Application-Oriented Mechatronic Systems with Pneumatic Actuation

Željko Šitum, Filip Čavić, Vid Pavlović, Lovro Zoričić, Ante Ivanković, Bernarda Galić, Antonio Varović

Abstract:
This paper introduces six novel mechatronic systems driven by pneumatic actuators, developed as instructional models aimed at enhancing the education of mechanical engineering students in pneumatic power systems and automatic control. The initial system presented is an autonomous vehicle prototype powered entirely by compressed air, utilizing pneumatic artificial muscles for propulsion. Subsequently, the article presents three robotic manipulators actuated pneumatically: a delta robot equipped with a vacuum gripper, a robotic arm with a flexible gripper, and a conveyor-based manipulator capable of obstacle avoidance. The final section focuses on two systems with potential industrial applications: a pneumatic screw drive mechanism and an automated pneumatic sorting machine designed for bean classification. Together, these six systems offer practical demonstrations of pneumatic technology in automation, providing effective hands-on learning platforms for mechatronics and control engineering education.

Keywords:
mechatronics, pneumatic actuators, robotic educational manipulators, automatic control, industrial automation

1 Introduction

Mechatronics is experiencing rapid advancement through the integration of mechanical engineering, electronics, computer science, and intelligent control systems. Contemporary mechatronic designs increasingly incorporate flexible and adaptive elements that facilitate the precise and autonomous execution of complex operations [1]. Among various actuation methods, pneumatic actuation is notable for its simplicity, cost efficiency, and superior power-to-weight ratio, making it suitable for both industrial implementations and educational purposes [2]. Current developments in robotics emphasize compliant, bio-inspired actuators such as pneumatic artificial muscles (PAMs), which enhance safety in human-robot collaboration and offer improved performance relative to traditional rigid actuators [3]. The emergence of Industry 4.0 has accelerated the integration of smart, networked automation systems, where pneumatic components are often combined with sensors and controllers to enable real-time monitoring and adaptive control [4]. At the same time, engineering education increasingly demands hands-on, project-based learning approaches. Pneumatically driven educational platforms allow students to engage practically with fundamental topics including fluid dynamics, control strategies, sensor fusion, and system optimization in an interactive and tangible manner [5]. This article presents six novel mechatronic systems developed to illustrate the effective application of pneumatic actuation within automation and robotic contexts.

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2 Compressed-air-driven autonomous vehicle using PAMs

Autonomous mobile vehicles represent a rapidly advancing interdisciplinary field, integrating mechanical, electronic, and software engineering disciplines to address the increasing global demand for efficient, safe, and sustainable transportation solutions. These vehicles operate without human intervention, utilizing sophisticated sensor arrays, advanced control algorithms, and artificial intelligence to navigate complex and dynamic environments. The spectrum of autonomy ranges from ba-

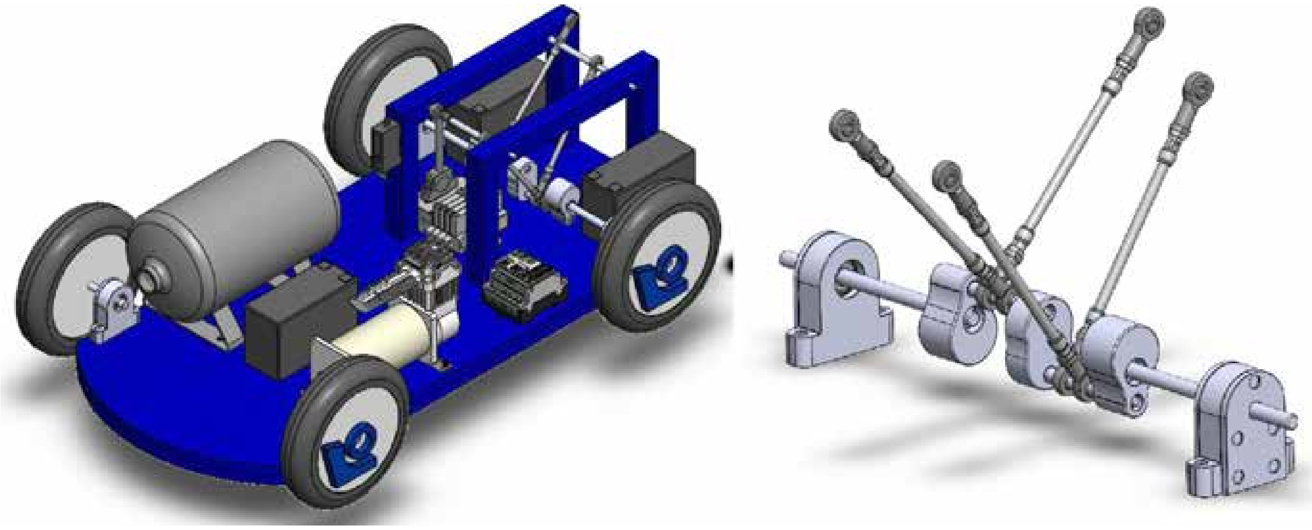

Figure 1 : *CAD model of the vehicle and V-configuration crankshaft*

sic driver assistance systems to full self-governance, with applications spanning logistics, passenger transport, domestic support, and the exploration of hazardous or remote areas such as underwater or extraterrestrial environments. Despite notable progress, several challenges persist, including high system costs, limited reliability of navigation in unfamiliar surroundings, complexity of system integration, susceptibility to sensor or algorithmic failures, and significant energy consumption associated with advanced onboard technologies. In this project, a hybrid propulsion system integrating both electric and pneumatic power sources was developed to improve overall energy efficiency. The system incorporates Festo block valves and pneumatic artificial muscles actuated by an electric compressor. Compressed air is stored within a 5-liter steel tank, with flow regulated according to actuator demands (*Figure 1*). Control functions are implemented using a Controllino MAXI Power PLC, based on the ATmega2560 microcontroller, powered by a sealed lead-acid battery (Yuasa NP7-12, 12 V, 7 Ah capacity) equipped with integrated protection circuitry. Pressure sensors and a relay ensure safe operation of the compressor. This hybrid configuration presents an innovative approach to propulsion systems for autonomous platforms, with the integration of renewable energy sources.

The mechanical subsystem was fabricated through a combination of 3D printing and conventional machining techniques. Preliminary testing employed a radial-drive configuration consisting of three pneumatic muscles arranged at 120° intervals around a crankshaft, which demonstrated limited motion due to insufficient contraction length and geometric constraints. The final design adopts a V-shaped arrangement featuring four pneumatic muscles (two per crank arm, oriented 180° apart), enabling complete crankshaft rotation via sequential muscle activation. The frame was constructed from wood to simplify manufacturing and reduce overall weight.

Figure 2 : *Autonomous vehicle actuated by PAMs*
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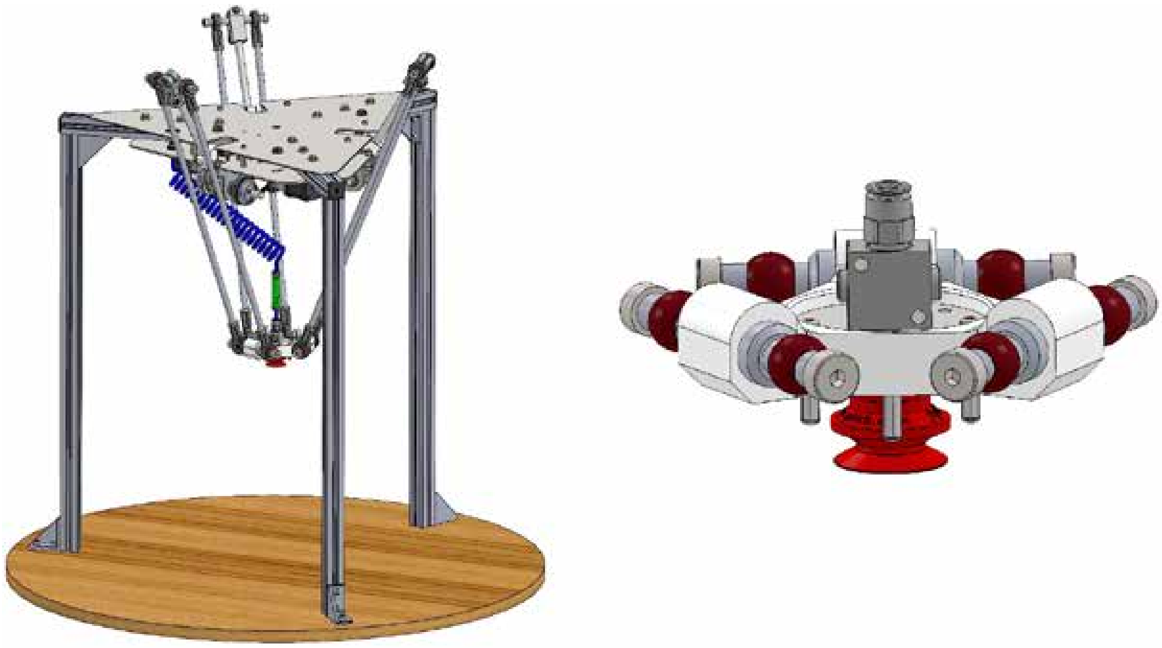

Figure 3 : CAD model of the delta robot structure and robot gripper with vacuum ejector

The crankshaft assembly includes flywheels, custom-designed 3D-printed bearing housings, and wheel rims, complemented by steel half-axles, M6 threaded rods, and standard solid tires secured with conventional screws. The fully assembled vehicle is depicted in *Figure 2*.

3 Robotic manipulators with pneumatic drive

3.1 Delta robot with a vacuum gripper

This project presents the design and realization of a delta robot prototype optimized for high-speed pick-and-place tasks (*Figure 3*). The robot employs a parallel kinematic architecture comprising three independently actuated arms connected to a shared end-effector, enabling low inertia and rapid responsiveness. The kinematic model incorporates analytical inverse kinematics and numerically computed forward kinematics. Workspace evaluation is performed through Matlab simulations by iterating over actuator angles. Dynamic modeling, 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. 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.

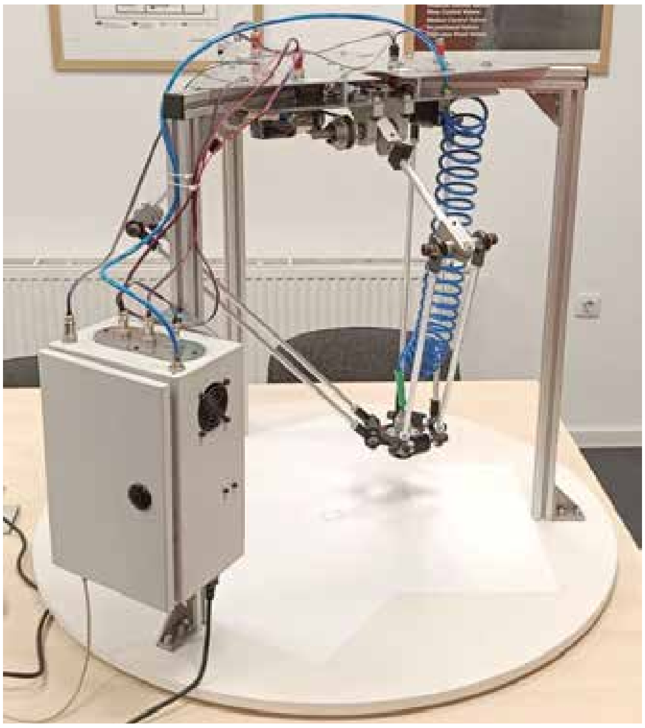

Figure 4 : Assembled delta robot with frame, end-effector, and control interfaces
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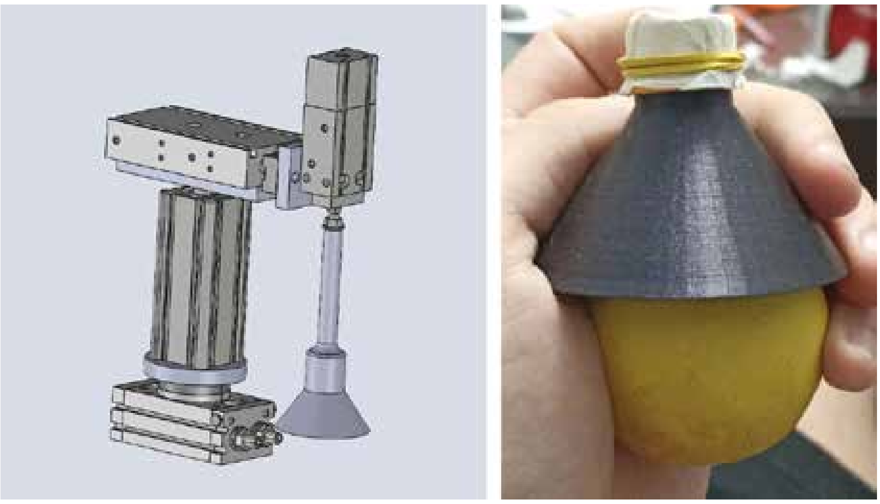

Figure 5 : CAD model of the pneumatic robotic manipulator and the adaptive gripper

3.2 Pneumatic robotic manipulator with flexible gripper

This section describes the development of a pneumatic robotic manipulator featuring three degrees of freedom and an adaptive soft gripper, designed for repetitive handling of irregularly shaped objects. The design integrates the compliance characteristic of soft robotics with the robustness of pneumatic actuation. The manipulator adopts an RTT (Rotational-Translational-Translational) configuration, comprising one rotary and two linear actuators (*Figure 5*). Rotational movement is provided by the SMC MSQB10A actuator, offering up to 190° of rotation via a rack-and-pinion mechanism. Translational motions are achieved through two pneumatic cylinders: the SMC CQ2Z32 for horizontal displacement and the SMC CXSM20 for vertical positioning, the latter also supporting the gripper's weight. The gripper functions on the granular jamming principle, utilizing a latex balloon filled with ground coffee that conforms to the object's shape under compression. Upon applying a vacuum inside the balloon, the particles lock together, creating a rigid structure capable of securely grasping the object. The vacuum is generated by an SMC ZH10B-06-06 ejector utilizing the Venturi effect, with actuation control provided by an SMC ZCDUKC20-10D vacuum cylinder. To prevent contamination, a coffee filter is placed inside the balloon. The gripper housing, including the flange and funnel, is 3D printed to reduce weight and facilitate integration. Power is supplied via a KSE 06024N AC/DC converter, delivering stabilized 24 V DC to the control system. Each actuator is controlled by compact SMC VQD1121 solenoid valves arranged in a 4/2 configuration, with flow control check valves employed to regulate actuator speed and optimize airflow efficiency.

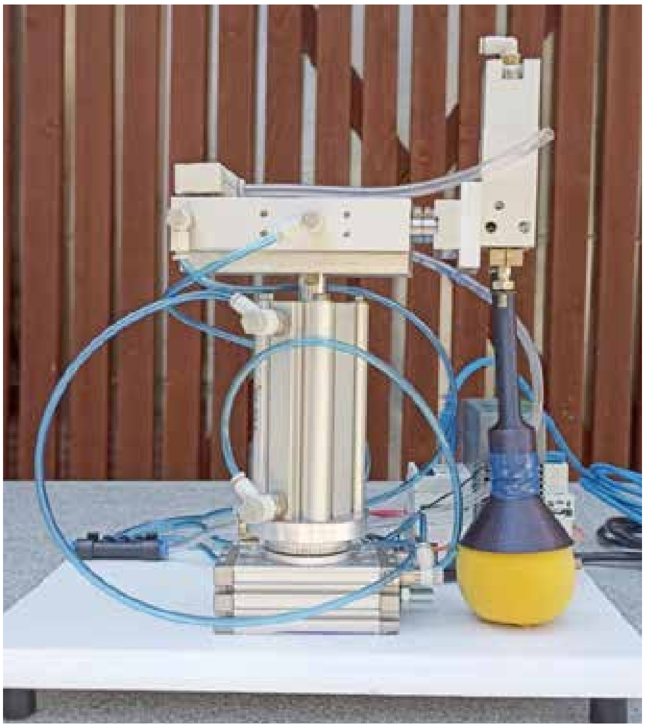

Figure 6 : Final assembly of the manipulator with the flexible gripper
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The system is controlled by a Controllino MINI PLC, programmed via the Arduino IDE. The PLC executes real-time logic for actuator sequencing and gripper control using digital I/O. The resulting prototype combines mechanical, pneumatic, and electronic elements into a compact, modular system suited for reliable manipulation and ease of adaptation for various applications (*Figure 6*).

3.3 Pneumatic manipulator for obstacle avoidance on conveyor belt

This section presents an experimental system designed to demonstrate obstacle detection and real-time response using a pneumatic manipulator (*Figure 7*). The primary function of the system is

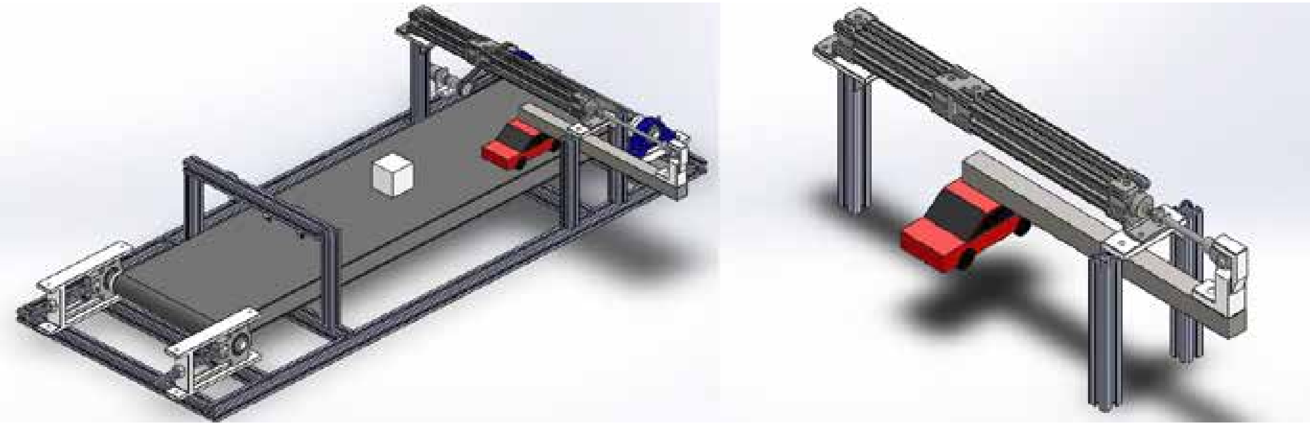

Figure 7 : *CAD model of the manipulator for obstacle avoidance*

to detect obstacles placed by a user on a conveyor belt and reposition a small cart via pneumatic actuation to prevent collisions. By integrating mechanical design, sensor input, and control logic, the system forms a compact prototype suitable for simulating automated obstacle avoidance scenarios, such as those encountered in road transport systems. The system consists of two main components: a conveyor belt transport mechanism and a pneumatic manipulator. Objects are conveyed along the belt 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.

Structurally, the system is built using aluminum profiles for ease of assembly and modularity. The conveyor consists of a PVC belt looped around two shafts, with custom 3D-printed components ensuring alignment and tensioning. The transport mechanism is powered by a DSMP320-12-0014-BF DC motor equipped with an integrated planetary gearbox, connected to the conveyor via a toothed belt and flexible coupling. The cart and actuator linkage are constructed from steel tubing and 3D-printed brackets, combining structural integrity with design flexibility.

Figure 8 : *Pneumatic manipulator for obstacle avoidance on conveyor belt*
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:9736 [9]

The pneumatic system includes a SMC CP96S-DL32-100C-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. The control logic is implemented using a Controllino MINI PLC, which processes input from three HW-201 IR sensors. Each sensor is equipped with an LM393 voltage 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 (SMC D-M9BL) confirms actuator status to ensure reliable execution. This prototype demonstrates a modular, sensor-driven system for automated object handling and path correction. Due to its compact design and educational value, it is well-suited for instructional purposes or as a foundation for further development into more advanced sorting or robotic automation applications (*Figure 8*).

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, developed for experimental linear positioning tasks (*Figure 9*). In contrast to con-

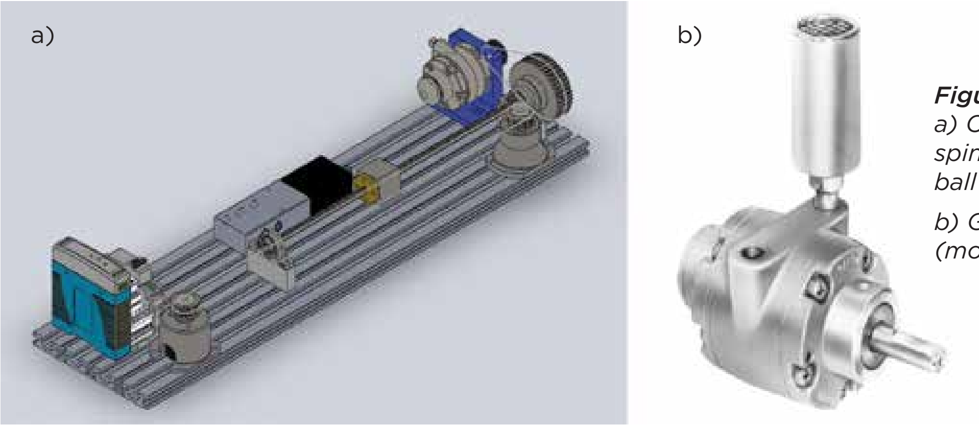

Figure 9 :
a) CAD model of the pneumatic spindle drive mechanism with ball screw,

b) GAST pneumatic motor (model 1AM-NRV-63A)

ventional systems driven by electric motors, this configuration employs a pneumatic vane motor, offering advantages such as a high power-to-weight ratio, thermal robustness, and simplified maintenance. The system serves as a test platform for investigating the potential of pneumatic control in precision mechatronic applications. The mechanical structure is built on an aluminum profile frame, ensuring both stability and modularity. At its core is a 400 mm Tr8 trapezoidal leadscrew, supported at both ends by bearings.

Rotary motion is generated by a GAST 1AM-NRV-63A pneumatic vane motor, coupled to the spindle via a belt and pulley transmission with a gear reduction ratio greater than 1, thereby enhancing torque output. The motor is compact and reversible, converting compressed air into continuous rotary motion through internal rotor vanes. Linear motion is produced by the translation of the nut along the leadscrew as it rotates. To provide accurate position feedback, a rotary encoder is connected to the spindle nut via a secondary belt drive, enabling direct measurement of linear displacement. The pneumatic motor is controlled by a Festo MPYE-5-1/8-HF-010-B proportional valve,

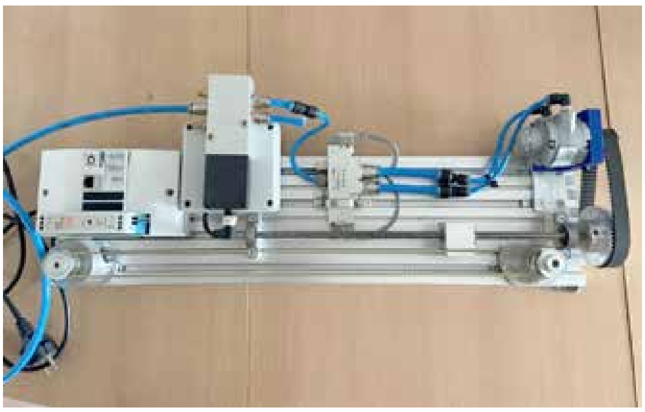

Figure 10 : *Screw spindle mechanism with pneumatic drive*
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which modulates airflow based on control input. An additional on/off valve (SMC SY7420) ensures safe engagement and shutdown of the pneumatic circuit. The complete pneumatic screw spindle mechanism is illustrated in *Figure 10*.

The control system is implemented on a Controllino MAXI Automation PLC, which supports both analog output for valve control and digital inputs for processing encoder signals. The encoder provides pulse signals proportional to spindle nut displacement, with dual output channels enabling 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 under step and sinusoidal excitation, confirming its suitability for educational use and prototyping in the field of linear actuation and pneumatic control.

4.2 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 to enable precise classification and reliable ejection of non-compliant grains. At the core of the system is a transport mechanism developed through iterative 3D modeling, featuring 3D-printed PLA rollers driven by a DC motor. The rollers are stabilized using a threaded rod, bearings, and a belt-based tensioning system (*Figure 11*).

A wooden hopper, with a capacity of up to 14 kg of beans, also serves to shield the optical inspection chamber from ambient light interference. 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 in-

Figure 11 : *CAD model of the sorting system and examples of defective bean grains*

Figure 12 : *Final fabricated prototype of the bean grain sorting machine*
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spection. An ultrasonic sensor monitors grain levels to ensure continuous flow.

The sensing subsystem consists of an infrared sensor, an incremental rotary encoder (KY-040), and an Arducam CMOS AR0134 camera equipped with a global shutter and 12-bit raw output, enabling high-resolution imaging suitable for real-time defect detection.

Conveyor motion is transmitted via a toothed belt with a 2:1 reduction ratio to optimize speed and control. System logic is controlled by a Controllino Maxi PLC programmed via Arduino IDE. Faulty grains identified through image processing are removed by a high-speed Matrix pneumatic valve, ensuring precise and timely ejection. This modular prototype provides an efficient and adaptable platform for automated agricultural product sorting, demonstrating a practical application of pneumatic actuation and embedded vision systems in quality control (*Figure 12*).

5 Conclusion

This study has presented six pneumatically actuated mechatronic systems developed as educational platforms to enhance hands-on learning in mechanical engineering curricula. Through the integration of mechanical design, control systems, and pneumatic technologies, these prototypes effectively illustrate fundamental concepts in automation, fluid dynamics, and sensor-based control. Ranging from bio-inspired mobile robots to industrial automation models, the systems showcase the adaptability and effectiveness of pneumatic actuation across diverse applications. By bridging theoretical instruction with practical implementation, the work aligns with contemporary pedagogical approaches such as project-based learning and supports the competencies required by Industry 4.0. Overall, the work underscores the value of pneumatic systems in modern engineering education and highlight their potential for scalable application in real-world industrial environments.

Sources

[1] Lee, J., Bagheri, B., & Kao, H. A. (2024). The Integration of Advanced Mechatronic Systems into Industry 4.0 for Smart Manufacturing. Sustainability, 16(19), 8504. https://doi.org/10.3390/su16198504.

[2] Zhao, S., Nguyen, C. C., Hoang, T. T., Do, T. N., & Phan, H.-P. (2023). Transparent pneumatic tactile sensors for soft biomedical robotics. Sensors, 23(12), 5671. https://doi.org/10.3390/s23125671.

[3] Kalita, G. R., Faruque, R. K., Saha, S., & Ghosh, S. K. (2023). A Review on the Development of Pneumatic Artificial Muscle Actuators: Force Model and Application. Actuators, 11(10), 288. https://doi.org/10.3390/act11100288.

[4] Even, S., Zheng, T., Lin, H., & Ozkan-Aydin, Y. (2023). Stable real-time feedback control of

a pneumatic soft robot. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). https://doi.org/10.1109/IROS55552.2023.10342212.

[5] Durocher, A., & Morin, P. (2019). Project-based learning in mechatronics education using low-cost pneumatic systems. Int. Journal of Mechanical Engineering Education, 47(2), 126–140.

[6] Čavić, F. (2023). Mobile vehicle with pneumatic muscle engine. Undergraduate thesis (in Croatian), University of Zagreb, Fac. of Mech. Eng. and Naval Arch.

[7] Pavlović, V. (2024). Design and manufacturing of delta robot with a vacuum gripper. Master's thesis, (in Croatian), University of Zagreb, Fac. of Mech. Eng. and Naval Arch.

[8] Zoričić, L. (2023). Pneumatic robotic manipulator with flexible gripper. Undergraduate thesis (in Croatian), University of Zagreb, Fac. of Mech. Eng. and Naval Arch.

[9] Ivanković, A. (2023). Pneumatic manipulator for obstacle avoidance on conveyor belt. Undergrad. thesis (in Croatian), University of Zagreb, Fac. of Mech. Eng. and Naval Arch.

[10] Galić, B. (2023). Screw spindle with pneumatic drive. Undergraduate thesis (in Croatian), University of Zagreb, Fac. of Mech. Eng. and Naval Arch.

[11] Varović, A. (2024). Machine for separating bad beans. Undergraduate thesis (in Croatian), University of Zagreb, Fac. of Mech. Eng. and Naval Arch.

Uporabniško usmerjeni mehatronski sistemi s pnevmatičnimi aktuatorji

Povzetek:
Članek predstavlja šest novih mehatronskih sistemov, ki jih poganjajo pnevmatski aktuatorji, razvitih kot učni modeli, namenjeni izboljšanju izobraževanja študentov strojništva na področju pnevmatskih energetskih sistemov in avtomatskega krmiljenja. Začetni predstavljeni sistem je prototip avtonomnega vozila, ki ga v celoti poganja stisnjen zrak in za pogon uporablja pnevmatske umetne mišice. Nato članek predstavlja tri pnevmatsko krmiljene robotske manipulatorje: delta robota, opremljenega z vakuumskim prijemalom, robotsko roko s fleksibilnim prijemalom in manipulator na osnovi tekočega traku, ki se lahko izogiba oviram. Zadnji del se osredotoča na dva sistema s potencialno industrijsko uporabo: pnevmatski vijačni pogonski mehanizem in avtomatiziran pnevmatski sortirni stroj, zasnovan za razvrščanje zrn. Teh šest sistemov skupaj ponuja praktične demonstracije pnevmatske tehnologije v avtomatizaciji in zagotavlja učinkovite praktične učne platforme za izobraževanje na področju mehatronike in krmilnega inženirstva.

Ključne besede:
mehatronika, pnevmatski aktuatorji, robotski izobraževalni manipulatorji, avtomatsko krmiljenje, industrijska avtomatizacija