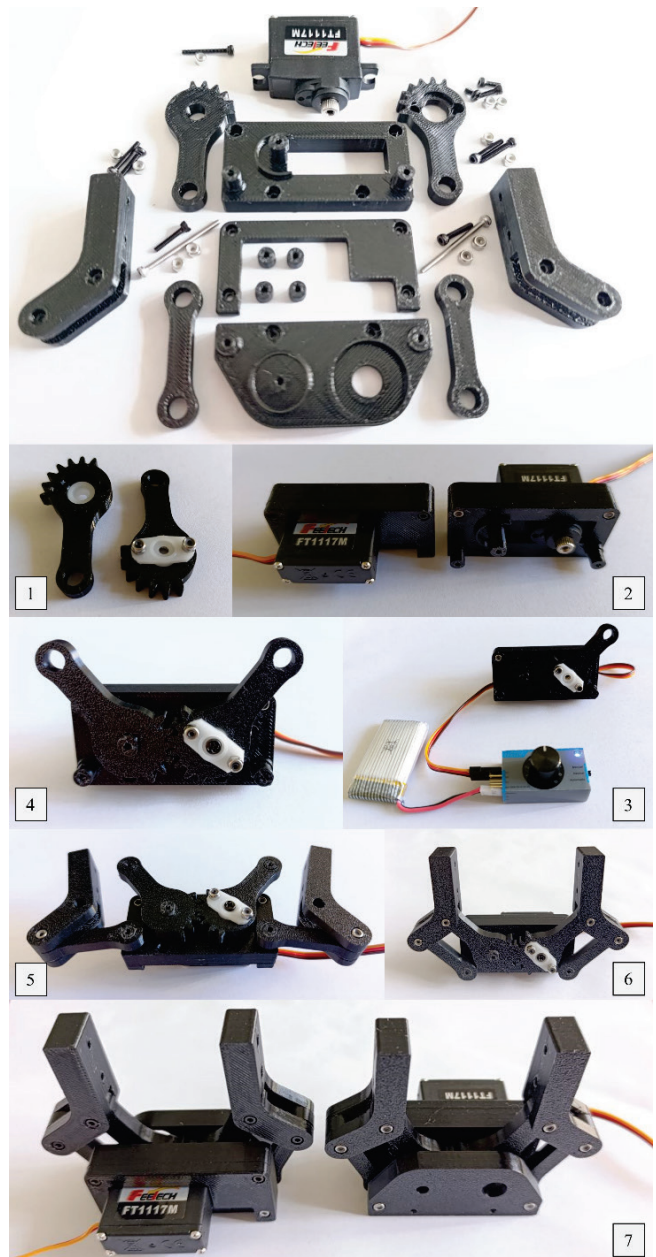


Figure 7 Assembly steps of the gripper components into a functional unit

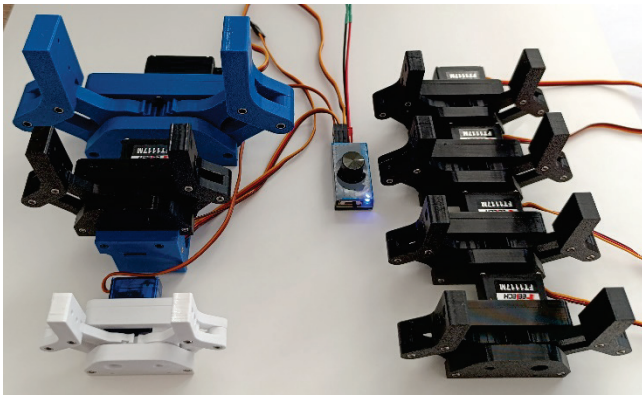


Figure 8 Display of three gripper sizes during preliminary testing

Once all the parts of the prototype or series of prototypes have been printed, along with connecting elements (bolts, nuts), the gripper assembly can begin, as shown in Fig. 7. The assembly process starts with mounting the servo adapter to the motor gear (Step 1) and continues with attaching the servo motor to the frame parts (Step 2). Step 3 involves testing the motor with the motor gear and adjusting the initial angle. Subsequently, in Steps 4, 5, and 6, the remaining mechanism parts are assembled. Finally, in Step 7, the cover is installed to secure all the elements into the assembly.

Fig. 8 illustrates the three prototyped robotic gripper sizes developed in this research during the preliminary testing phase of the full assembly. For this and previous testing stages, a module with four AA batteries and a servo tester, used to send the control PWM signal, were employed.

5 DISCUSSION

The design and prototyping of the robotic gripper demonstrate alignment with the learning outcomes of IUP11, IUP12, IUP14, IUP17, and IUP27 from the undergraduate professional mechatronics study. The mechanical gripper system can function both independently and as part of integrated robotic systems, whether industrial or mobile. For standalone use, the hardware gripper can be further enhanced by integrating sensors. An experiment to measure the gripping force using a sensor setup is under consideration, aligned with IUP21. To facilitate force measurement, 5 kg load cell sensors with HX711 amplifiers will be connected to the control system. From the perspective of the gripper, further work will focus on integrating sensors into the mechanism's jaws, as closed-loop systems require the use of sensors to perform tasks effectively. Given the gripper's intended low-cost design, the following sensors are being considered: a load cell sensor (similar to those used in force measurements) and a pressure sensor. As an extension of the experiment, a mechanical system with independent left and right motors for the parallel gripper mechanism can be incorporated. This setup allows for a comparison of the forces generated by a two-motor mechanism versus a single motor with a mechanical linkage. The integration of a computer and control system for data collection, measurement, and visualization is aligned with IUP25.

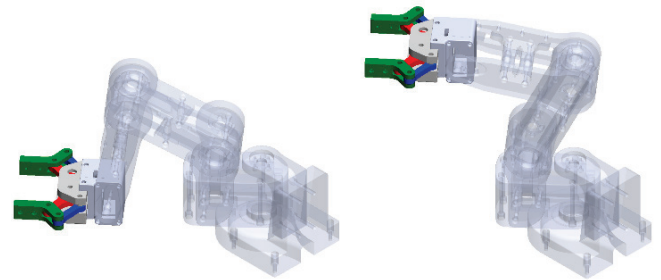


Figure 9 Integration of the robotic gripper and rotational degree of freedom with an RRR robotic arm configuration.

In further work, the integration of an inertial measurement unit (IMU) for rotational control, providing an additional degree of freedom, is under evaluation (Fig. 3b). Fig. 9 presents the CAD model of the proposed design for the robotic gripper integrated onto a robotic arm with three degrees of freedom (DoF). For this purpose, the design of robotic modules will be undertaken to integrate the proposed educational robotic gripper. These modules will include both the existing mobile platforms presented in previous research [22] and new robotic modules for industrial simulators with two, three, and four degrees of freedom.

6 CONCLUSION

This paper presents the design, prototyping, and testing of a scalable and low-cost robotic gripper. The aligned learning outcomes have been demonstrated within the undergraduate professional mechatronics study program through various aspects of the robotic gripper. A robotic gripper with a parallel mechanism was described, and its system parameters were defined. A low-cost, scalable, and easily upgradeable design for the gripper mechanism was proposed. FDM technology was selected for the production of the mechanism parts, and the additive manufacturing process was illustrated. The assembled robotic grippers were tested and are now ready for integration into the educational process. An additional advantage of the proposed design and manufacturing technology is its applicability across various levels of education. In future work, the proposed gripper design will be integrated with robotic modules to create complete robotic systems.

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