INNOVATIVE MECHATRONIC SYSTEMS WITH ADVANCED CONTROL METHODS

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This article presents four handmade laboratory systems with pneumatic and electric drive which have been designed as educational test models in the field of mechatronic control systems The article first presents a system of pneumatically powered wheelchair, which could lift patients into a horizontal lying position up to the height of the hospital bed, which enables a simple procedure for transferring the patient to the bed. Then, an automated system for mixing liquids in a defined ratio, where the construction solution, component selection, manufacturing and control program are presented. The article then describes the design, construction, and control of a pneumatically driven system for sorting objects according to their colour. The final section of the article describes the design and manufacture of a mobile robot with a pneumatic drive that can move on vertical surfaces. Climbing is achieved using vacuum grippers, and the surfaces on which the robot can move is limited to smooth ones.

Keywords:
pneumatically powered wheelchair,
automated beverage mixing system,
sorting objects by colour,
wall climbing robot,
mechatronic control systems

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1 Intruduction

The development of modern fluid power systems is moving towards greater inclusion of microprocessors, sensors, and communication components in the final product solutions. Mechatronic engineering, which includes mechanical, electrical and information technologies, the direction of modernization of traditional disciplines such as hydraulic and pneumatic systems and enables their digital transformation and new areas of application [1]. The rapid technological progress of digital technologies, concepts such as the Internet of Things, visual systems, 5G network or artificial intelligence are becoming the subject of scientific research and practical applications in various fields, including the area of fluid power systems [2]. The question arises whether "traditional" techniques such as pneumatic and hydraulic systems can survive in the future digital era and retain their current wide applicability, in terms of the radical demands of digital technologies and energy efficiency? Therefore, the realization of high-performance fluid power systems that would be applied in modern industrial plants requires a symbiosis of mechanical systems with technologies such as microelectronics, sensors, and sophisticated control methods to achieve optimal system behaviour. In many applications, pneumatic drives can be a cheaper alternative to electric and hydraulic systems, especially for small loads, but significant attention should be directed towards more advanced ways of controlling these systems [3]. The use of electronic components for sending and processing signals enables the application of advanced control methods in fluid power systems and their application in industrial and mobile plants that use the principles of modern digital technology. This extends the potential application of these systems to the field of flexible modules that are connected in complex production systems, robotic systems, transportation systems, modern systems in the production of renewable energy sources, etc. [4].

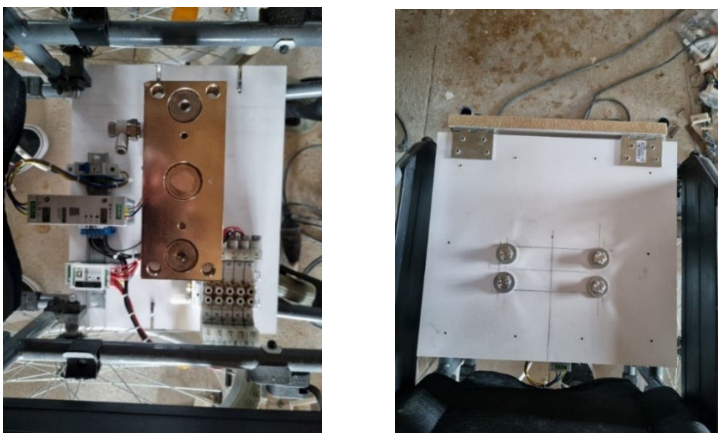
This paper presents several self-made experimental mechatronic systems driven by pneumatic and electric drives, which indicate development trends, and can be used for education in the field of advanced control techniques.

2 Pneumatically powered wheelchair

This chapter describes the design and manufacture of a pneumatically powered wheelchair which could lift the patient into a horizontal lying position up to the height of the hospital bed, thus enabling a simple procedure for transferring the patient to the bed. Lifting patients with limited mobility from their wheelchairs and transferring them to the bed is a very demanding activity for the medical staff. Realization of an automated system that enables the easy transfer of patients from a wheelchair to a bed and vice versa would greatly facilitate this physically demanding activity, which is mainly performed by female medical staff. Such wheelchairs should be stable, safe and ergonomic. It is necessary to ensure that structural elements can endure the weight of all components, the weight of the patient, withstand the dynamic loads during lifting, lowering and moving the patient, and the final product should have a simple control.

2.1 Designing and manufacturing of structural parts

The mechanical parts were designed in the SolidWorks software package and then made by hand. In order to reduce the price of the product, for making the lower plate, connecting plate and top plate, as well as the footrest and backrest, wood was chosen that ensures sufficient strength of the structure, Figure 1. Parts like angle profiles for attaching the cylinders, a slider and a telescopic rod for height adjustment were also used.

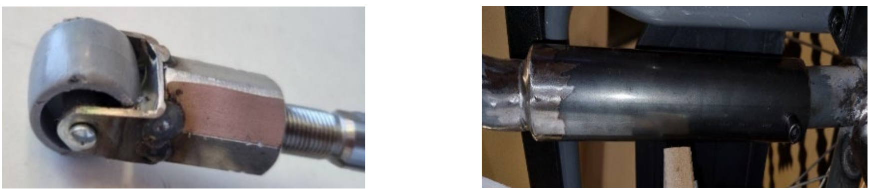


a) b)

Figure 1: Lifting mechanism, a) components on the lower plate, b) upper plate.

Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8493 [5]

The seat is the most loaded part of the system because the components are located on it, and it must have sufficient strength to withstand the weight of the patient during lifting and lowering. The bottom plate and the seat are connected with screws, and a pneumatic cylinder (SMC MGPM50-250) is attached that allows the patient to be lifted. The footrest enables raising the legs and achieving a horizontal position of the patient together with the backrest, as well as a simpler and more stable transfer from the wheelchair to the hospital bed. The rotational movement of the footrest plate from 0° to 90° is achieved using two pneumatic cylinders placed at an equal distance from the centre of the footrest panel. Rotation is enabled by the hinges, placed between the connecting plate and the footrest plate. To reduce friction and damage the foot plate during the movement of the cylinder piston rod, a nut with a wheel is installed at the end of the piston rod as shown in Figure 2a. The footrest is smoothly placed in a horizontal position by using the wheels. In the case of a fully extended cylinder piston, the height of the wheelchair handgrip limited the transfer of the patient to the bed. For this reason, the handles were removed, and a telescopic rod was installed that has the ability to adjust the height, Figure 2b. This made it possible to pull in and out the rod during raising and lowering the wheelchair.



a) b)

Figure 2: Made parts for the system operation, a) nut with wheel, b) telescopic rod.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8493 [5]

All parts on which the patient lies are covered with a 2 cm sponge and then with canvas for a better aesthetic. Additional 4 cm sponges are placed at the bottom of the footrest for better comfort and ergonomics. Also, for better aesthetics of the wheelchair, stainless steel plates with a thickness of 1.2 mm are also attached, which also protect the wooden plates. The back part of the backrest, the lower part of the footrest and the edges of the seat are covered with panels, thus hiding the pneumatic cylinders used to raise the legs.

2.2 Control system

Controllino Mini PLC with software that is fully compatible with Arduino is used as a control device. The basis of the Controllino device is the ATMEGA328P microcontroller, which is actually an integrated chip that controls devices and processes, stores and executes the program. A valve block with electromagnetic valves (SMC SY5320-5DZ-C6F-Q) is used to control the direction of movement of the cylinders. To adjust the speed of cylinder movement, speed control valves (SMC AS2201F-02-06SA) with a locking rotary knob are used, Figure 3.

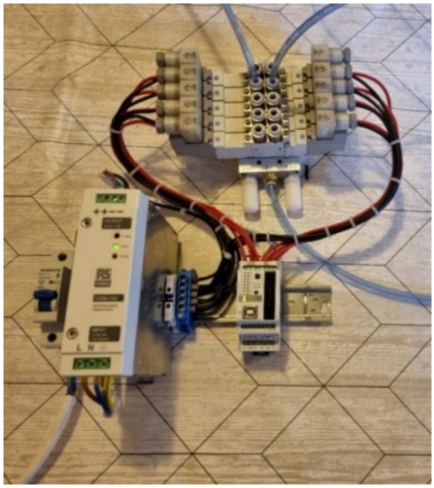


Figure 3: Control components.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8493 [5]

At the beginning of the program, Controllino initializes all necessary variables, then certain pins are assigned the property of input or output pins. When the program is run, the control algorithms are saved in Controllino and executed in an infinite loop where the values of the variables are examined and the given actions are performed. By sending an electrical signal, the positions of the electromagnetic valves are controlled, which determines the direction of movement of the cylinders. Electric signal transmitters send information about the position of the cylinder piston and allow the system to work properly. By using a microswitch, the action of raising and lowering the wheelchair is enabled.

2.3 Description of system operation

The modified wheelchair is used to raise the patient from a sitting position to the height of the hospital bed, Figure 4. The transfer of the patient takes place in the stages of lifting to the working height, moving the patient to the hospital bed and lowering the wheelchair to the starting position. When we place the patient in the wheelchair, the legs should first be connected using a strap, in order to secure them from unwanted movements and to secure the patient during the lifting process. After that, the patient is raised in a lying position, parallel to the hospital bed. The working height of a hospital bed is usually from 75 to 95 cm. The manufactured wheelchair in its final position, when the piston rod of the lifting pneumatic cylinder is fully extended, has a working height of 95 cm. The telescopic rod for height adjustment allows to reduce the height by 20 cm, and adjust the height to the required value. Using a microswitch mounted on the handle for pushing the wheelchair, raising and lowering operations are initiated.

Figure 4: Functioning of wheelchair.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8493 [5]

This type of wheelchair system allows the medical staff to transfer patients more easily, but they are still needed to move the patient from a lying position on the wheelchair to the hospital bed and to manually adjust the height of the wheelchair lift to the working height of the hospital bed.

3 Automated system for mixing liquids in a defined ratio

Mixing liquids in a defined ratio is represented in many applications, for example: in production processes for mixing various adhesives and catalysts, in the catering industry for mixing non-alcoholic and alcoholic beverages, in agriculture for the preparation of pesticides, for the preparation of a mixture of fuel and two-stroke oil and many others. In all the processes mentioned above, there is a need for automated systems for mixing certain liquids. The goal of this project was to create a conceptual device for mixing liquids in a defined ratio that would be easily portable and inexpensive.

3.1 Device construction

The device is structurally designed so that on the front side there is an LCD screen with control buttons and potentiometers, on the left side there is a stand for a container and a glass into which two liquids will be poured and mixed, and two liquid containers with built-in pumps. The back part is adapted to glass containers. Considering that the tanks are heavy enough without liquid, no support is provided for them. Figure 5 shows a 3D model of the device, which was used for the production of structural parts on a 3D printer.

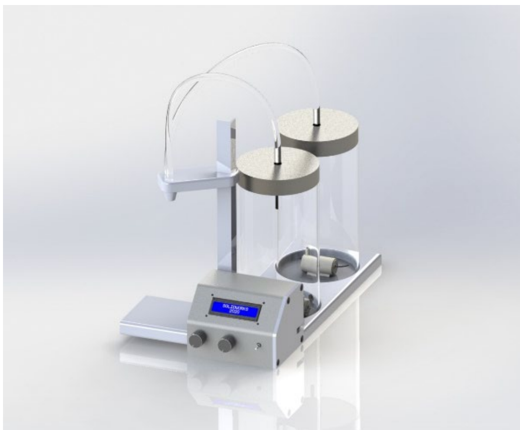


Figure 5: 3D model of the device.
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3.2 Control and measuring components of the device

An Arduino Nano microcontroller was used to program the device. This created a simple and cheap platform for connecting a computer to a real device. Initializing specific pins is very easy, as well as sending or receiving data through them. An LCD screen with 16 characters in 2 lines was chosen to display the status and menu on the device, as shown in Figure 6. This screen is widely used as a display of basic information on simple mechatronic devices, because it is small in size, has good backlighting, and is easy to program and mount on devices.

Figure 6: LCD screen on the device.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8460/datastream/PDF [6]

In order to reduce the number of outputs on the microcontroller, an I2C adapter is installed that reduces the required number of outputs to only 4 outputs: two for powering the screen and two for I2C communication. The accuracy of the process of pouring liquid into the tank is ensured by using the tank filling sensor in the feedback loop. A weight sensor with strain gauge technology is used for this purpose, Figure 7. Due to the very small changes between the diagonals on the measuring bridge, it is necessary to amplify the signal and convert it into digital form. For this purpose, a 24-bit analogue-to-digital converter (HX711) was used, which has two input channels connected to the diagonals of the bridge.

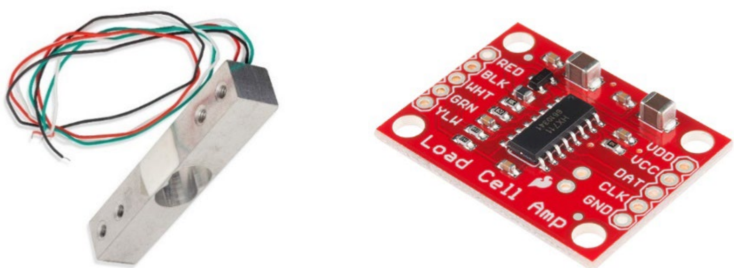

Figure 7: Force sensor with converter.
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For the compactness of the device, submersible centrifugal pumps with a smaller nominal flow rate were chosen. In order to protect the Arduino microcontroller from excessive loads by directly connecting the pumps, relays were used to power the pumps from a separate circuit. The basic technical characteristics of the pumps are: power supply: 3 V to 6 V, pump delivery height: 40 to 110 cm, flow rate: 120 L/h, pump dimensions: diameter 24 mm and length 33 mm.

3.3 Description of system operation

Two glass containers with a volume of 1500 ml containing liquid A and liquid B are located in the rear part of the device. At the bottom of each tank is a submersible centrifugal pump that pushes the liquid through a pipeline to an external tank where mixing takes place. The external tank is on the stand where the mass of the supplied liquid is measured. On the front of the device is an LCD screen that shows the desired ratio of two liquids and the volume of the mixing tank. The ratio and volume parameters are changed using two potentiometers. The mixing process is started by pressing the start button. The final system is given in Figure 8.

Figure 8: Automated beverage mixing system.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8460/datastream/PDF [6]

4 System for sorting items by colour

Sorting products according to different features is a very common task in automated production lines. Humans usually do not have serious problems with classifying objects based on colour and shape, because they have a developed visual system in their eyes. However, manual sorting of products in industry is an extremely monotonous process, and the continuous process of manual sorting of products brings problems in quality assurance. On the other hand, when using a machine for sorting objects by colour, various problems can arise, such as insufficient lighting and shadows created by other objects.

Building an educational model of a sorting system using colour detection sensors can be useful for explaining object recognition and sorting technology in various applications.

4.1 System construction

The device has four compartments for sorted items, as shown in Figure 9. Sorting is done using two turntables that are driven by pneumatic cylinders, which rotate depending on the colour of the object. The pivot plates are placed along the edge of the back plate, which ensures that the cylinder does not perform a useless stroke. A wide hole is designed on the back of the box so that turntables can enter and exit without touching the box. The turntables are connected to pneumatic actuators. An electric servomotor rotates the disk and brings the objects individually from the tubular feeder into the scanning position, and then to the hole where they fall onto the turntable. The colour detection sensor is glued to the wooden support. Pneumatic cylinders are attached to aluminium profiles that ensure precise adjustment of the device's operation, Figure 10.

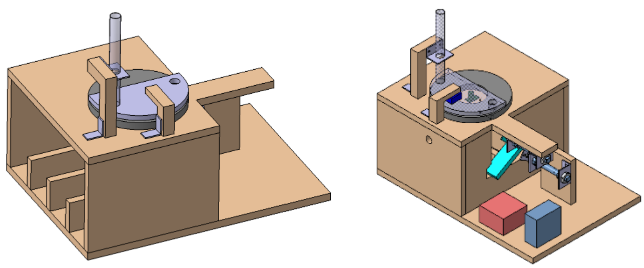

Figure 9: 3D model of the system for sorting items by color.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8482 [7]

The supports and the upper turntable are made of a standard aluminum L-profile with dimensions of 20x30x2 mm. The lower turntable is made of wood and has larger dimensions. Two single-acting pneumatic cylinders (SMC CD85N10-30S-B) controlled by electromagnetic valves (SMC SYJ512-5LOU-M5-Q) are used for rotating the turntables.

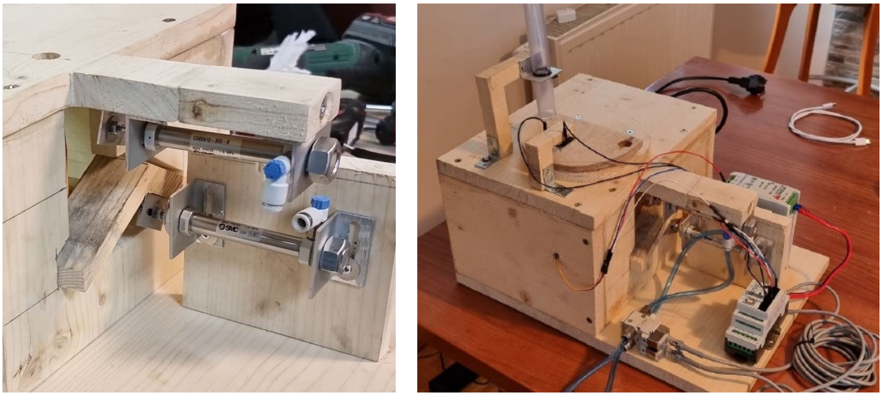

Figure 10: Actuators and turntables.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8482 [7]

4.2 Control and measuring components of the system

PLC Controllino Mini was applied as the control device. For the sorting process, a colour detection sensor (TAOS TCS3200) was used, Figure 11. The sensor has 4 groups containing 16 photodiodes each. Three groups have optical filters that do not allow certain wavelengths to pass to the photodiodes. In this way, the intensity of red, blue and green light is detected. The fourth group of photodiodes has no filter. This type of sensors are cheap and easy to integrate into the system.

Figure 11: PLC Controllino Mini and color sensor TAOS TCS3200.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb:8482 [7]

4.3 Description of system operation

The logical commands executed in the control algorithm are as follows:

- the servo motor turns the moving disk to the position under the tubular feeder and the object falls into the hole on the disk,
- the servomotor rotates the disk with the item to the colour sensor,
- the colour sensor reads the state and sends a signal to the Controllino device, where the colour of the object is determined,
- the actuators are placed in one of four possible positions,
- the servomotor rotates the disc to the hole through which the object falls onto the turntable.
- the procedure is repeated.

The algorithm is executed in the control loop, where it is determined which turntables are activated based on the detected colour of the object.

5 *Pneumatic powered wall-climbing robot*

Mobile robots that can move on vertical surfaces leave an intense impression on the observer and represent a demanding engineering task that requires knowledge of constructions, electronics and programming. Such robots should ensure strong adhesion to the wall, carry work tools and equipment, and flexible motion during the execution of specific tasks. Various methods are used to achieve adhesion and movement of robots on vertical surfaces, which include bio-inspired soft robotics, magnetic adhesion systems or the application of vacuum techniques. Application of vacuum is a widely used method for wall-climbing robots, and the main limitation is the requirement for good sealing of vacuum grippers, so such systems are only effective on smooth surfaces.

5.1 Conceptual solutions of a mobile robot

The initial concept in the development of the mobile robot contained six vacuum grippers, as shown in Figure 12. After testing the system, it was seen that four grippers are sufficient to firmly hold the robot on a vertical surface, and this concept was accepted. However, the rubbers on the vacuum grippers were not hard enough and did not slide well on the vertical surface, which caused difficult movement. Finally, the problem was adequately solved by installing four grippers of a larger diameter with harder rubber.

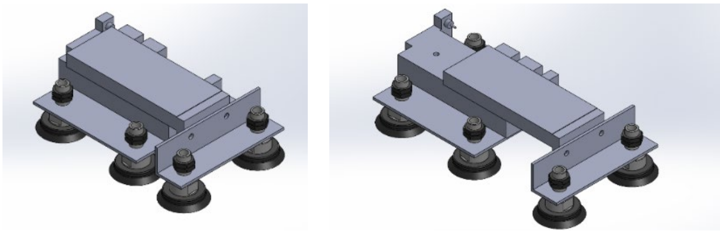

Figure 12: 3D model of the initial concept of the robot.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8470 [8]

5.2 The main components of the robot

The realized robot for movement on smooth vertical surfaces is driven pneumatically, and holding the robot on a vertical surface is achieved using four vacuum grippers. A pneumatic cylinder (SMC MXS16L-75B-X42) was used as the body of a mobile robot on which vacuum grippers (ZPT63HN-A16) were mounted. Two ejectors (ZH10B-06-06) are used to create a vacuum on the grippers, and their operation is based on the Bernoulli principle. The ejector weighs only 13.6g, which practically means that it can be placed on the air supply pipe. The main components of the robot are shown in Figure 13. Three electromagnetic 5/2 valves (SY3120-5MOU-C6-Q), which are mounted on the connection plate (SS5Y3-20-03-00F-Q), are used to control the direction of movement of the cylinder as well as to control the vacuum in the grippers. The control device PLC Controllino Mini is used to control the movement of the robot. Controllino offers the flexibility of using open-source code, but also ensures the reliability of industrial PLCs.

a) b) c)

Figure 13: Main components: a) pneumatic cylinder, b) vacuum gripper, c) ejector.
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8470 [8]

5.3 Operation of the mobile robot system

The control of the vacuum grippers and the cylinder is done using the Controllino device, from which the control signals are sent to three electromagnetic valves. By changing the working position of the valves that control the grippers, the vacuum on that pair of grippers is lost and they have the possibility of sliding on the surface. By changing the working position, the valve that controls the cylinder moves to the upper or lower end position. Pneumatic powered wall climbing robot is shown in Figure 14.

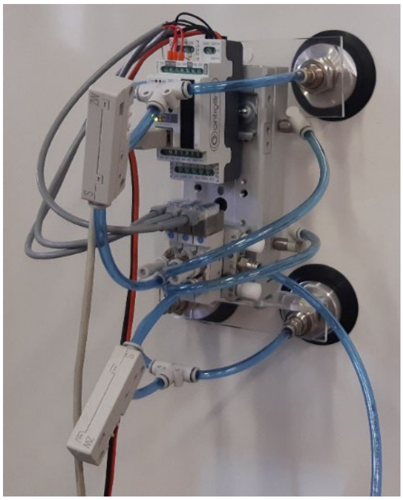

Figure 14: ***Pneumatic powered wall climbing robot.***
Source: https://repozitorij.fsb.unizg.hr/islandora/object/fsb%3A8470 [8]

6 Conclusion

The paper has presented four handmade experimental systems with pneumatic and electric drive which have been designed as educational test models in the field of mechatronic control systems. The laboratory systems can be used as test models within the field of fluid power drives and automatic control education of mechanical engineering students.

By using such systems, students have the opportunity to learn about mechanical systems construction and control of practical systems built from real industrial components [9, 10]. The educational process, which includes theoretical and practical applications of different control techniques applied to various mechatronic systems, gives students an insight into the control of real systems.

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