Mehatronic Prototypes for Engineering Education: Bridging Theory and Practice

Željko Šitum, Fran Hruškar, Lovro Meštrić, Mateo Šego, Tomislav Drašković, Eros Stemberger

Abstract:
This article presents five innovative mechatronic prototypes developed as educational tools to enhance engineering education by bridging theoretical concepts with practical implementation. The systems are organized into two thematic sections. The first section, *Mechatronic systems simulating real-world applications*, includes three prototypes that replicate real-life engineering challenges: a robotic fire-fighting unit – *Firebot*, integrated with a water tanker for active fire suppression; a cargo transport model demonstrating load stability on uneven terrain; and a gyro-stabilized mini-vessel designed to reduce lateral rolling during marine navigation. The second section, *Applied mechatronics for conceptual exploration*, presents two systems aimed at illustrating specific principles through interactive demonstration: the oncooscillator, which generates oscillating magnetic fields using a rotating magnet for potential biomedical applications, and an automated chessboard capable of autonomous gameplay, piece manipulation, and board state recognition. Together, these prototypes serve as effective platforms for experiential learning, fostering a deeper understanding of mechatronic principles among engineering students.

Keywords:
mechatronics, laboratory prototypes, hands-on learning, system integration, educational robotics

1 Introduction

Mechatronics is a multidisciplinary engineering field that integrates mechanical, electrical, computer, and control systems, with applications extending well beyond traditional industrial automation into areas such as biomedical engineering, environmental monitoring, transportation, and interactive technologies [1], [2]. As mechatronic systems become increasingly complex and diverse, engineering education must adapt by placing greater emphasis on both theoretical knowledge and practical, hands-on experience [3]. One of the key challenges in teaching mechatronics lies in effectively translating abstract theoretical concepts into tangible, real-world systems. Traditional teaching methods are often not effective in conveying the integrated and interdisciplinary nature of mechatronic design and implementation [4]. To address this gap, educational laboratory prototypes have emerged as powerful tools for enhancing student engagement and understanding. These systems enable active learning by allowing students to interact directly with sensors, actuators, microcontrollers, and feedback mechanisms in realistic scenarios [5]. This article presents five educational laboratory prototypes developed to demonstrate fundamental mechatronic principles. The systems are grouped into two thematic sections based on their educational focus. The first section, *Mechatronic systems simulating real-world applications*, includes three prototypes that replicate practical engineering challenges: a robotic fire-fighting unit – Firebot, designed for active suppression; a cargo transport model that explores load stability on uneven terrain; and a gyro-stabilized mini-vessel that simulates marine navigation dynamics. These systems emphasize the application of mechatronics in solving real-world problems. The second section, *Applied mechatronics for conceptual exploration*, presents two prototypes designed to illustrate specific principles through interactive demonstration: the oncooscillator, which generates oscillating magnetic fields for potential biomedical applications, and an automated chessboard capable of autonomous gameplay, piece manipulation, and board state recognition. These systems serve as engaging platforms for conceptual learning and experimentation. Together, the five prototypes provide a comprehensive approach to mechatronics education, combining practical relevance with conceptual clarity, and fostering deeper understanding through experiential learning.

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2 Mechatronic systems simulating real-world applications

This section presents three educational prototypes that replicate real-world engineering challenges in safety, transport, and marine navigation. Each system demonstrates how mechatronic design can be applied to solve practical problems through integrated mechanical, electronic, and control components.

2.1 Firebot: robotic fire-fighting system

A compact and mobile fire-fighting robot has been developed for intervention in hazardous indoor and outdoor environments. Its primary function is water-based fire suppression, with water supplied via connection to a fire truck or external tank. Its compact dimensions enable operation in narrow and confined spaces, including stairways and steep terrain, where human access may be limited or unsafe. The robot is equipped with environmental sensors to measure gas concentrations and an infrared sensor to detect the hottest point in the area. A high-definition camera mounted on a rotating turret enables remote visual inspection and control via network connection. To ensure reliable mobility, a tracked chassis system was designed. The tracks allow the robot to climb stairs and traverse uneven ground. The chassis is constructed from hollow steel square tubes (30×30 mm, 5 mm thick) for structural strength, while PETG polymer joints, produced via 3D printing, are used in the prototype phase. Lightweight aluminium checker plates serve as protective covers. For simplified assembly and increased load capacity, standard wheels can be mounted on steel axles. Electric motors were chosen for propulsion due to their robustness and reliability in

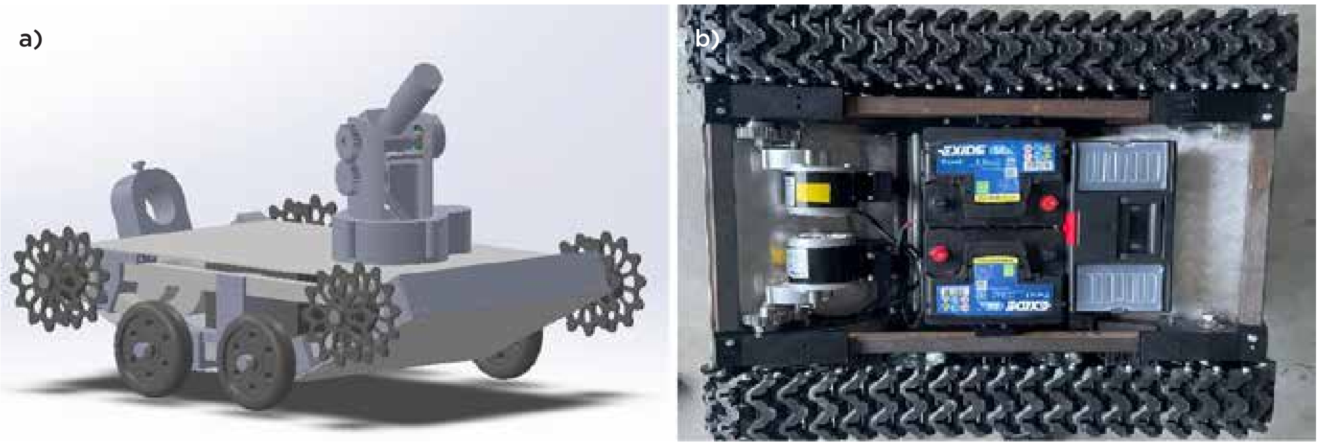

Figure 1 : *a) CAD model of Firebot, b) drive assembly with mounted components*

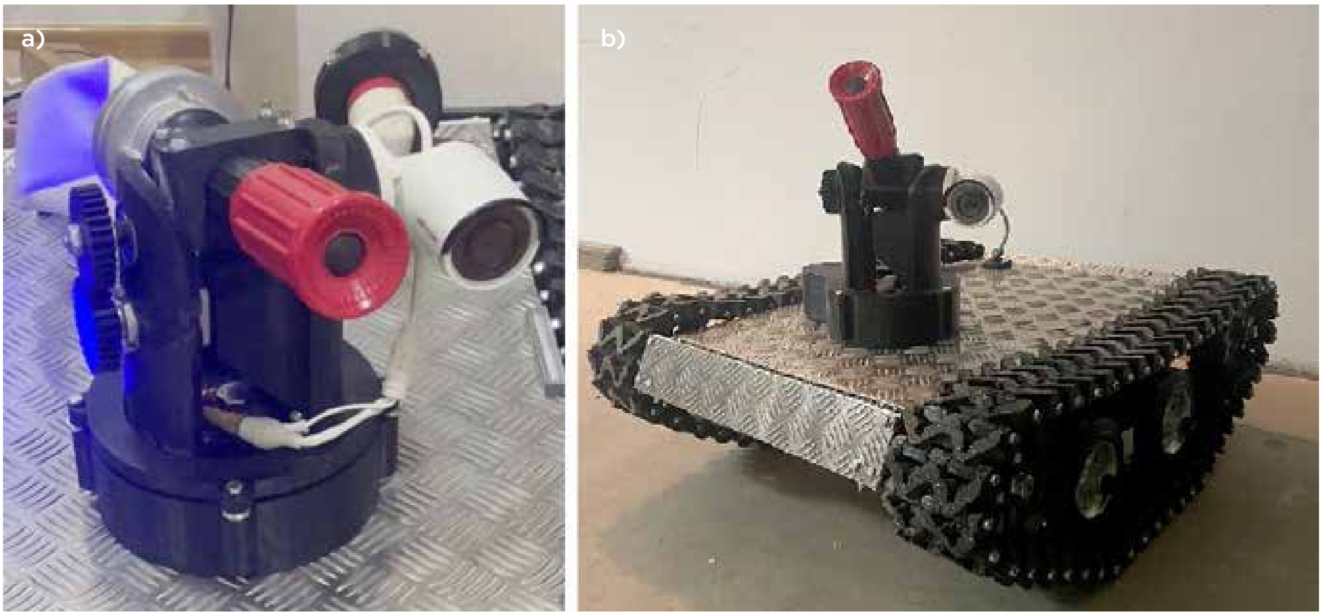

Figure 2 : *Mobile fire-fighting robot with mounted rotating turret*
Source: https://urn.nsk.hr/urn:nbn:hr:235:554997 [6]

oxygen-deficient environments. Each track is driven by a DC motor through a gear system, with shafts supported by press-fitted bearings. The drivetrain includes PETG-printed sprockets and track links, with future versions planned in metal for enhanced durability. Commercially available wheels and standardized steel axles were used to reduce production complexity. The fire-fighting turret mounted on top of the chassis provides two degrees of rotational freedom, controlled by two Nema 17 stepper motors. One motor controls horizontal rotation, while the other (equipped with a 32:1 planetary gearbox) controls vertical movement. The turret components are also 3D-printed. A high-definition camera is fixed on the turret for real-time feedback, connected via LAN and powered by a 12V supply. The control system is based on a Raspberry Pi 4 running Python scripts. Wireless communication over a local network ensures reliable remote operation. All electronic components including motor drivers (BTS7960 and TB6600), a DC-DC voltage regulator, and batteries are housed in a waterproof enclosure within the chassis (*Figure 1*).

The robot's low center of gravity, achieved by placing batteries at the base, contributes to its stability. Testing has shown that the created robot can climb standard-sized steps, pull heavy objects such as sandbags, and withstand mechanical stress.

The turret rotation and camera positioning improve hazard detection and casualty identification. The final prototype of the mobile fire-fighting robot is shown in *Figure 2*. Future enhancements may include integration of LIDAR, advanced gas sensors, and semi-autonomous navigation capabilities for operation in low-visibility conditions.

2.2 Cargo transport model: load stabilization on uneven terrain

A prototype transport vehicle was developed to simulate the challenges of carrying liquids or low-density materials over uneven or inclined surfaces. The system addresses common stability issues by implementing an active suspension mechanism that dynamically adjusts the chassis inclination in real time. The goal of this educational prototype is to demonstrate the advantages of electronically controlled suspension in reducing vehicle oscillations caused by surface irregularities. *Figure 3* shows the CAD model of the transport vehicle and the motorized conveyor belt used to simulate uneven terrain. The system incorporates two MPU6050 gyroscopic sensors positioned at the front and rear axles to measure angular displacement. Sensor data is processed by an Arduino Nano, which sends corrective signals to MG995 servo motors. These motors adjust the axle positions to counteract tilting and maintain stability. To simulate a realistic load, a plexiglass container holding 400 ml of water is mounted on the chassis. Road disturbances are emulated using a motorized conveyor belt with surface bumps, powered by a Nema 17 stepper motor with gear reduction. The belt is controlled via an Arduino Nano and A4988 driver, housed in a control unit with an LCD display. This setup enables controlled and repeatable testing of the suspension system's response. A dynamic model of the system was created in Simulink, incorporating road input and a sliding PID controller. The controller generates voltage outputs to stabilize the vehicle. Based on simulation results, mechanical components were designed in CAD and fabricated using FDM 3D printing with PETG filament. The chassis, axles, and joints were assembled using U-profiles, springs, and servos. A custom two-layer PCB, designed in Altium Designer, processes sensor signals and controls motor actuation.

Figure 4 shows the completed vehicle prototype equipped with the electronic stability control system. Testing was conducted under both static and dynamic conditions. In static tests, the vehicle remained stable over a 7 mm obstacle, even when loaded. During dynamic tests on the moving belt (0.04 m/s), angular data confirmed rapid sensor and servo response, keeping the chassis nearly ho-

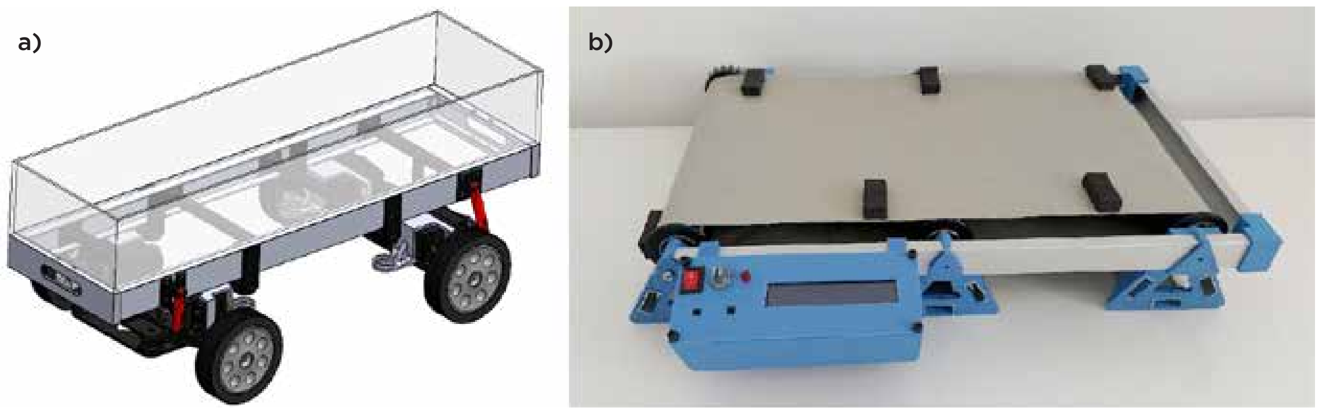

Figure 3 : *a) CAD model of Firebot, b) drive assembly with mounted components*

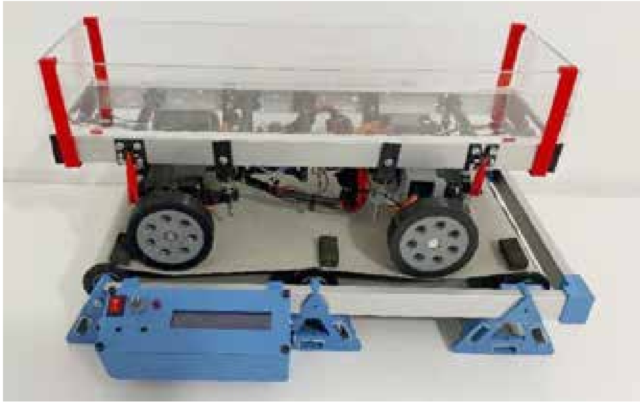

Figure 4 : Vehicle prototype equipped with electronic stability control system
Source: https://urn.nsk.hr/urn:nbn:hr:235:516852 [7]

rizontal. Full stabilization was achieved within a few seconds. The final prototype effectively demonstrates real-time tilt correction through active suspension and serves as a valuable educational tool for exploring electronic stability control in liquid transport systems.

2.3 Gyro-stabilized mini-vessel: simulating marine navigation stability

A scale model of a marine vessel equipped with a gyroscopic stabilization system was developed to reduce lateral rolling caused by wave action or side forces. In modern maritime engineering, improving vessel stability is essential for enhancing safety, comfort, and maneuverability. Among various stabilization methods, gyroscopic stabilizers are notable for their compact design, mechanical simplicity, and ability to generate stabilizing torque based on the conservation of angular momentum. The objective of this project was to demonstrate how gyroscopic stabilization can reduce the amplitude of roll angles and minimize the number of free oscillations within a ±2° range. The core component of the system is a high-speed spinning rotor, which when subjected to external torque exhibits precession and generates a stabilizing force perpendicular to the rolling motion.

The stabilization system integrates several key components:

- a rotor extracted from a lightweight RC aircraft motor,
- a NEMA 17 stepper motor to induce precession,
- a Dasduino CORE microcontroller for signal processing and control,
- a six-axis IMU sensor for estimating the vessel's roll angle.

The entire assembly was designed in SolidWorks, with the flywheel as the central element around which the system was compactly arranged. Figure 5 shows the CAD model of the gyroscopic stabilization system. The prototype was manufactured using a combination of turning, milling, and FDM 3D printing. Most parts were printed using PETG filament to allow geometric flexibility and ease of fabrication. After assembly, the system was tested in a controlled environment, i.e. in a water pool simulating calm sea conditions.

Validation of simulation results with experimental data was a key aspect of the project. Simulations were based on simplified equations of rolling motion, and experiments were designed to replicate these conditions by manually tilting the vessel and observing its free oscillation. *Figure 6* shows the mini-vessel during in-water testing. Real-time data acquisition was performed using Excel's Data Streamer function, with sensor signals collected on a laptop. MATLAB was used for post-processing and comparison of simulated and experimental results. Initial tests without stabilization confirmed that the simplified dynamic model accurately reflected real-world behavior. Subsequent tests with

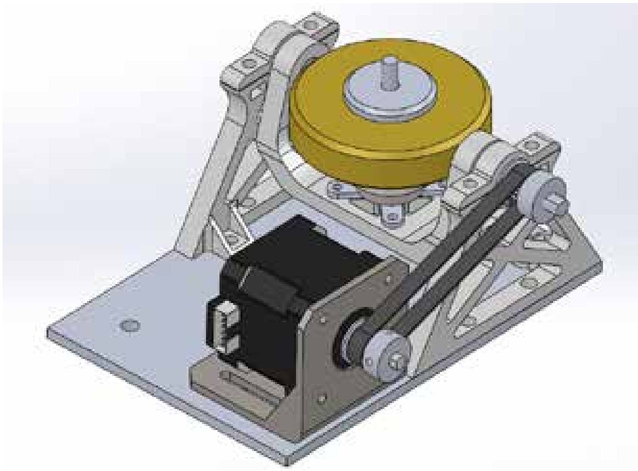

Figure 5 : CAD model of the gyroscopic stabilizer

Figure 6 : Mini-vessel model during water-based testing
Source: https://urn.nsk.hr/urn:nbn:hr:235:360882 [8]

the gyroscopic system (in passive mode, without active control) showed a significant reduction in oscillations. Starting from a 13° tilt, the unstabilized vessel required 11 oscillations to settle within ±2°, while the gyroscopic stabilizer reduced this to just 2 oscillations, which brings about an 80% improvement. Although active control could further enhance performance, the weight of the actuator system exceeded the mini-vessel's capacity, making full active testing impractical in this setup.

This project confirms the feasibility and effectiveness of gyroscopic stabilization in small marine vessels. Even without active control, the system significantly improved roll damping, validating both the simulation model and the physical design. Future work may focus on reducing system mass and integrating active control to further improve stabilization performance.

3 Applied mechatronics for conceptual exploration

This section presents educational prototypes designed to illustrate specific mechatronic principles through interactive and conceptual demonstration. Unlike systems that simulate real-world engineering applications, these prototypes focus on exploring advanced ideas in biomedical and intelligent systems, offering students insight into emerging technologies and their underlying mechanisms.

3.1 Oncooscillator: magnetic field generation for biomedical demonstration

The oncooscillator is an innovative biomedical device developed to explore non-invasive cancer treatment using oscillating magnetic fields (OMF). Recent research, particularly involving spinning oscillating magnetic fields (sOMF), suggests that such fields can selectively disrupt mitochondrial activity in tumor cells, leading to cell death while sparing healthy tissue [9]. This therapeutic approach targets the electron transport chain in mitochondria, increasing reactive oxygen species and causing energy failure in malignant cells.

The system consists of three oscillators that generate dynamic magnetic fields through the rapid rotation of strong permanent magnets. Each magnet is driven by a 24V brushed DC motor without gear transmission, providing high torque and suitable rotational speed. Motor control is handled by an Arduino Mega 2560 using PWM signals, with a DC-DC converter and integrated circuit driver (up to 1.5 A) ensuring stable voltage and current delivery. Mechanical components are made from industrial plastics and polymer-based materials selected for their thermal resistance, mechanical strength, and non-magnetic properties, which is essential for preventing interference with the magnetic fields. Ceramic bearings support the rotating magnets, offering low friction and thermal stability during extended operation. The magnets used are DX0X0-N52 type, known for their extremely high magnetic strength. Due to their powerful attractive force,

Figure 7 : CAD model and assembled OMF helmet

Figure 8 : *Application of OMF: a) wearable helmet, b) configuration for reclining patient*
Source: https://urn.nsk.hr/urn:nbn:hr:235:906046 [10]

careful handling and secure mounting are essential to prevent damage or injury. Their high magnetic induction and low mass make them suitable for OMF therapy applications. A key design feature of the oncooscillator is its use of inertial motion. After accelerating the magnets to the desired rotational frequency, motor power is reduced, and the system relies on the inertia of the rotating mass to maintain motion. This eliminates the need for mechanical braking and reduces energy consumption, improving overall efficiency. Speed monitoring is achieved using Hall-effect sensors, which detect changes in magnetic fields and provide feedback to the control system. This enables real-time adjustment of motor signals, ensuring synchronized operation of all three oscillators (*Figure 7*). Since all motors receive a common PWM signal, they operate at the same speed, assuming identical mechanical loads.

The device is made in two configurations: a wearable helmet and a version adapted for patients in a reclined position (*Figure 8*). Both devices are designed for localized treatment, and particularly for brain tumors such as glioblastoma. Preliminary findings from existing studies indicate that OMF exposure can selectively induce cell death in glioblastoma and lung cancer cells, while leaving healthy tissue unaffected. This selectivity is believed to be linked to the bioenergetic vulnerabilities of tumor mitochondria and the radical pair mechanism. With its non-invasive operation, low energy consumption, and precise control, the oncooscillator represents a promising direction in cancer therapy. Its potential applications may also extend to mental health and rehabilitation, where magnetic stimulation is already used in clinical practice.

3.2 Automated chessboard: autonomous gameplay and board recognition

The development of an automated chessboard capable of autonomous gameplay represents an interesting integration of embedded systems, mechanical design, and artificial intelligence. This system can detect player moves, calculate its own responses using a chess engine, and physically move pieces via an XY-axis magnetic actuator, which allows the board to function as a real, interactive chess opponent. The game begins from the standard initial position, with the human player always playing white to simplify programming logic. Move detection is achieved using 64 reed switches, one beneath each square. Each switch contains two ferromagnetic contacts sealed in an inert gas-filled tube. When a magnetic piece is placed near a square, the contacts close, signaling its presence. Since reed switches cannot distinguish piece color, the board scans all 64 squares twice per second to detect movement and captures. To overcome limitations in vertical magnetic alignment and reed switch geometry, the switches are offset from the center of each square. Four multiplexers are used to efficiently read all switches using limited input pins. A display connected via the I2C protocol provides user feedback, displays timers, and alerts players to illegal moves or game status. Upon startup, the board automatically calibrates using end-stop limit switches to locate the electromagnet's home position. The system is powered by an Arduino Nano and an ESP32 microcontroller, programmed via the Arduino IDE. The chess engine used is Micro-Max, a lightweight engine consisting of only 133 lines of C code, developed by *Harm Geert Muller*. It employs the *minimax algorithm* with *alpha-beta pruning technique* to optimize move generation, evaluating positions based on material balance, king safety, pawn structure, and move potential. A key innovation is the real-time move evaluation assistant. When a player lifts a piece, all legal destination squares light up using embedded multi-colored LEDs. The colors reflect the engine's evaluation of each move, helping players understand strategic consequences and learn as they play. *Figure 9* illustrates the electronic schematic connecting the reed switches, address multiplexers, stepper motor driver (TMC2208), and display to the Arduino.

Figure 10 shows the assembled automated chessboard, including the game board, drive mechanism, piece disposal zone, and visual feedback interface.

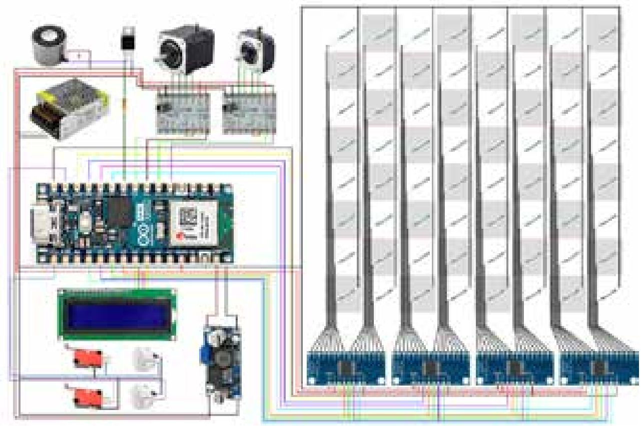

Figure 9 : *Electronic schematic connecting of chess board*

Figure 10 : *Automated chess board*
Source: https://urn.nsk.hr/urn:nbn:hr:235:563233 [11]

By combining tactile interaction, intelligent move generation, and online connectivity, this project revitalizes the traditional chess experience while simultaneously using modern technologies to enhance learning, engagement, and enjoyment.

4 Conclusion

This study has presented five mechatronic prototypes developed as educational platforms to support hands-on learning in engineering curricula. By integrating mechanical design, control systems, and sensor technologies, these systems effectively demonstrate key concepts in automation, dynamics, and embedded control. Grouped into two thematic sections: real-world application simulation and conceptual exploration, these prototypes show how theoretical knowledge in areas such as kinematics, feedback control, and programming can be translated into practical, interactive systems. Through the process of designing, building, and testing these devices, students engage directly with engineering challenges, fostering critical thinking, creativity, and problem-solving skills. These educational platforms not only enhance conceptual understanding but also encourage innovation and interdisciplinary collaboration. As widely recognized, laboratory-based learning remains essential in preparing future engineers for the complexity and integration required in modern mechatronic systems.

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Mehatronski prototipi za inženirsko izobraževanje: povezovanje teorije in prakse

Izvleček:
Članek predstavlja pet inovativnih mehatronskih prototipov, razvitih kot izobraževalna orodja za izboljšanje inženirskega izobraževanja s povezovanjem teoretičnih konceptov s praktično izvedbo. Sistemi so organizirani v dva tematska sklopa. Prvi sklop, Mehatronski sistemi, ki simulirajo aplikacije v resničnem svetu, vključuje tri prototipe, ki posnemajo resnične inženirske izzive: robotsko gasilsko enoto - Firebot, integrirano s tankerjem za vodo za aktivno gašenje požara; model tovornega prevoza, ki prikazuje stabilnost tovora na neravnem terenu; in žiroskopsko stabilizirano mini plovilo, zasnovano za zmanjšanje bočnega zibanja med pomorsko navigacijo. Drugi sklop, Uporabna mehatronika za konceptualno raziskovanje, predstavlja dva sistema, katerih cilj je ponazoriti specifična načela z interaktivno demonstracijo: onkoscilator, ki ustvarja nihajna magnetna polja z vrtečim se magnetom za potencialne biomedicinske aplikacije, in avtomatizirano šahovnico, ki je sposobna avtonomnega igranja, manipulacije s figurami in prepoznavanja stanja plošče. Ti prototipi skupaj služijo kot učinkovite platforme za izkustveno učenje, ki spodbujajo globlje razumevanje mehatronskih načel med študenti inženirstva.

Ključne besede:
mehatronika, laboratorijski prototipi, praktično učenje, sistemska integracija, izobraževalna robotika