Designing Educational Systems to Illustrate Mechatronic Principles

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This article presents six innovative laboratory mechatronic systems developed as educational prototypes to illustrate fundamental mechatronic principles to engineering students. The first prototype is an oncooscillator that generates oscillating magnetic fields via a rotating magnet driven by a DC motor, potentially demonstrating biomedical applications such as tumour cell disruption. The second is a robotic fire-fighting system ("firebot") connected to a water tanker for fire suppression. The third prototype models a cargo transport vehicle facing challenges of load instability on uneven terrain. The fourth is a mini-vessel equipped with a gyroscopic stabilization mechanism to minimize lateral rolling during navigation. The fifth is an automated chessboard capable of autonomous gameplay, piece movement, and board state recognition. The final system is a compact underwater vehicle (submarine) designed for submerged exploration and operational tasks. These prototypes serve as practical tools for bridging theoretical knowledge with hands-on learning in mechatronics education.

Keywords:
mechatronic models,
automatic control,
biomedical engineering,
underwater robotics,
gyroscopic stabilization

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1 Introduction

Mechatronics is an interdisciplinary field combining mechanical, electrical, computer, and control engineering, with applications expanding beyond traditional industrial automation into biomedical, environmental, transportation, and interactive systems [1], [2]. As mechatronic systems grow in complexity and scope, engineering education must evolve accordingly, emphasizing both theoretical foundations and hands-on experience through practical learning platforms [3]. One of the main challenges in teaching mechatronics is translating abstract theoretical concepts into real systems. Conventional instruction often falls short in conveying the integrated, multidisciplinary nature of real-world engineering tasks [4]. To address this gap, educational laboratory prototypes have become essential tools in teaching. These systems promote active learning, critical thinking, and innovation by allowing students to work directly with sensors, actuators, microcontrollers, and feedback systems in real applications [5]. This article presents six such educational prototypes developed to illustrate fundamental mechatronic principles. These include: an oncooscillator generating oscillating magnetic fields for biomedical research; a robotic fire-fighting platform (firebot); a vehicle stabilization system for transporting liquid cargo; a gyroscopically stabilized mini-vessel simulating dynamic marine balance; an automated chessboard capable of autonomous play; and a compact underwater vehicle for submerged exploration. These prototypes serve both as didactic tools and as foundations for advanced research in robotics and intelligent system design.

2 Biomedical and environmental mechatronic prototypes

2.1 Oncooscillator for the treatment of tumour diseases

The oncooscillator is an innovative medical device developed for non-invasive cancer treatment using oscillating magnetic fields (OMF). Based on recent research, particularly in the form of spinning oscillating magnetic fields (sOMF), these devices have shown the potential to selectively disrupt mitochondrial activity in tumour cells, leading to their death without affecting healthy cells [6]. This approach targets the electron transport chain in mitochondria, increasing reactive oxygen species and causing energy failure in malignant cells. The therapeutic system consists of three oscillators that generate dynamic magnetic fields through the rapid rotation of strong permanent magnets. The rotation is achieved using 24 V brushed DC motors without gear transmission, providing high torque and suitable speeds. The motors are controlled by an Arduino Mega 2560 using PWM signals, with a DC-DC converter and IC driver (up to 1.5 A) ensuring stable voltage and current. Key mechanical components are constructed from industrial plastics and polymer-based materials, chosen for their excellent thermal and mechanical properties, as well as non-magnetic behaviour. This prevents interference with magnetic fields and ensures system safety. Ceramic bearings are used to support the rotating magnets due to their low friction and non-magnetic characteristics, preventing heat buildup and maintaining mechanical integrity during extended use. The magnets used in the system are of type DX0X0-N52, known for their extremely high magnetic strength. These magnets must be handled with care due to their strong attractive force, which poses a risk of damage or injury if not properly secured. Their high magnetic induction and relatively low mass make them ideal for OMF therapy applications. An important design strategy in the oncooscillator is the use of inertial motion. Motors accelerate the magnets to the desired rotational frequency, after which power is reduced, and the system relies on the inertia of the rotating mass to maintain consistent motion. This eliminates the need for mechanical braking and reduces power consumption, improving overall efficiency. Speed monitoring is enabled by Hall-effect sensors, which detect variations in magnetic fields and provide feedback to the control system. This allows real-time adjustment of the motor drive signals, ensuring synchronized operation of all three oscillators (Figure 1). Because the system uses a common PWM signal, all motors operate at the same speed, assuming identical mechanical loads.

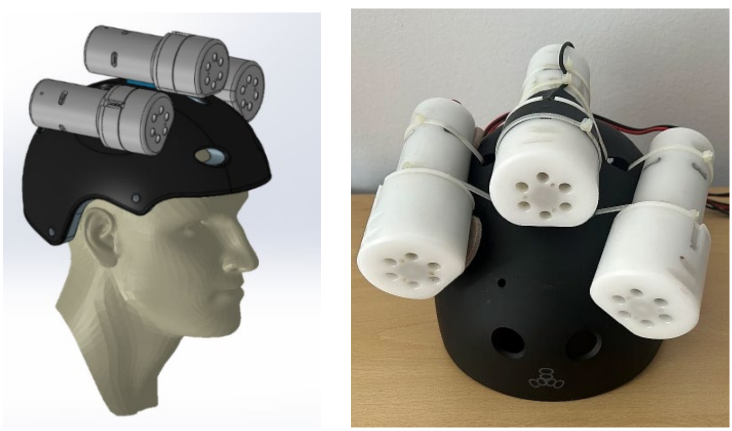


Figure 1: CAD model and assembled OMF helmet.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:10889 [7]

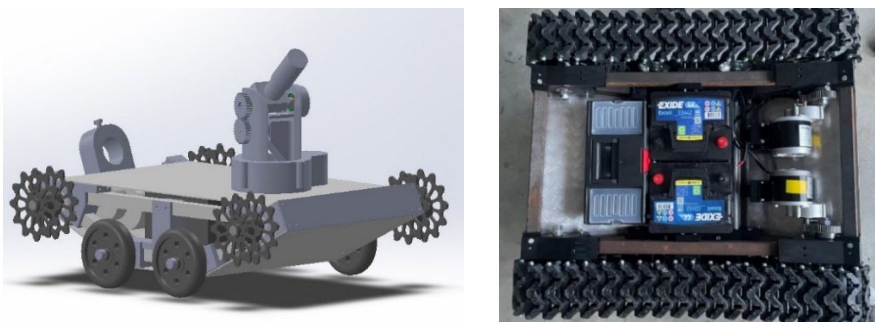
Figure 2: Application of OMF: a) wearable helmet, b) configuration for reclining patient.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:10889 [7]

The device is implemented in two configurations: a wearable helmet and a version adapted for patients in a reclined position (Figure 2). Both are designed to provide localized treatment, particularly for brain tumours such as glioblastoma. Preliminary reports and findings from existing studies show that OMF exposure can trigger selective cancer cell death in GBM and lung cancer cells, while sparing normal tissues. This selectivity is believed to be linked to the bioenergetic vulnerabilities of tumour mitochondria and the radical pair mechanism.

With its non-invasive nature, low energy consumption, and precise control, the oncooscillator represents a promising addition to the field of cancer therapy. Its potential applications extend beyond oncology to include mental health and rehabilitation treatments, where magnetic stimulation is already in use.

2.2 Mobile fire-fighting robot (firebot)

A compact, mobile fire-fighting robot has been designed and built for indoor and outdoor intervention in hazardous environments. Its primary function is water-based fire suppression, with water supplied via connection to a fire truck or water tank. Its compact dimensions enable operation in narrow and confined spaces, including stairways and steep terrain, where human access may be limited or dangerous. Additionally, the robot integrates environmental sensors to measure gas concentrations and an infrared sensor to detect the hottest point in the area. A camera mounted on a rotating turret allows for remote visual inspection and control via network connection. To ensure the robot's mobility and performance, a tracked chassis system was developed. Tracks allow climbing stairs and traversing uneven ground. The chassis consists of hollow steel square tubes (30x30 mm, 5 mm thick) for structural integrity, and PETG polymer joints manufactured via 3D printing for the prototype stage. Lightweight aluminium checker plates are used as protective covers, with the option of mounting standard wheels on axles for simplified assembly and improved load capacity. The robot is powered by electric motors due to their robustness and reliability in oxygen-deficient environments. Each track is driven by a DC motor via a gear system, while shafts are supported by bearings press-fitted into the chassis. The drivetrain was built using PETG-printed sprockets and track links, with future versions planned in metal for improved durability. The drive assembly also includes commercially available wheels and standardized steel axles to reduce production complexity. The fire-fighting turret mounted on top of the chassis enables two degrees of rotational freedom using two Nema 17 stepper motors. One motor controls horizontal rotation, while the other, equipped with a planetary gearbox (32:1), handles vertical movement. The turret's components are also 3D-printed. A high-definition camera is fixed on the turret for real-time visual feedback, connected via LAN and powered by a 12V supply. The control system is built on a Raspberry Pi 4 using Python scripts. Wireless communication over the network ensures reliable remote control. All electronic components, including motor drivers (BTS7960 and TB6600), a DC-DC voltage regulator, and batteries, are housed in a waterproof enclosure inside the robot chassis, Figure 3.



(a) (b)

Figure 3: a) CAD model of firebot, b) drive assembly with mounted components.
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The robot's low centre of gravity, with batteries placed at the base, ensures stability. Tests showed it can climb obstacles (e.g., standard-sized steps), pull heavy objects (e.g., sandbags), and endure mechanical stress. The turret rotation system and camera positioning enhance hazard and potential casualty detection. The final mobile fire-fighting robot is shown in Figure 4. Future upgrades may include LIDAR, gas sensors, and semi-autonomous navigation for low-visibility conditions.

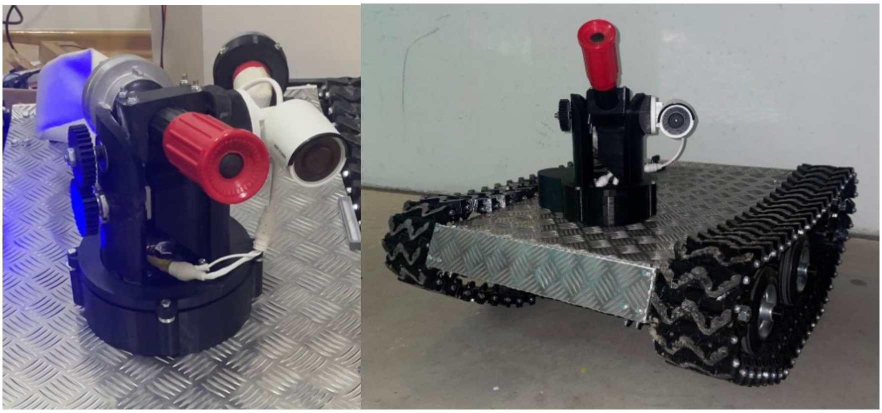

Figure 4: Mobile fire-fighting robot with mounted rotating turret.
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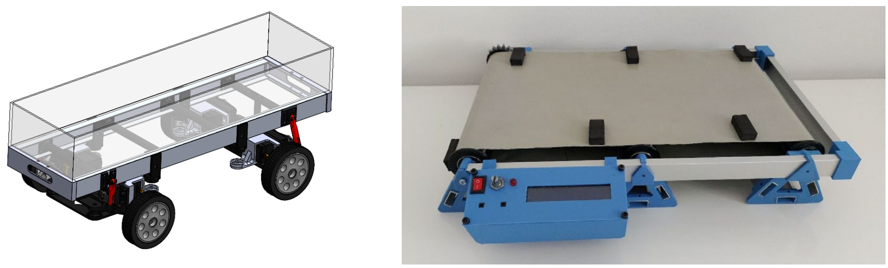
3 Mobility and stability systems in mechatronics

3.1 Electronic stability control of liquid transport vehicles

A model of a transport vehicle designed for carrying liquids or low-density materials was developed to address common stability issues encountered during operation on uneven or inclined surfaces. The proposed solution includes an active suspension system that dynamically maintains vehicle stability by controlling chassis inclination in real time. The aim of this project is to demonstrate, through an educational prototype, the benefits of electronically controlled suspension in mitigating vehicle oscillations due to road surface irregularities. Figure 5 shows the CAD model of the transport vehicle and the created conveyor belt with surface bumps. The system integrates two MPU6050 gyroscopic sensors placed at the front and rear axles to measure angular displacement. Their data is processed by an Arduino Nano, which sends corrective signals to MG995 servo motors. These motors adjust the axle positions to counteract tilting. A plexiglass container holding 400 ml of water is mounted on the chassis to simulate a real load. To simulate road disturbances, a motorized conveyor belt with surface bumps was built. The belt is powered by a Nema 17 stepper motor with gear reduction and controlled via an Arduino Nano and A4988 driver housed in a control unit with an LCD display. The setup allows controlled and repeatable testing of suspension response. A Simulink dynamic model was created, incorporating road input and a sliding PID controller. This controller generates voltage outputs to stabilize the vehicle. Based on simulation results, parts were modelled in CAD and produced using FDM 3D printing with PET-G filament. The chassis, axles, and joints were assembled using U-profiles, springs, and servos. A custom two-layer PCB designed in Altium Designer processes signals and realizes motor control.



(a) (b)

Figure 5: a) CAD model of the transport vehicle, b) conveyor belt with surface bumps.
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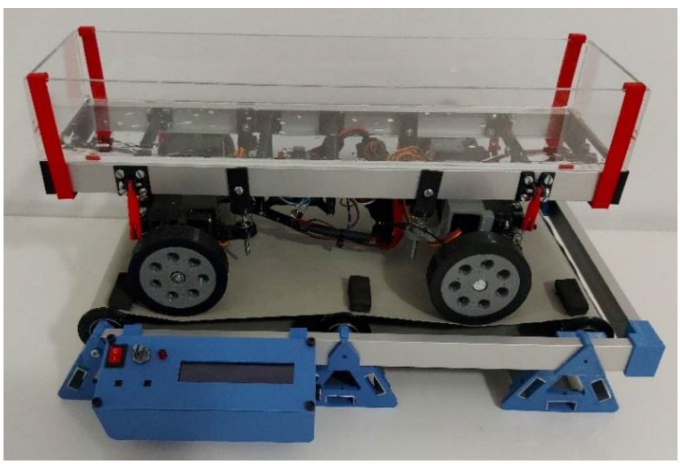

Figure 6: Vehicle prototype equipped with electronic stability control system.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:10871 [9]

Figure 6 shows the completed vehicle prototype equipped with electronic stability control system. Testing involved both static and dynamic conditions. In static tests, the vehicle-maintained stability over a 7 mm obstacle, even when loaded. During dynamic tests on the moving belt (0.04 m/s), angular data was collected, showing fast sensor and servo motors response that kept the chassis nearly horizontal. Stabilization occurred within 8 seconds. The final model demonstrates effective real-time tilt correction via active suspension and provides a valuable educational tool for studying electronic stability in liquid transport systems.

3.2 Mini-vessel with gyroscopic stabilization

A scale model of a vessel equipped with a gyroscopic stabilization system was designed to reduce lateral rolling caused by wave action or side forces. In modern maritime engineering, improving vessel stability enhances safety, comfort and manoeuvrability. Among available stabilization methods, gyroscopic stabilizers stand out for their compactness, mechanical simplicity, and ability to produce required stabilizing torques by using the law of conservation of angular momentum. The goal of this project was to show a way to reduce the amplitude of the roll angle, and the number of free roll oscillations within a range of $\pm 2°$. The basic component of the system is a high-speed spinning rotor. When subjected to external torques, the rotor exhibits precession, producing a stabilizing force perpendicular to the rolling motion. The vessel stabilization system integrates several components: a rotor (which is extracted from a lightweight RC aircraft motor), a NEMA 17 stepper motor for achieving precession, a Dasduino CORE microcontroller for signal processing and control, and a six-axis IMU sensor to estimate the vessel's roll angle. The entire assembly was modelled in SolidWorks, with the flywheel as the central element around which the system was compactly designed. The CAD model of the gyroscopic stabilization system is shown in Figure 7.

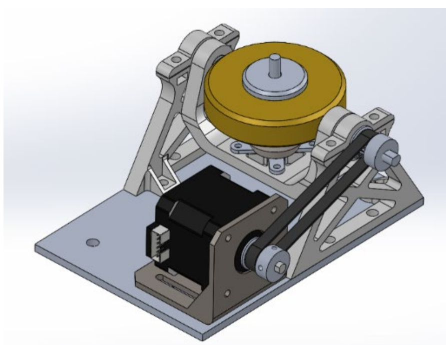

Figure 7: CAD model of the gyroscopic stabilizer.
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Practical production of the system was carried out using available technologies including turning, milling, FDM, and 3D printing. Most parts were printed using FDM for ease of manufacture and geometric flexibility. After assembling all the parts, the system was tested in a controlled environment, i.e. a water basin simulating calm sea conditions. Validation of simulation results with experimental data is a key element in engineering development. Simulations used simplified rolling motion equations, and experiments were designed to match these scenarios by manually tilting the vessel and observing its free oscillation. Figure 8 shows the mini-vessel model during its in-water testing. Real-time data acquisition was performed using the "data streamer" function in Excel, collecting sensor signals on a laptop. Matlab was used for post-processing and comparing simulated and experimental results. Initial testing without stabilization confirmed that the simplified dynamic model accurately reflected real-world behaviour. Subsequent testing with the gyroscopic system (passive mode, without active control) showed a significant reduction in oscillations. Starting from a 13° tilt, the unstabilized vessel needed 11 oscillations to settle within ±2°, while the gyroscopic stabilizer reduced this to just 2 oscillations (82 % improvement). Although active control could enhance performance further, the actuator system's weight exceeds the mini-vessel's capacity, making full active testing impractical in this setup.

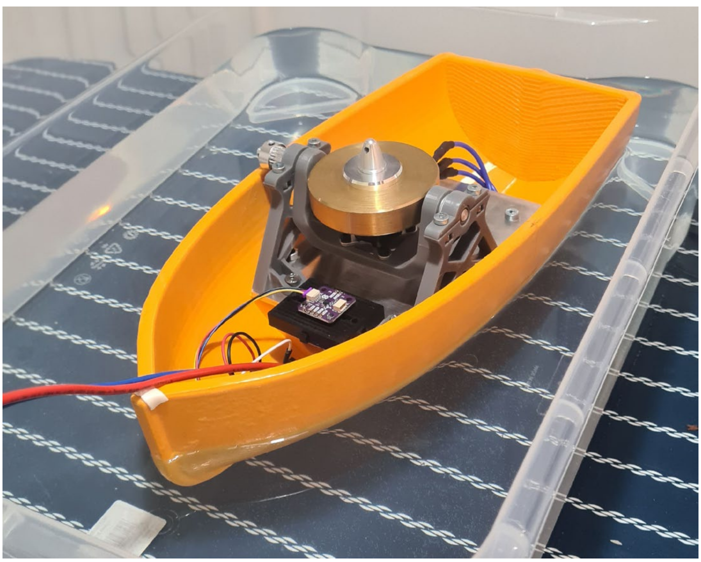

Figure 8: Mini-vessel model during water-based testing.
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This project confirms the feasibility and effectiveness of gyroscopic stabilization in small marine vessels. The system significantly improved roll damping even without active control, validating both the simulation and design. Future work may focus on reducing mass and adding active control to improve the stabilization response of the vessel.

4 Autonomous and underwater mechatronic platforms

4.1 Automated chess board with autonomous gameplay

The design and development of an automated chess board capable of autonomous gameplay represents an interesting intersection of embedded systems, mechanics, and artificial intelligence. The system can detect the player's moves, compute its own responses using a chess engine, and physically move the pieces using an XY-axis magnetic actuator. This allows the board to act as a real, physical chess opponent. The game begins in the standard initial position, whereby the human player always playing with white pieces to simplify programming logic. The detection system uses 64 reed switches, one beneath each square. Each switch contains two ferromagnetic contacts in a sealed, inert gas-filled tube. When a magnetic piece is near, the contacts close, signalling its presence. Since reed switches can't distinguish piece colour, all 64 squares are scanned twice per second to detect piece movement, including captures. The magnets embedded in the pieces are vertically aligned, which poses detection challenges due to reed switch geometry. This was resolved by offsetting the placement of the switches from the centre of each square. To connect all switches with limited input pins, four multiplexers are used to address and read the 64 switches efficiently. A display connected via I2C protocol provides user feedback, shows allowed player timers, and alerts about illegal moves or game status. Upon powering up, the board automatically calibrates using end-stop limit switches to locate the electromagnet's home position. The board is powered by an Arduino Nano with ESP32 microcontroller, programmed via the Arduino IDE. The gameplay engine is Micro-Max, a lightweight chess engine of only 133 lines of C code, developed by Harm Geert Muller. It uses the minimax algorithm with alpha-beta pruning technique to optimize move generation. Minimax simulates future game states by assuming both players play optimally, evaluating positions based on balance of figures, king safety, pawn structure, and possibilities of playing the next move. A key innovation is real-time move evaluation assistance. When a player lifts a piece, all legal destination squares light up using embedded multi-coloured LEDs.

The colours reflect the engine's evaluation of each possible move, helping players of all levels understand strategic consequences and learn in real time. Figure 9 illustrates the electronic schematic connecting the reed switch, address multiplexer, stepper motor driver (TMC2208) and display to the Arduino.

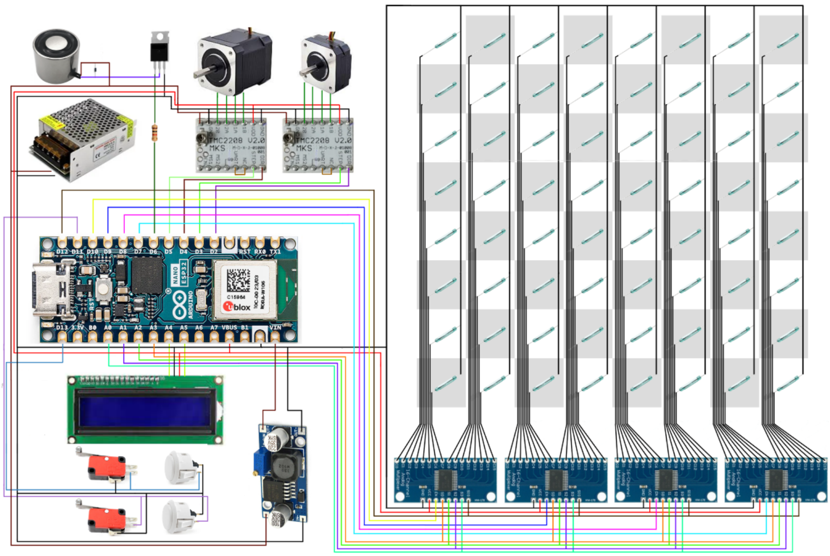

Figure 9: Electronic schematic connecting of chess board.
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Figure 10: Automated chess board.
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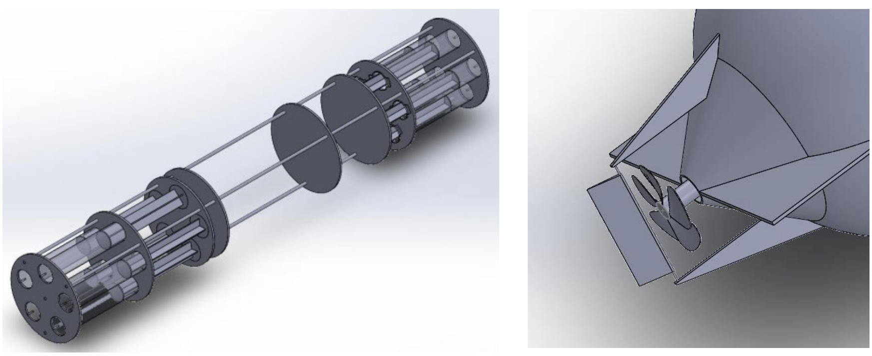
Figure 10 shows an assembled automated chessboard consisting of a game board with pieces, a drive mechanism, a piece disposal zone, and a visual feedback interface. By combining intuitive physical interaction, smart move generation, and online connectivity, this project not only revives the tactile experience of traditional chess but also uses modern technologies to enhance player engagement, education, and fun.

4.2 Underwater vehicle (submarine) for submerged exploration

This project presents the design and construction of a small-scale underwater vehicle (submarine) intended for underwater research. Unlike ground-based or aerial robotics, underwater vehicles must address challenges like waterproofing under hydrostatic pressure and maintaining buoyancy control at varying depths. The developed submarine is pressure-resistant up to 10 meters and utilizes ballast tanks and electric propulsion for depth and movement control. The submarine's frame is built from a 95 mm diameter, 550 mm long acrylic tube, offering both a lightweight structure and sufficient resistance to pressure up to 8 bar. Acrylic was chosen for its transparency, strength, and low weight. Sealing is achieved using O-rings and silicone sealant to ensure watertight integrity. Buoyancy regulation is based on Archimedes' principle. When the buoyant force exceeds the vehicle's weight, it ascends; when lower, it descends. This principle is exploited via a custom-designed ballast system with ten piston-driven cylinders that intake or expel water using motorized actuators. Figure 11 shows the location of the ballast tanks and the design of the submarine's rudder and propeller.



(a) (b)

Figure 11: a) ballast tanks, b) rudder and propeller.

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Motor torque was calculated including piston friction and the force required to displace water, based on internal and hydrostatic pressures. The propulsion system uses a DC motor (RS-385) driving a custom 3D-printed propeller, generating a pressure difference to create thrust that moves the submarine forward. Steering is achieved by a servo-controlled rudder (SG90), also made by 3D printing. A custom PCB controller, built with an Adafruit Pro Trinket (ATmega328) and nRF24L01 radio module, enables wireless control. Due to radio signal attenuation underwater, communication is relayed via a surface buoy with an antenna, connected to the vehicle through a wired link. Onboard control is handled by an Arduino UNO R3, which processes joystick and switch inputs to operate motors, ballast systems, and servo-controlled rudder (Figure 12). The system is powered by a 6000 mAh Li-ion battery, with motor control via an L298N dual H-bridge driver. Communication stability is maintained through configuration of the radio module. Testing in controlled water environments confirmed effective propulsion and depth control. However, sealing remains a weak point, and long-range signal reliability needs improvement. Future developments will focus on better sealing, adding cameras, and modular hardware. The project confirmed the educational possibilities of building a functional, low-cost ROV using accessible tools and components for underwater exploration.

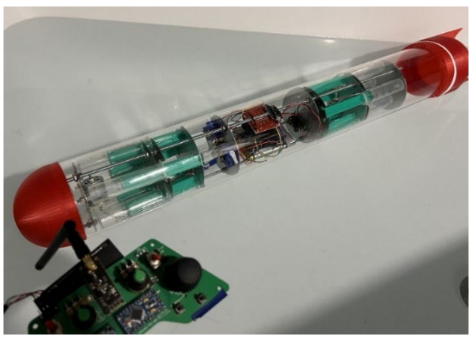

Figure 12: Underwater vehicle (submarine).
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5 Conclusion

Laboratory-based learning plays a vital role in engineering education, particularly in fields such as mechatronics and robotics where interdisciplinary integration is essential. The six presented prototypes demonstrate how theoretical concepts, ranging from kinematics and control systems to sensor integration and embedded programming, can be effectively applied into hands-on applications. Through constructing and testing these systems, students actively engage with real-world design challenges, developing critical thinking and problem-solving skills. These educational platforms not only enhance conceptual understanding but also inspire creativity and innovation. As is well known, laboratory work remains necessary in preparing future engineers for the complexities of modern mechatronic systems.

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