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Advanced Mechatronic Systems Featuring Pneumatic Actuation

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This article presents eight innovative mechatronic systems powered by pneumatic actuators, designed as educational models for teaching pneumatic power systems and automatic control to mechanical engineering students. The first system introduced is a prototype of an autonomous vehicle that operates on compressed air and is driven by pneumatic artificial muscles. Next, four robotic systems are described, representing pneumatically actuated manipulators. These include a delta robot with a vacuum gripper, a robotic arm with a flexible gripper, a manipulator capable of avoiding obstacles on a conveyor belt, and a flexible pneumatic manipulator. The final section highlights three systems with potential industrial applications: a pneumatically powered screw mechanism, a system for automated bottle filling and capping, and an automated pneumatic machine designed to sort beans. All eight systems provide practical insights into the application of pneumatics in automation and serve as valuable tools for hands-on learning in mechatronics and control engineering.

Keywords:
mechatronics,
pneumatic actuators,
robotic manipulators,
educational models,
industrial automation

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1 Introduction

Mechatronics is rapidly evolving through the integration of mechanical engineering, electronics, computer science, and intelligent control systems. Modern mechatronic systems increasingly feature flexible and adaptive components, enabling precise and autonomous execution of complex tasks [1], [2]. Among various actuation technologies, pneumatic actuation stands out for its simplicity, cost-effectiveness, and high power-to-weight ratio, making it suitable for both industrial and educational applications [3], [4]. Recent trends in robotics highlight compliant and bio-inspired actuators, such as pneumatic artificial muscles (PAMs), which offer enhanced safety in human-robot interaction and greater capability compared to rigid actuators [5], [6]. The rise of Industry 4.0 has further encouraged the development of smart, interconnected automation systems where pneumatic devices are increasingly integrated with sensors and controllers for real-time monitoring and control [7]. At the same time, there is a growing demand in engineering education for hands-on, project-based learning tools. Pneumatically powered educational models provide students with an effective way to explore core concepts such as fluid dynamics, control algorithms, sensor integration, and system optimization in a touchable and interactive manner [8]. This article presents eight innovative mechatronic systems designed to demonstrate the practical implementation of pneumatic actuation in automation and robotics.

2 Compressed-air-driven autonomous vehicle using PAMs

Autonomous mobile vehicles represent a rapidly evolving interdisciplinary field, merging mechanical, electronic, and software engineering to meet the growing global demand for efficient, safe, and sustainable transportation. These vehicles operate without human intervention, relying on advanced sensor arrays, control algorithms, and artificial intelligence to navigate complex environments. Autonomy ranges from basic driver assistance to full self-governance, with applications in logistics, transport, domestic aid, and exploration of hazardous or remote environments like underwater or extraterrestrial terrains. Despite significant advances, challenges remain, including high system costs, limited navigation reliability in novel environments, integration complexity, vulnerability to sensor or algorithm failures, and substantial energy consumption due to advanced onboard technologies. In this project, a hybrid driving system combining electric and pneumatic sources to enhance energy efficiency was used. The system employs Festo block valves and pneumatic muscles powered by a electric compressor. Compressed air is stored in a 5-liter steel tank, with flow control according to actuators (Figure 1). Control is realized through a Controllino MAXI Power PLC (ATmega2560-based), powered by sealed lead battery (type Yuasa NP7-12, voltage 12 V, electric capacity 7 Ah) with integrated protection. Pressure sensors and a relay ensure safe compressor operation. This hybrid model offers a novel approach to propulsion systems for autonomous platforms with the integration of renewable energy sources.

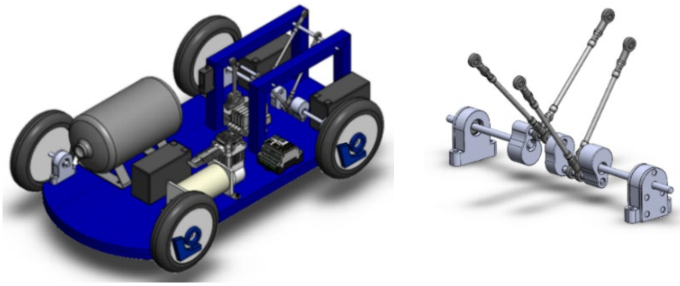

Figure 1: CAD model of the vehicle and V-configuration crankshaft.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9221 [9]

Figure 2: Autonomous vehicle actuated by PAMs.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9221 [9]

The mechanical subsystem was developed using a combination of 3D printing and traditional machining. Initial tests with a radial-drive setup (three pneumatic muscles at 120° around a crankshaft) showed limited motion due to insufficient contraction and geometric constraints. The final design adopts a V-shaped layout with four muscles (two per crank arm, turned 180°), achieving full crankshaft rotation through sequential activation. The frame is constructed from wood for ease of fabrication and reduced weight. The crankshaft includes flywheels, custom housings for bearings, and wheel rims (all 3D-printed) along with steel half-axles, M6 threaded rods, and standard solid tires secured with regular screws. The completed vehicle is shown in Figure 2.

3 Robotic manipulators with pneumatic drive

3.1 Delta robot with a vacuum gripper

This project presents the design and implementation of a delta robot prototype optimized for high-speed pick-and-place operations (Figure 3). Utilizing a parallel kinematic structure with three independently actuated arms connected to a common end-effector, the robot achieves low inertia and high responsiveness. The kinematic model includes analytical inverse kinematics and numerically solved forward kinematics. Matlab simulations are used to evaluate the workspace by iterating actuator angles. Dynamic modelling, based on virtual work principles and Jacobian matrices, estimates actuator torques for specific trajectories. The robot is built using aluminium profiles and steel plates, with stepper motors (Nema 17HS19) driving the joints via 1.76:1 belt transmission (Figure 4). Bearings support the shafts, and adjustable motor mounts ensure proper belt tension.

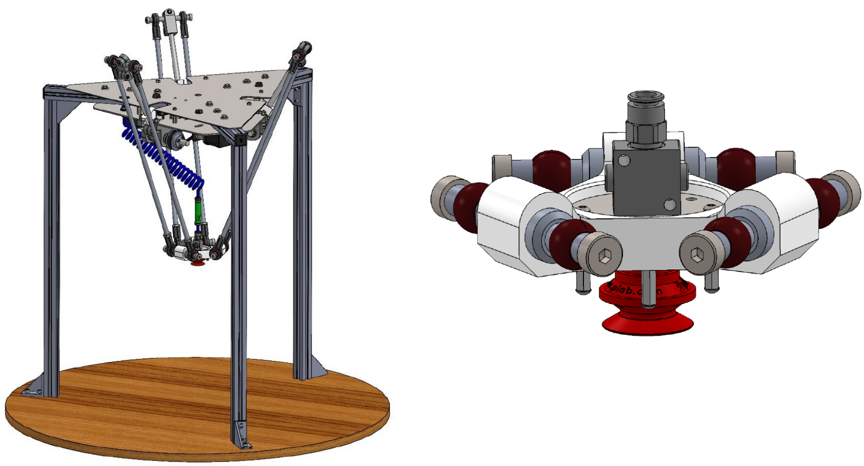

Figure 3: CAD model of the delta robot structure and robot gripper with vacuum ejector.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:11268 [10]

The ESP32 microcontroller, paired with DRV8825 drivers, controls motion, while limit switches handle homing. The system supports joint-space and Cartesian motion profiles. Motion commands are received via a serial interface, with real-time joint limit and collision monitoring. A 3/2 electro-pneumatic valve, manufactured by Camozzi, controls the vacuum ejector (PIAB piINLINE MICRO Ti). The gripper is secured with alignment pins. A Python-based GUI allows .txt-based program execution. Experimental tests under a 0.56 kg load confirmed repeatable performance, with torques remaining below 0.5 Nm and consistent vacuum grip across all trajectories.

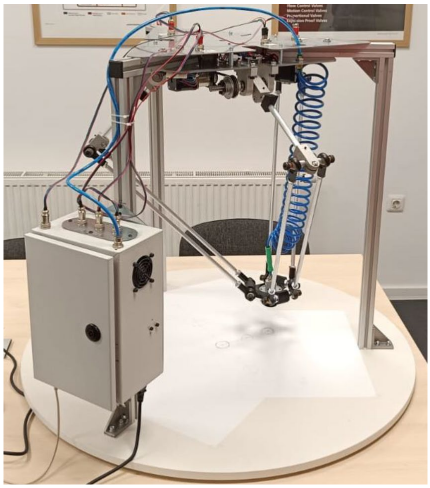

Figure 4: Assembled delta robot with frame, end-effector, and control interfaces.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:11268 [10]

3.2 Pneumatic robotic manipulator with flexible gripper

This section presents the development of a pneumatic robotic manipulator with three degrees of freedom and an adaptive soft gripper, intended for repetitive handling of irregularly shaped objects. The design combines the compliance of soft robotics with the reliability of pneumatic actuation. The manipulator uses an RTT (Rotational-Translational-Translational) configuration, consisting of one rotary and two linear actuators, Figure 5. The SMC MSQB10A rotary actuator provides up to 190° of rotation via a rack-and-pinion mechanism. Translational motion is achieved with two pneumatic cylinders: a SMC CQ2Z32 for horizontal movement and a SMC CXSM20 for vertical positioning, which also supports the weight of the gripper. The gripper operates on the granular jamming principle. A latex balloon filled with ground coffee adapts to the object's shape under compression. When a vacuum is applied inside the balloon, the particles lock together, forming a rigid structure that can securely grip the object. The vacuum is generated using a SMC ZH10B-06-06 ejector based on the Venturi effect, while a SMC ZCDUKC20-10D vacuum cylinder provides controlled actuation. To prevent contamination, a coffee filter is inserted inside the balloon. The gripper's housing, including the flange and funnel, is 3D printed for reduced weight and ease of integration. Power is supplied by a KSE 06024N AC/DC converter, delivering stabilized 24V DC to the control system. Each actuator is controlled via compact SMC VQD1121 solenoid valves in a 4/2 configuration, with flow control check valves used to regulate speed and ensure efficient airflow.

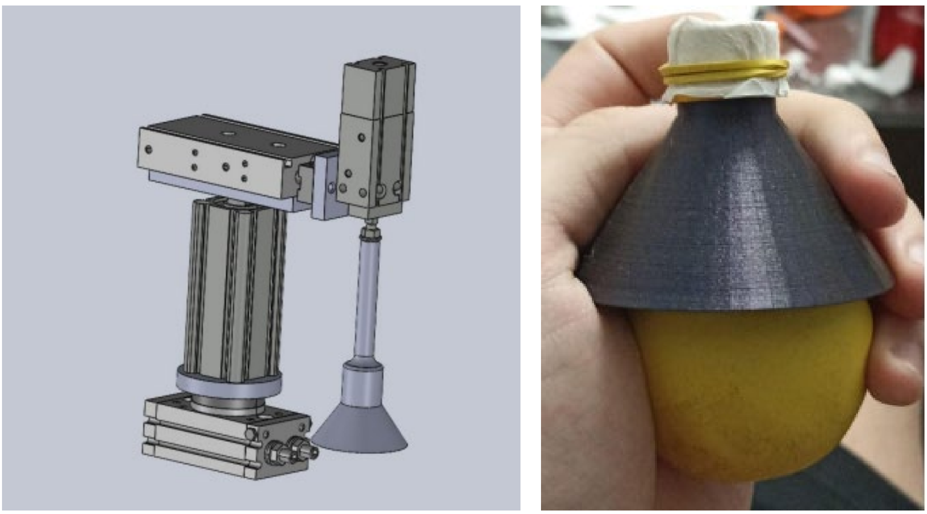

Figure 5: CAD model of the pneumatic robotic manipulator and the adaptive gripper.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9628 [11]

The system is controlled by a Controllino MINI PLC, programmed via the Arduino IDE. The PLC executes real-time logic for actuator sequencing and gripper control using digital I/O. The final prototype combines mechanical, pneumatic, and electronic elements into a compact, modular system suited for reliable manipulation and easy adaptation across applications (Figure 6).

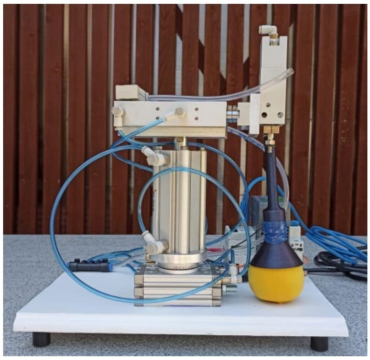

Figure 6: Final assembly of the manipulator with the flexible gripper.
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3.3 Pneumatic manipulator for obstacle avoidance on conveyor belt

This section presents an experimental system developed to demonstrate obstacle detection and real-time response using a pneumatic manipulator, Figure 7. Its main function is to detect user-placed obstacles on a conveyor belt and reposition a small cart using pneumatic actuation to avoid collisions. The system combines mechanical design, sensor input, and control logic, forming a compact prototype that can be used for simulations of automated obstacle avoidance on roads.

The system consists of two main components: a conveyor belt transport mechanism and a pneumatic manipulator. Objects are transported along the conveyor and detected by infrared (IR) sensors. When an obstacle is identified, the manipulator, powered by a dual-stroke pneumatic cylinder, repositions the cart to a predefined lane. The manipulator enables movement to three discrete positions (0 mm, 100 mm, and 200 mm), allowing dynamic path adjustment.

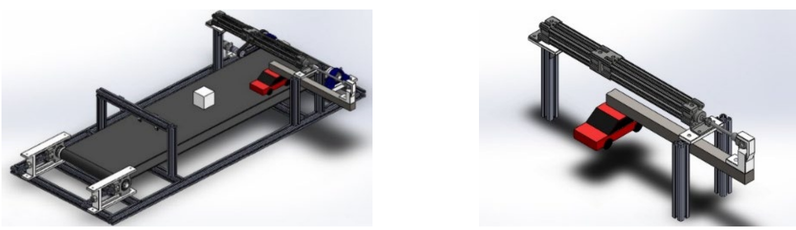

Figure 7: CAD model of the manipulator for obstacle avoidance.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9736 [12]

Mechanically, the structure is assembled using aluminum profiles. The conveyor is built from a PVC belt looped around two shafts, with custom 3D-printed parts ensuring alignment and tensioning. A DSMP320-12-0014-BF DC motor with an integrated planetary gearbox drives the system via a toothed belt and flexible coupling. The cart and actuator linkage are built from steel tubing and 3D-printed brackets, providing both strength and modularity.

The pneumatic system includes a SMC CP96SDL32-100C-XC11 dual-stroke actuator, controlled by two 5/2 solenoid valves (SMC SY3120), mounted on a valve manifold. A throttle check valve ensures smooth motion. Control is handled by a Controllino MINI PLC, which processes input from three HW-201 IR sensors. Each sensor includes an LM393 comparator and a range-adjustable potentiometer. When an object is detected, the PLC activates the appropriate valve combination to shift the cart. An electronic position sensor (D-M9BL) confirms actuator status. This prototype demonstrates a modular, sensor-driven system for automated object handling and path correction. Its structure is suitable for educational use or further expansion into more advanced sorting or robotic applications (Figure 8).

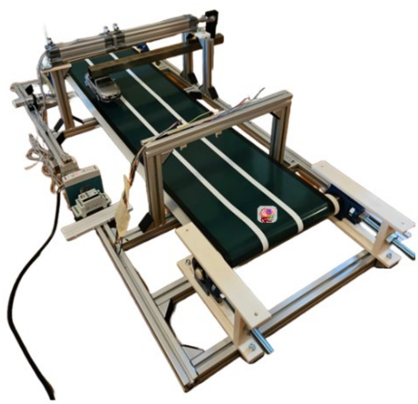

Figure 8: Pneumatic manipulator for obstacle avoidance on conveyor belt.
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3.4 Flexible pneumatic manipulator

This section presents the design and construction of a flexible pneumatic manipulator based on soft robotics principles, Figure 9. The system is composed of a control subsystem and an actuation subsystem, optimized for safe, adaptable, and energy-efficient object manipulation. Inflatable actuators enable compliant motion, while a vacuum-based gripper ensures secure object handling.

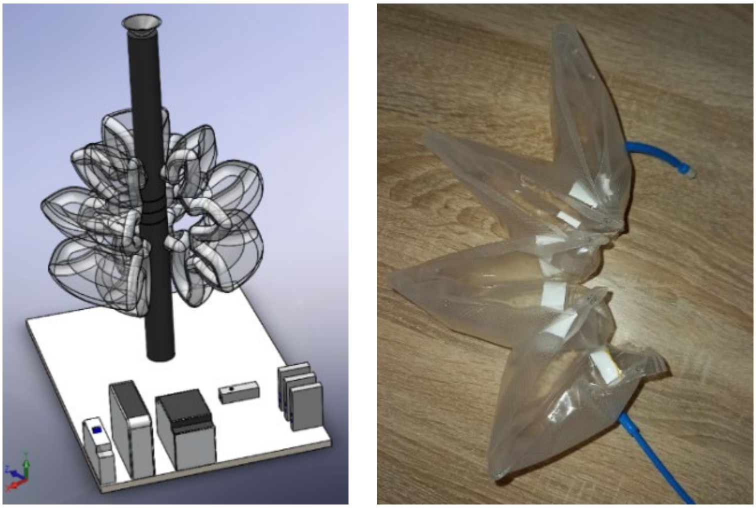

Figure 9: Conceptual design of the flexible pneumatic manipulator.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9163 [13]

The control subsystem regulates airflow using a Controllino MINI PLC, powered via a 24V DC converter protected by a single-pole safety breaker. The PLC communicates with a PC over USB and controls three Festo 3/2 solenoid valves. In their default state, the valves allow airflow to inflate the actuators. When the system is turned on, the valves send air to an ejector (SMC ZH10B-06-06), which generates a vacuum using the Venturi effect and turns on the vacuum gripper (SMC ZPT25DN-A6). The control logic minimizes power use by deactivating only one actuator at a time, while others stay inflated to provide support. Compressed air flows through a filter, safety valve, and gauge to dual-layer actuators with bellows-like folds. When inflated, they bend flexible polyethylene tubing reinforced with PVC, with radial cuts allowing directional motion. Maintaining vacuum continuity is essential during operation. The control algorithm ensures at least one actuator always remains active to avoid pressure loss and ensure the object stays gripped. The manipulator is mounted on a platform that integrates all major components: power supply, PLC, valves, actuators and vacuum gripper. This soft robotic manipulator showcases the potential of inflatable actuators for safe, adaptable, and low-power automation, Figure 10.

Figure 10: Flexible pneumatic manipulator.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9163 [13]

4 Automation systems with pneumatic drive for industrial tasks

4.1 Screw spindle mechanism with pneumatic drive

This section presents the design and operation of a pneumatic spindle mechanism based on a ball screw drive, intended for experimental linear positioning tasks (Figure 11). Unlike typical electric motor-driven systems, this setup uses a pneumatic vane motor, offering benefits such as a high power-to-weight ratio, resistance to overheating, and simple maintenance. The system is developed as a test platform to explore the potential of pneumatic control in precision mechatronic applications. The mechanical structure is built on an aluminum profile frame for stability and modularity. At its core is a 400 mm Tr8 trapezoidal leadscrew, supported at both ends by bearings.

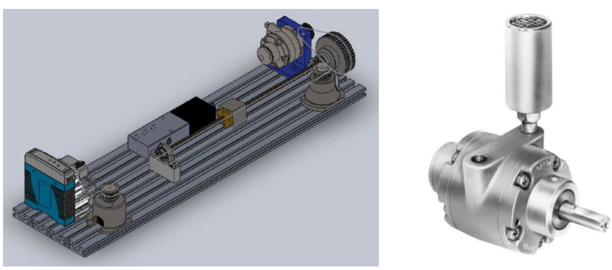

Figure 11: a) CAD model of the pneumatic spindle drive mechanism with ball screw, b) GAST pneumatic motor (model 1AM-NRV-63A).
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9627 [14]

Rotary motion is provided by a GAST 1AM-NRV-63A pneumatic vane motor, coupled to the spindle via a belt and pulley system with a gear reduction ratio greater than 1, improving torque output. The motor is reversible and compact, converting compressed air into continuous rotary motion through internal rotor vanes. Linear motion is achieved by the nut traveling along the spindle as the leadscrew rotates. For accurate feedback, a rotary encoder is linked to the nut using a secondary belt drive, enabling direct position measurement. Pneumatic motor is controlled by a Festo MPYE-5-1/8-HF-010-B proportional valve, which adjusts airflow to the motor. An additional on/off valve (SMC SY7420) ensures safe engagement and shutdown of the pneumatic circuit. The realized screw spindle mechanism with pneumatic drive is shown in Figure 12.

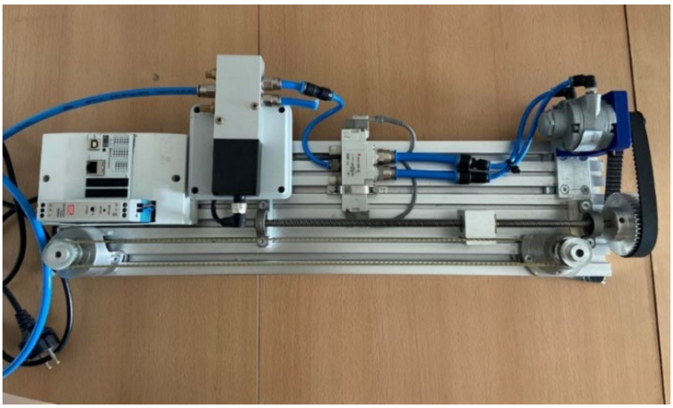

Figure 12: Screw spindle mechanism with pneumatic drive.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9627 [14]

The control system is implemented on a Controllino MAXI Automation PLC, which supports both analog output for valve control and digital input for encoder signal processing. The encoder outputs pulses corresponding to spindle nut displacement, with dual channels allowing direction detection. A PID control algorithm minimizes tracking error between the reference input and actual position, enabling real-time adjustments. Various motion profiles, including step, sinusoidal, and random inputs, were tested. The system demonstrated fast response, stable positioning, and reliable tracking performance, particularly for step and sinusoidal signals, confirming its suitability for educational and prototyping use in linear actuation and pneumatic control.

4.2 Automatic bottle filling and capping system

This section outlines the development of a compact automated system for bottle filling, closing, and capping, intended for small-scale production in pharmaceutical, food or chemical industries. The system minimizes operator involvement while ensuring consistent throughput. It consists of a conveyor with three stations: filling, closing, and capping. The conveyor features a continuous PVC belt driven by a DC motor and supported by a rigid aluminium frame (20×20 mm profiles) for mechanical stability. Bottles are manually loaded and automatically transported between stations (Figure 13).

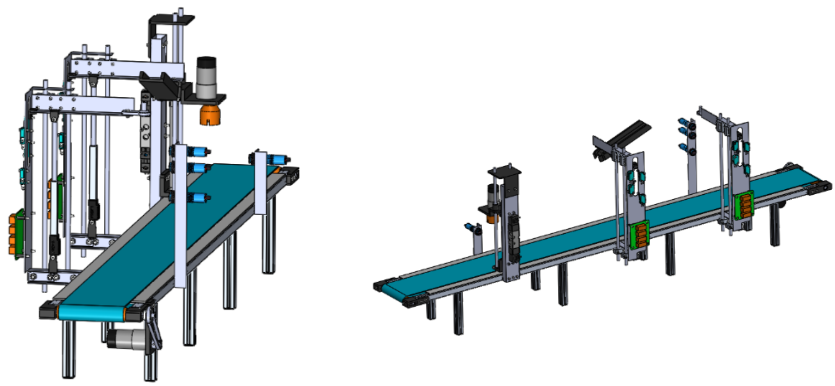

Figure 13: CAD model of the conveyor system transporting bottles.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:11155 [15]

Filling and closing operations are executed by lead screw-driven linear actuators with limit switches, ensuring precise, repeatable motion. The capping station utilizes a pneumatic cylinder mounted vertically, controlled by a 5/2 solenoid valve and regulated via a throttle check valve to prevent impact forces. The system is controlled by a Controllino MAXI PLC, which receives input from PE18 photoelectric sensors detecting bottle presence and height. Based on sensor feedback, the PLC selects one of three actuator positions (low, medium, high), activating relays accordingly. Dual power supplies (12 V and 24 V) manage transport and valve operation. The complete experimental system illustrating actuator integration and capping mechanism is presented in Figure 14.

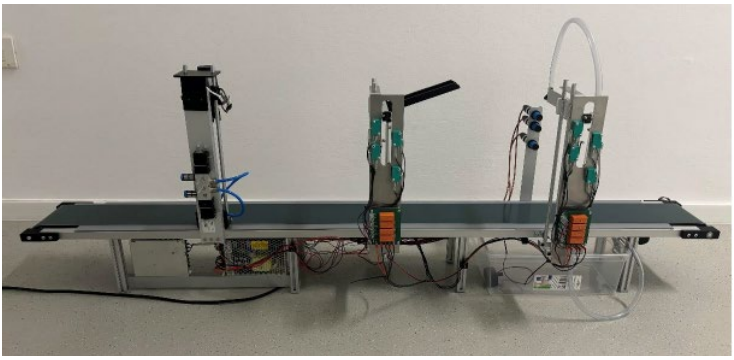

Figure 14: Final assembled automatic bottle filling and capping system.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:11155 [15]

4.3 Automated pneumatic machine designed to sort beans

This section presents an automated pneumatic system for sorting and removing defective bean grains to ensure consistent product quality. The system integrates mechanical, electronic, and software components for precise classification and reliable grain ejection. At its core is a transport mechanism, developed through iterative 3D modelling, featuring 3D-printed PLA rollers driven by a DC motor and stabilized by a threaded rod, bearings, and a tensioning system (Figure 15).

Figure 15: CAD model of the sorting system and examples of defective bean grains.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:10352 [16]

A wooden hopper holds up to 14 kg of beans and shields the detection chamber from ambient light. A dosing unit with four cylindrical channels, driven by a Nema 17 stepper motor, dispenses beans in pulses, forming four aligned rows on the conveyor for inspection. An ultrasonic sensor monitors grain levels to ensure continuous flow. The sensing system includes an infrared sensor, incremental encoder (KY-040), and an Arducam CMOS AR0134 camera with a global shutter and 12-bit raw output for high-resolution imaging. Conveyor speed is managed via a toothed belt with a 2:1 reduction. System logic is controlled by a Controllino Maxi PLC programmed via Arduino IDE. Faulty grains are identified through image processing and ejected using a high-speed Matrix pneumatic valve. This modular prototype offers an efficient and adaptable solution for automated agricultural sorting (Figure 16).

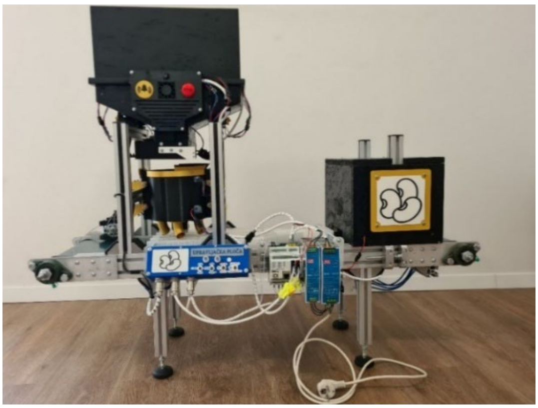

Figure 16: Final fabricated prototype of the bean grain sorting machine.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:10352 [16]

5 Conclusion

This article presented eight pneumatic mechatronic systems developed as educational platforms to enhance hands-on learning in mechanical engineering. By combining mechanical design, control systems, and pneumatic technologies, the models effectively demonstrate core principles of automation, fluid dynamics, and sensor-based control. Spanning from bio-inspired robots to industrial automation prototypes, they highlight the versatility of pneumatic actuation in both teaching and real-world applications. These systems bridge theoretical knowledge and practical skills, aligning with trends in project-based learning and Industry 4.0. Overall, the work underscores the value of pneumatic systems in modern engineering education and their potential for broader industrial use.

Acknowledgments

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