

Two-axis Pneumatic Manipulator as a Test Bed for Teaching Energy Efficiency of Compressed Air Systems

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Abstract: *The two-axis pneumatic manipulator has a wide range of possible applications in terms of experimental tests. In this paper, the pneumatic manipulator was used as a test bed on which students tested two different control methods in terms of the energy efficiency of the compressed air systems. Traditional proportional control and stand-alone performance using fast switching directional control valves for Pulse Width Modulation (PWM) control were considered. The circular movement of the pneumatic manipulator carrying the tool and processing by planing lighter material such as plastic was chosen. The results showed that lower consumption is achieved with PWM control.*

Keywords: *teaching; energy efficiency; compressed air; programmable pneumatic manipulator; PWM control; proportional control*

1. INTRODUCTION

The shortage of energy sources means that more attention must be paid to their rational consumption. When describing the quality of energy consumption, terms "combined into one" are used - Energy efficiency [1-4]. The performance of the observed system should not be impaired by the application of energy efficiency. In addition to rational consumption, the motive for applying energy-efficient systems is reduced energy consumption which implies money saving, since unnecessary consumption is eliminated. Therefore, energy efficiency should not be seen as forced savings or reduced energy consumption, but a thoughtful approach to rationed energy consumption that maintains the functionality of the system to which it is applied. Reducing energy consumption has, apart to financial, other non-energy benefits, such as environmental implications.

Compressed air is often used as a drive energy in industry. But compressed air represents a relatively expensive source of energy, and it is justified and desirable to introduce energy efficiency concepts into compressed air systems [5], [6].

Teachers and researchers around the world have begun to involve energy efficiency concepts in teaching [7-9]. Namely, in order for energy efficiency to be taken seriously, it should be presented to young people so that they use energy rationally. There are researches conducted to determine the degree of presence of energy efficiency in teaching as well as methods for better

mastery of these principles by students [7], [9]. The advantages of spreading relevant information and participating in energy education projects, using the example of students and parents who have improved their behavior to be more energy efficient are highlighted in [8].

The importance of applying energy efficiency, especially in the field of compressed air system, is also recognized at the Faculty of Technical Sciences in Novi Sad. Courses on Master's and Doctoral studies dedicated to the possibilities of practical application of energy efficiency have been introduced. Subjects in which the theoretical concepts of energy efficiency are practically applied are Energy efficiency of compressed air systems within the Master's studies [10], [11] and Selected chapters of the energy efficiency of automated systems within the Doctoral studies [12], [13], both in study programmes of Industrial Engineering and Mechatronics.

As the part of the above, several research papers have already been done on the mentioned topic [14-18].

The main goal of this paper is to present a way for testing energy efficiency of compressed air systems during practical classes using the two-axis pneumatic manipulator [19]. In this way, it is possible to clarify theoretical knowledge as well as the various possibilities of practical application of energy efficiency for future engineers, who will apply it in their later works depending on how specific tasks allow them to do that.

2. EXPERIMENTAL STATION FOR EDUCATIONAL PURPOSE

In order to test different types of pneumatic control systems in contact tasks, a two-axis manipulator was developed [19]. At the same time, this device enables the monitoring and analysis of energy efficiency, as well as the realization of the desired processing process.

2.1. Acquaintance of students with assigned tasks

With the help of two-axes manipulator, excess material can be removed from the workpieces. Therefore, with this practical example, the characteristics of the software and hardware can be analyzed for two control methods on the experimental station.

With the developed two-axis pneumatic manipulator, a wide range of tests is open to students. The following possibilities can be realized:

1. Modularity:
 - change of actuators,
 - change of measuring pistons (position sensors),
 - implementation of three or more axes;
2. Testing:
 - force sensor,
 - remote sensors,
 - different types of processing,
 - different types of materials,
 - energy efficiency,
 - etc.;
3. Systematization of remote control in accordance with the I4.0 concept.

2.2. Two-axis pneumatic manipulator

As the first step, a 3D model of two-axis pneumatic manipulator (Fig. 1) was created [19]. The numbered components are given in Table 1.

Fig. 2 shows the practical realization of two-axis pneumatic manipulator. It represents a mechatronic system and consists of mechanical, pneumatic and electronic components, with appropriate control components. This mechatronics system is also used for the preparation of graduation, master's theses, professional practices of students, as well as research works of young associates.

For the purposes of this paper, one cycle of the tool movement of the programmable two-axis pneumatic manipulator in the planing process is used and it is shown in Fig. 3. Respectively, numbers from one to four represent the movement

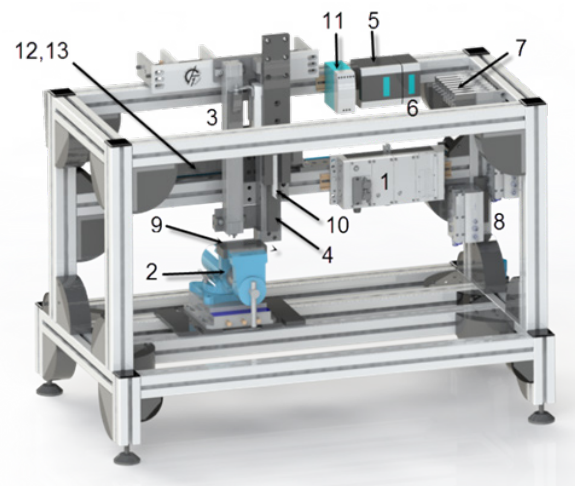


Figure 1. 3D model of the developed station

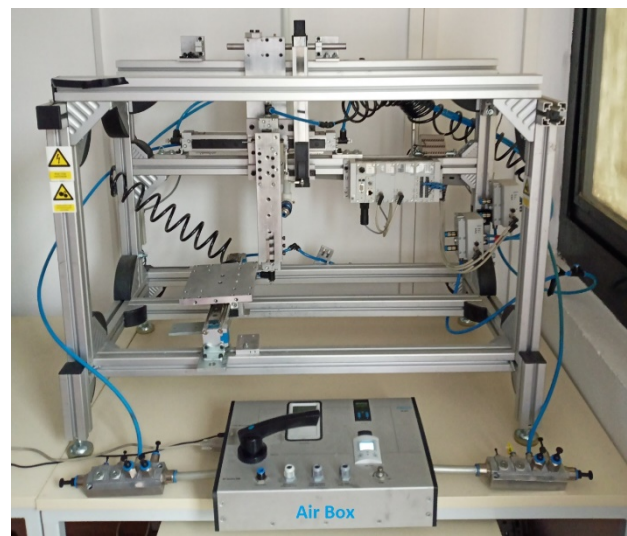


Figure 2. Two-axis pneumatic manipulator

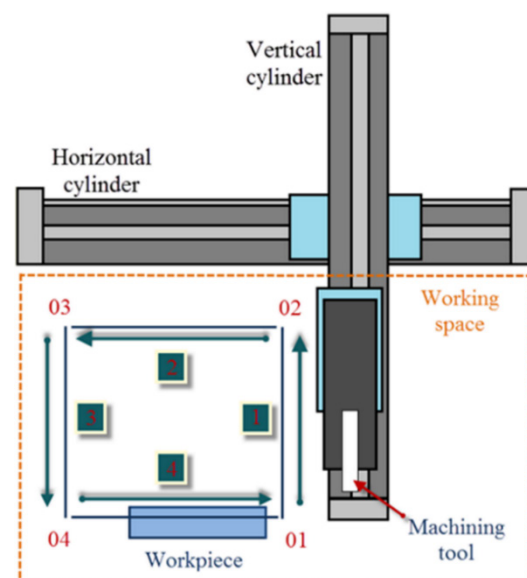


Figure 3. Material processing by planing

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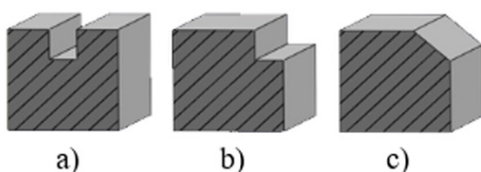
Table 1. Specification of components

Name	Type	Description/Purpose
PLC	Festo - 50E-T06GCQST21T21YJ-Z	For proportional control (CPX); Fig. 1, position 1
Clamp	-	For workpiece clamping; Fig. 1, position 2
Linear encoder	MLO-POT-225-TLF	Analogue displacement encoders, stroke 200 mm, resolution 0.01 mm; Fig. 1, positions 3,13
Vertical and horizontal cylinder	DGPL-25-200-PPV-A-B-KF-KU-D2	The rodless cylinders, with stroke 200 mm; Fig. 1, positions 4-12
PLC	Fatek - FBs - 24MAT2 - D24	For PWM contro; Fig. 1, positions 5
Data Acquisition System (DAQ) module	Fatek - FBs - 4A2D	For PWM control; Fig. 1, position 6
Solenoid valves	MHE3-MS1H-3/2G-1/8	Fast switching 3/2-way directional control valves, normally closed, monostable, nominal flow rate 200 L/min, for PWM control; Fig. 1, position 7
Proportional valve	Festo - VPWP-6-L-5-Q8-10-E-G	5/3-way proportional control valves, nominal flow rate 700 L/min; Fig. 1, position 8
Workpiece	Polyethilen (PE)	Fig. 1, position 9
Machining tool	High Speed Steel	Fig. 1, position 10
Power supply	Festo 220 to 24VDC	Fig. 1, position 11
Air Box	FESTO GHDA-FQ-M-FDMJ-A	Measurement of compressed air consumption; Fig. 2 marked as Air Box

path of the manipulator axis. The planing machining process (work stroke), which removes shavings from the workpiece, is performed by moving a machining tool along a horizontal path from position four to position one (left to right).

Before performing the exercises, students are reminded of the basics of machining and the used procedure - planing. Planing implies the removal of material from the workpiece by linear movement of the planing knife. Using a pneumatic manipulator, the planing of flat surfaces by removing material takes place using a programmable device.

Fig. 4 shows some of the possible material profiles obtained by planing, i.e. realized grooves with different shapes. In this paper, it is obtained a shape which is shown in Fig. 4a.

**Figure 4.** Material profiles obtained by cutting

2.3. Measuring the compressed air consumption

For the purposes of this research from the aspect of energy efficiency, the laboratory device Air Box type GHDA-FQ-M-FDMJ-A [20], manufactured by Festo, was used. The flow meter enables the monitoring and measurement of compressed air

consumption on individual components or in the entire system, as well as leakages in the system. In the specific task, the emphasis is on measuring compressed air consumption.

The Air Box was placed immediately after the compressed air service unit. In this way, it is possible to measure the consumption of the entire system. The maximum pressure at the input port of the AirBox is 10 bar, with a deviation of less than 100 mbar. Air Box is shown on Fig. 2 and is marked as Air Box.

Total consumption for one cycle was calculated as the area under the graph of the consumption function:

$$Q = \frac{1}{2} \sum_{i=1}^n (t_i - t_{i-1}) (q_i - q_{i-1}) \quad (1)$$

where:

Q is compressed air consumption in Nl ,

t_i is measurement time in s ,

t_{i-1} previous measurement time in s ,

q_i is compressed air flow in t_i in Nl/min and

q_{i-1} is compressed air flow in t_{i-1} in Nl/min .

2.4. PWM and proportional control

After familiarizing with the hardware structure of the experimental station, students are able to produce the appropriate control actions. It is important to compare the behavior of the system from the aspect of energy efficiency in the next step.

As part of the teaching, two control methods are considered - proportional and PWM.

In order to compare two different ways of control, the execution of an identical cycle for both control methods will be observed.

For PWM control system, control valves must have a very short state change time, otherwise PWM control will not be able to be realized. Namely, if the duration of the PWM pulse is less than the opening/closing time of the directional control valve, the valve will not react. Otherwise, if the duration of the high level of the PWM signal is longer than the difference between duration of the PWM pulse and the sum of the time required for opening and closing, the valve will not close. The compressed air flow to the cylinder will remain open until the next cycle. These switching valves do not have the possibility of changing their flow due to the construction of the valve. With proportional valves, the flow of fluid through it can be changed and it is proportional to the current (or voltage) flowing through the armature windings of the valve. That means that they are more expensive than standard control direction valves.

For realization of PWM control, P regulator has been used and that way of control is discussed in [21]. Also, it were used 3/2-way fast switching monostable directional control valves, with one port blocked (function as 2/2-way valve) and the main control unit with build-in HSPWM (High Speed Pulse Width Modulation) outputs.

The pneumatic scheme of PWM control is shown in Fig. 5. Valves Y7 and Y0 are responsible for moving cylinder A in one direction, (Y2 and Y1 for cylinder B), and for moving in the opposite direction valves Y4 and Y5 (Y2 and Y1 for cylinder B).

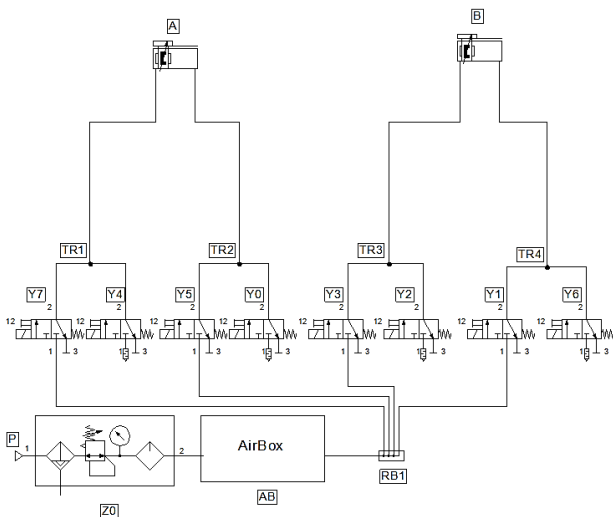


Figure 5. Pneumatic control scheme for PWM control

Output frequency for the HSPWM can be calculated by using equation (2):

$$f_{pwm} = \frac{18432}{P_n + 1} \quad (2)$$

where P_n is the value of the output frequency in the range from 0 to 255.

For the experimental verification of the PWM control, the initial value of the register was set to be optimal for horizontal (210) and vertical (213) cylinders. It follows that the time period for the horizontal cylinder is 11.45 ms, and for the vertical 11.61 ms.

The architecture of the system in the case of proportional control includes a controller CPX-CEC with separate modules for controlling pneumatic axes marked as CPX-CMAX-C1-1 and 5/3-way proportional pneumatic valve, marked as VPVP-6, by Festo manufacturer. Fig. 6 shows the corresponding pneumatic scheme for appropriate system.

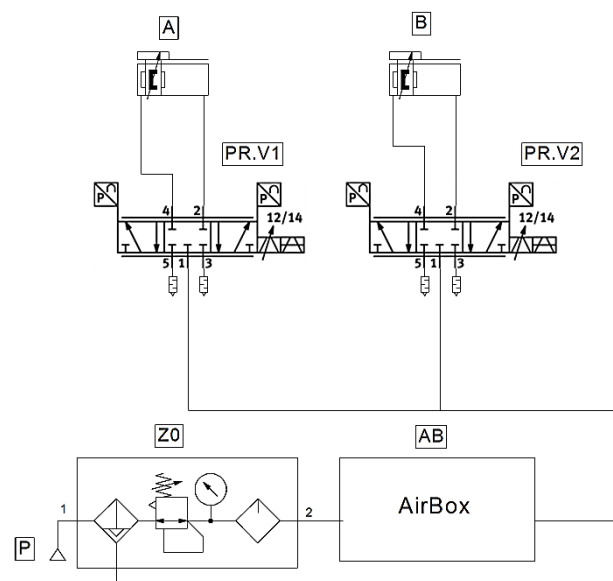


Figure 6. Pneumatic control scheme for proportional control

3. RESULTS AND DISCUSSION

Since the two control models used were compared in terms of energy efficiency, it is necessary to compare their compressed air consumption.

An identical knife with a width of 3 mm was used for both control models. Measurements were made on three different materials: Polyethylene (PE), Polypropylene (PP), Polyamide (PA). Compressed air consumption was measured for one identical grooving cycle on each of the three materials, for the cutting profile shown on Fig. 4a.

In Fig. 7 is presented a comparison of compressed air consumption of the entire system during one cycle with proportional and PWM control when machining three different materials (PE, PP, PA).

For easier understanding, in Fig. 8 and Fig. 9 are shown two examples of compressed air consumption when PWM and proportional control were applied in case of processing PE workpieces, respectively.

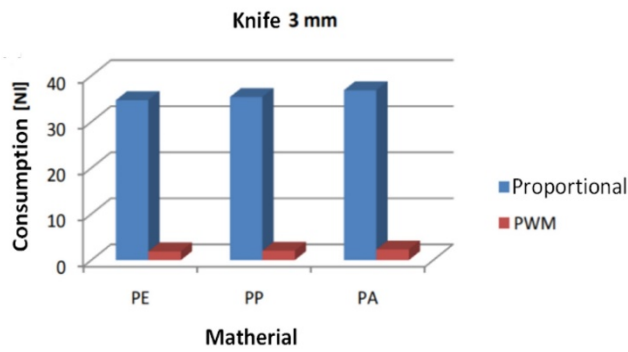


Figure 7. Compressed air consumption of the entire system per cycle during the machining of three different materials

With proportional control, compressed air consumption ranges from 34.69 Nl to 36.84 Nl per cycle, while with PWM control, compressed air consumption is from 1.88 Nl to 2.3 Nl also per cycle. Namely, PWM and proportional control methods are characterized by two different ways of maintaining the achieved position. With proportional control, for the purpose of maintaining the position, compressed air is constantly consumed. With PWM control, both chambers of the rodless cylinder are filled and the supply of compressed air is blocked with the fast switching direction control valves.

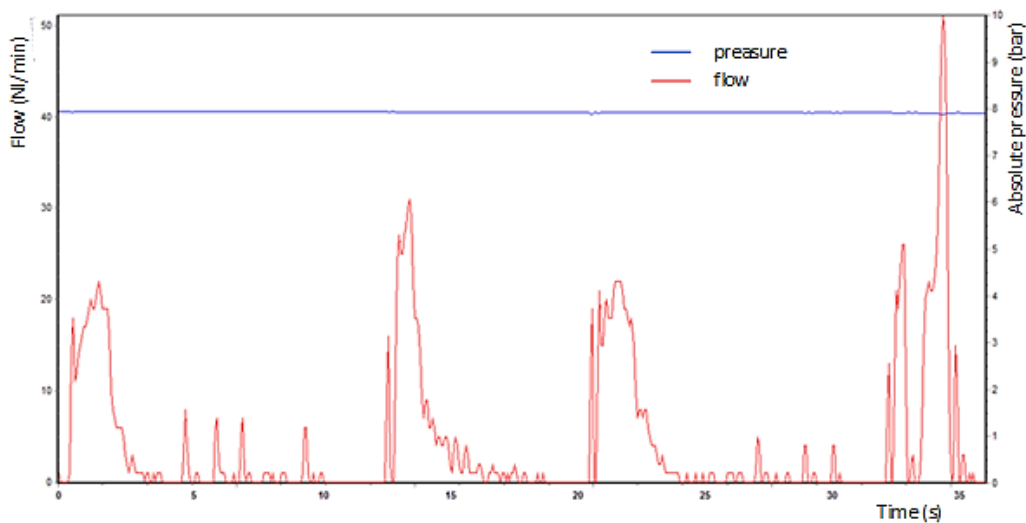


Figure 8. Compressed air consumption for PWM control and PE workpiece

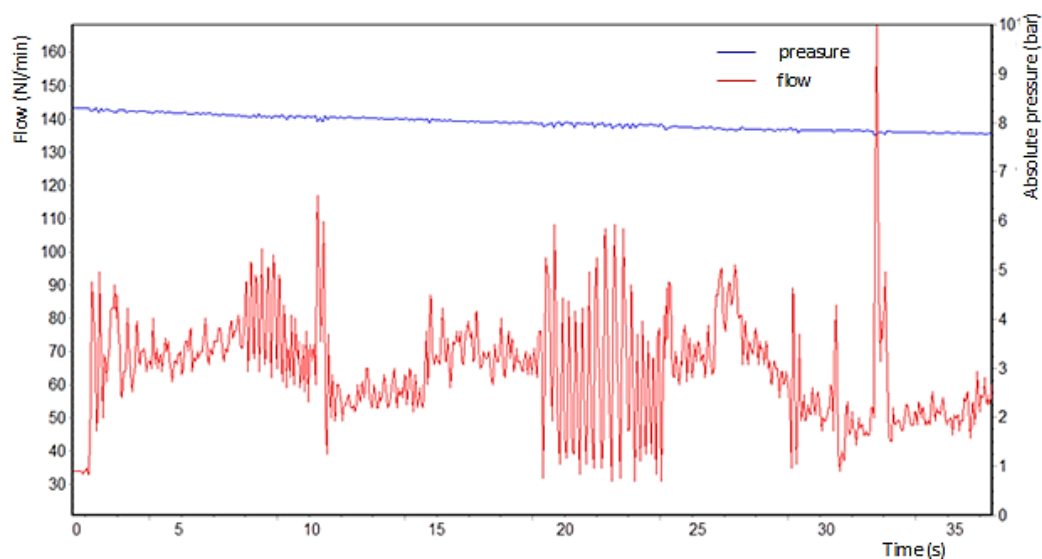


Figure 9. Compressed air consumption for proportional control and PE workpiece

4. CONCLUSION

In order to enable students to become practically acquainted with the energy efficiency of compressed air systems, a two-axis manipulator with pneumatic drives was used. A realistic planing machining operation task adapted for performing laboratory exercises was chosen.

After carrying out practical exercises on the testing of energy efficiency of the compressed air system, students will be able to:

- Build and connect the system;
- Collect and process data;
- Calculate compressed air consumption;
- Analyze the obtained results;
- Draw appropriate conclusions.

Students were given the opportunity to apply a traditionally known proportional control system, which is inherently expensive and has a high compressed air consumption, but is effective in performing accurate and fast positioning tasks. After that, by considering a different type of control system - PWM, the goal was to achieve successful performance of the same task. Functionality was maintained (performance may be slightly impaired up to the permitted limit), but consumption was reduced (the system becomes more energy efficient) and more profitable.

Based on the measurement results, it can be concluded that the compressed air consumption with proportional control is 15÷20 times higher compared to PWM control.

By forming their own control circuit and analyzing the obtained results, students get the conclusion that the same functionality can be achieved by using standard and cheaper components comparing to the ready-made solution that is available. The advantage of such an approach is seen through the achievement of a more economical and energy efficient device for use in contact tasks.

REFERENCES

- [1] Hasanbeigi, A. & Price, L. (2012). A review of energy use and energy efficiency technologies for the textile industry. *Renewable and Sustainable Energy Reviews*, 16 (6), 3648-3665. <https://doi.org/10.1016/j.rser.2012.03.029>
- [2] Li, M. J. & Tao, W. Q. (2017). Review of methodologies and policies for evaluation of energy efficiency in high energy-consuming industry. *Applied Energy*, 187, 203-215. <https://doi.org/10.1016/j.apenergy.2016.11.039>
- [3] Koutitas, G. & Demestichas, P. (2010). A Review of Energy Efficiency in Telecommunication Networks. *Telfor Journal*, 2(1), 2-7. https://journal.telfor.rs/Published/Vol2No1/Vo12No1_A1.pdf
- [4] Menghi, R., Papetti, A., Germani, M. & Marco Marconi, M. (2019). Energy efficiency of manufacturing systems: A review of energy assessment methods and tools. *Journal of Cleaner Production*, 240, 118276, <https://doi.org/10.1016/j.jclepro.2019.118276>.
- [5] Saidur, R., Rahim, N.A. & Hasanuzzaman, M. (2010). A review on compressed-air energy use and energy savings. *Renewable and Sustainable Energy Reviews*, 14 (4), 1135-1153. <https://doi.org/10.1016/j.rser.2009.11.013>
- [6] Radgen, P. & Blaustein, E. (2001). *Compressed Air Systems in the European Union. Energy, Emissions, Savings Potential and Policy Actions*. Stuttgart, Germany: Fraunhofer Institute for Systems Technology and Innovation, LOGUL X Verlag GmbH
- [7] Desha, C. J. & Hargroves, K. (2010). Surveying the state of higher education in energy efficiency, in Australian engineering curriculum. *Journal of Cleaner Production*, 18(7), 652-658. <https://doi.org/10.1016/j.jclepro.2009.07.004>
- [8] Zografakis, N., Menegaki, A. N. & Tsgarakis, K. P. (2008). Effective education for energy efficiency. *Energy Policy*, 36(8), 3226-3232. <https://doi.org/10.1016/j.enpol.2008.04.021>
- [9] Altan, H. (2010). Energy efficiency interventions in UK higher education institutions. *Energy Policy*, 38(12), 7722-7731. <https://doi.org/10.1016/j.enpol.2010.08.024>
- [10] Subject: Energy efficiency of compressed air systems, Master Academic Studies: Industrial Engineering, Faculty of Technical Sciences in Novi Sad. <http://ftn.uns.ac.rs/351802087>
- [11] Subject: Energy efficiency of compressed air systems, Master Academic Studies: Mechatronics, Faculty of Technical Sciences in Novi Sad. <http://ftn.uns.ac.rs/825882375>
- [12] Subject: Selected chapters of the energy efficiency of automated systems, Doctoral Academic Studies: Industrial Engineering, Faculty of Technical Sciences in Novi Sad. <http://ftn.uns.ac.rs/1282337347>
- [13] Subject: Selected chapters of the energy efficiency of automated systems, Doctoral Academic Studies: Mechatronics, Faculty of Technical Sciences in Novi Sad. <http://ftn.uns.ac.rs/1482887492>
- [14] Dudić, S., Reljić, V., Šešlija, D., Dakić, N. & Blagojević, V. (2021). Improving Energy Efficiency of Flexible Pneumatic Systems. *Energies*, 14, 1819. <https://doi.org/10.3390/en14071819>
- [15] Šešlija, M., Reljić, V., Šešlija, D., Dudić, S., Dakić, N. & Jovanović Z. (2021). Reuse of Exhausted Air from Multi-Actuator Pneumatic Control Systems. *Actuators*. 10(6):125. <https://doi.org/10.3390/act10060125>

- [16] Šešlija, D., Milenković, I., Dudić, S. & Šulc, J. (2016). Improving energy efficiency in compressed air systems - practical experiences. *Thermal Science*, 20(2), 355-370.
<https://doi.org/10.2298/TSCI151110022S>
- [17] Ignjatović, I., Komenda, T., Šešlija, D. & Mališa, V. (2013). Optimisation of compressed air and electricity consumption in a complex robotic cell. *Robotics and Computer-Integrated Manufacturing*, 29(4), 70-76.
<https://doi.org/10.1016/j.rcim.2012.11.001>
- [18] Šešlija, D., Stojiljković, M., Golubović, Z., Blagojević, V. & Dudić, S. (2009). Identification of the possibilities for increasing energy efficiency in the compressed air systems. *Facta universitatis-series: Mechanical Engineering*, 7(1), 37-60.
- [19] Šulc, J., Reljić, V., Bajči, B. & Šešlija, D. (2016). *Design and Development of Experimental Setup for Analysis and Synthesis of Control Laws in Manipulator Contact with Environment*. 3rd International Scientific Conference "Conference on Mechanical Engineering Technologies and Applications" - COMETA, Jahorina: Faculty of Mechanical Engineering, East Sarajevo, 7-9 Decembar, 2016, 87-92, ISBN 978-99976-623-7-8.
- [20] Festo. (2006). *Air Box Type GHDA-FQ-M-FDMJ-A—Operating Instructions*. Esslingen, Germany
- [21] Šulc, J., Šešlija, D., Reljić, V., Bajči, B. & Čajetinac, S. (2016). *PWM Control of Coupled Motion of Two Axis Pneumatic Programmable Manipulator*. 13th International Conference on Systems, Automatic Control and Measurements - SAUM, Niš, 9-11 Novembar, 2016