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Design and control of mechatronic systems with pneumatic and hydraulic drive

ŽELJKO ŠITUM, JURAJ BENIĆ, KLARA PEJIĆ, MARKO MIROSLAV BAČA, IVAN RADIĆ & DOMINIK SEMREN

Abstract This paper presents four handmade laboratory systems with pneumatic and hydraulic drive. The article first presents an example of a pneumatic motor speed control using a proportional directional control valve. Then the paper presents the design and control of a test device with pneumatic drive for determining the dynamic strength of materials, on which the fracture mechanics of materials due to the action of dynamic stress can be experimentally demonstrated and the resistance of materials to cyclic stress can be analyzed. The article then describes the design, construction and control of a pneumatically driven system for sorting products marked with a bar code using a vision system. The final section of the article describes an experimental setup for precise position control of a hydraulic cylinder using 2/2 cartridge valves, which can clearly demonstrate the application possibilities of these valves in industrial plants and mobile systems.

Keywords: • speed control • dynamic strength of materials • product sorting • cartridge valves • position control •

CORRESPONDENCE ADDRESS: Željko Šitum, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000 Zagreb, Croatia, e-mail: zeljko.situm@fsb.hr. Juraj Benić, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000 Zagreb, Croatia, e-mail: jbenic@fsb.hr. Klara Pejić, Marko Miroslav Bača, Ivan Radić & Dominik Semren, students at the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000 Zagreb, Croatia, email: kp204938@stud.fsb.hr; mb213853@stud.fsb.hr; ir210937@stud.fsb.hr; ds199138@stud.fsb.hr.

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1 Introduction

We are witnessing rapid technological growth, advances in digital technology, and concepts such as the Internet of Things, Industry 4.0, vision systems, 5G networks or artificial intelligence are becoming the subject of scientific research and practical applications in various fields [1]. However, for now the mentioned advanced technologies are rarely associated with fluid power systems. There are even opinions that in today's digital era, pneumatics and hydraulics as "traditional" techniques do not have the potential to adapt to new solutions based on information technologies. The question is: can pneumatic and hydraulic systems preserve their current wide applicability also in the future, in relation to the radical demands of digital technologies and energy efficiency? Many designers and constructors of technical solutions consider pneumatic and hydraulic components as energy inefficient systems, and manufacturers of industrial equipment in the field of fluid power technology focus on ensuring the basic tasks of the system by trying to eliminate the shortcomings of these systems. The directions of development of modern fluid power systems are towards greater involvement of microprocessors, sensors and communication components. Mechatronic engineering, which includes mechanical, electrical and information technologies, represents a way to modernize traditional fields such as hydraulic and pneumatic systems and enables the digital transformation of these established disciplines as well as new areas of application [2]. The realization of high performance systems in modern industrial applications requires a symbiosis of mechanical systems with technologies such as microelectronics, sensorics, and sophisticated control methods in order to achieve optimal system behaviour. In many applications, pneumatic drives can be a cheaper alternative to electric and hydraulic systems, especially for light loads [3]. Unfortunately, position, speed or force control of pneumatic and hydraulic actuators are often quite complex due to existing nonlinear effects in fluid power systems, variations of load and process parameters during operation etc. Thus, increased attention is being paid to the development of better working elements of the system, as well as to the improvement of control strategies. By introducing the electronic data transfer and signal processing, the application of advanced control techniques to fluid power drives and the application of these systems in industrial and mobile plants based on the principles of modern digital technology is enabled. Thus, the range of potential applications of pneumatic and hydraulic systems is extended to the field of flexible modules that are networked in complex production systems, robotic systems, modern systems for the production of renewable energy sources, etc. [4]. This paper presents several self-made experimental systems actuated by pneumatic and hydraulic drives, which have been designed and manufactured as test models within the fields of fluid power systems, mechatronics and feedback control education, based on the application of modern digital technologies.

2 Pneumatic servo system

Rotational motion in many drive systems is most often achieved by using different types of electric motors. However, pneumatic motors also have many positive features that could give them an advantage over electric motors in certain applications [5]. The favorable characteristics of pneumatic actuators such as high specific power, insensitivity to overload and drive failure, safety in explosive environments, high rotational speeds, the possibility of self-cooling, etc. may give preference to the use of pneumatic motors over commonly used electric motors [6]. However, they also have certain disadvantages such as their lower efficiency compared to electric motors, the problem of compressed air supply, the need for an air tank, the existence of noise during operation, etc. Despite certain shortcomings, there are many opportunities to further examine the possibility of using pneumatic actuators in automated industrial plants and mobile systems instead of the use of electrical actuators.

In order to test the advanced methods for speed control of the pneumatic motor in different operating modes, an experimental setup of the pneumatic servo drive was made, which is shown in Figure 1. The pneumatic servo system contains the drive, measuring and control part. The drive part includes the pneumatic vane motor (GAST 2 AM-ARV-92), the proportional valve (FESTO MPYE-5-1/8-HF-010-B), the magnetic coupling (FL-6-S) and two claw couplings. An incremental encoder with 600 ppr is used to measure the rotational speed of the pneumatic motor. The control part of the system consists of a PWM driver (HEYO-24V916PWM) for the magnetic coupling, a control card (NI USB-6001) and a power supply (SPD2460). The components are mounted on holders and connected to an aluminum profiled plate. The electromagnetic clutch has two axes and is located between the pneumatic motor and the incremental encoder, and is connected to them by two claw couplings. The driver (PWM controller) for controlling the magnetic coupling and the signal acquisition card are also attached to the base plate. The proportional valve is used to control the air flow to the vane pneumatic motor (four-bladed reversible model). The acquisition card receives the measuring signals from the encoder and sends the control signals to the proportional valve. A laptop PC is used as a control device, while the control algorithm and visualization process was realized in the LabView program.

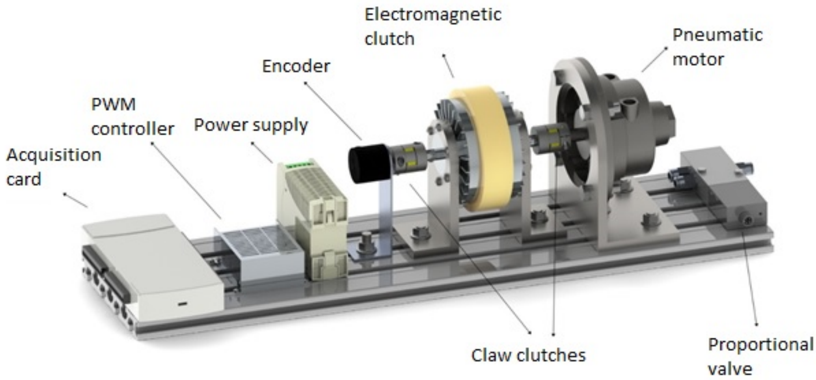


Figure 1: Conceptual design of a pneumatic servo system.

The driver for controlling the magnetic coupling and the proportional valve require a 24 V power supply, while the acquisition card needs a 5 V power supply which it receives from the computer. The encoder is connected to the acquisition card. The electromagnetic powder clutch/brake has a stator part and a rotor part. When electricity is supplied to the clutch, the magnetic field inside the coil begins to fluctuate depending on the ratio of the current intensity. The magnetic field fluctuations affect the viscosity of the magnetic powder between the rotor and the stator which produces friction and braking occurs. When the current is disconnected, centrifugal force presses the powder against the stator. This subsequently releases the rotor, which can be rotated freely again. The pneumatic motor slows down as the load increases. At the same time the torque increases to the point where it corresponds to the load. When the load is reduced, the engine accelerates, and the torque is now reduced to match the load. When the load is increased or decreased, the speed can be regulated by decreasing or increasing the air pressure. The initial engine torque is less than the torque during engine operation. Although this allows the engine to start smoothly without high initial pressure. To start the engine under heavy loads it is necessary to have additional pressure in the air line.

To demonstrate the operation of the system, it is necessary to connect the valve to the compressor and the acquisition card to the laptop PC. After the air is released, the motor shaft together with one shaft of the magnetic coupling begins to rotate. By adjusting the PWM driver current to the magnetic coupling the other shaft also begins to rotate. In this way we check whether the set-up is correctly arranged and then the system control can be achieved. The constructed pneumatic servo system is shown in Figure 2.

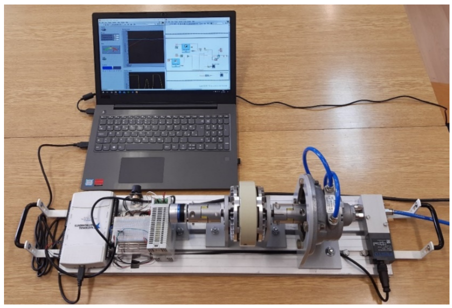


Figure 2: Pneumatic servo system.

2.1 Position and speed control of the pneumatic motor

A standard PID controller was used to control the position and speed of the pneumatic motor, and the control algorithm was performed in the LabView program, shown in Figure 3.

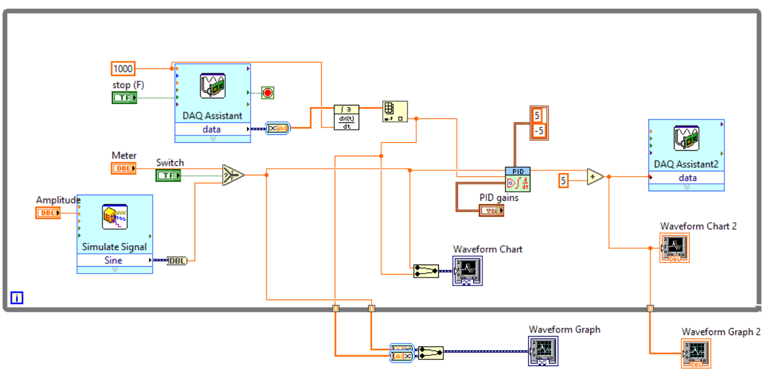
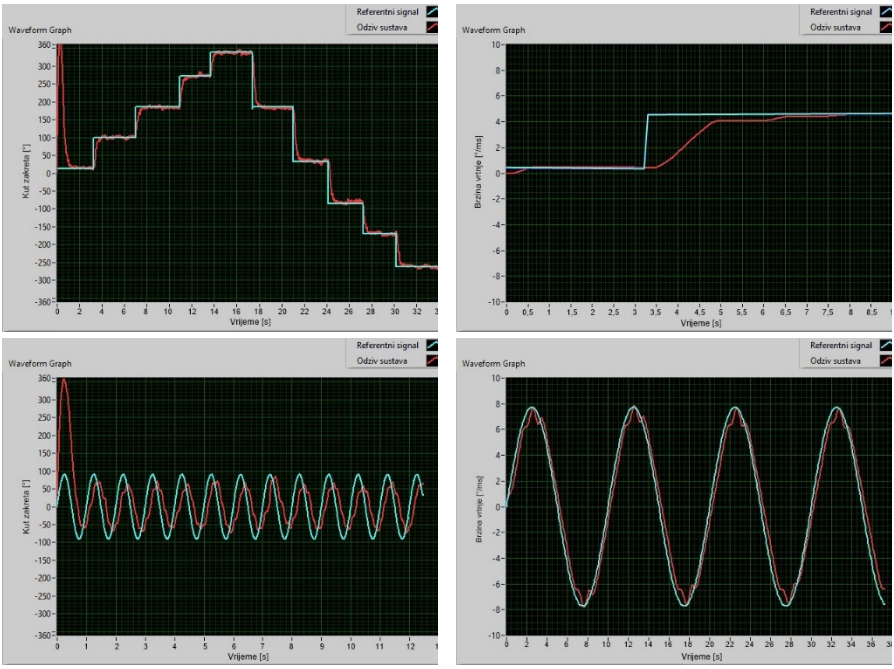


Figure 3: Control algorithm in the graphical program LabVIEW.

Experiments were made for angular position control and speed control of air engines. A PD controller was used for angular position control and a PI controller was used for speed control. In both cases, the sine and step functions are applied as reference signals, but it is also possible to define reference inputs using random points selected on the interaction interface. The parameters of the controller for different operating modes were determined experimentally, and the obtained results are shown in Figure 4.



a) Position control for step and sinusoidal reference signal

b) Speed control for step and sinusoidal reference signal

Figure 4: Experimental results for position and speed control.

For angular position control of the motor, a relatively fast system response and good trajectory tracking for the step reference signal can be observed, and slightly lower accuracy for sinusoidal functions. For speed control the response is more accurate and slightly slower for both step and sine reference signal.

3 Pneumatic device for testing dynamic strength of materials

In materials science, tests of mechanical properties of different materials under conditions of long-term dynamic action of variable stress have special significance because the results of these tests determine the dimensional calculation of mechanical structures [7]. Understanding the fatigue mechanism is important for considering various technical conditions and this knowledge is essential for the analysis of fatigue properties of an engineering structure [8].
The realization of our own laboratory and educational test device, which serves for experimental demonstration of the fracture mechanics of materials caused by dynamic stress, analysis of the resistance of materials to cyclic stress and the development of cracks due to material fatigue is a valuable achievement in deepening knowledge of materials. An important feature of this test device is the use of pneumatic components to achieve the required dynamic forces and a user interface with a touch screen to set the parameters of the material testing process, while reference and measured force values are displayed on the screen in real time. The construction of the test device is made from standard aluminium profiles due to the high modularity and wide choice of shapes that allow the connection of various profiles using angle joints. The upper horizontal beam is used as a support for the pneumatic cylinder. It is movable along the vertical axis and ensures the required position of the pneumatic actuator. The conceptual design of a pneumatic device for testing dynamic strength of materials is shown in Figure 5.

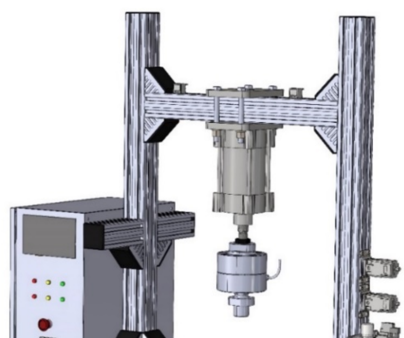


Figure 5: Conceptual design of a device for dynamic testing of materials.

Pneumatic part of the system. In order to achieve low piston speeds with low pressure in the cylinder chambers, a smooth, slow-moving cylinder of the new generation, type SMC C96YDB125-100, was chosen. A proportional pressure regulator is used to control the pressure in the cylinder chamber. The selected model ITV2050-312N3 on the pneumatic side contains 3 connections. The first input is connected to the line from the compressor, the second output from the regulator is connected to the cylinder, and the third output is the line for connecting a silencer. The pressure valve is supplied with a standard industrial voltage of 24V, and the control voltage signal is in the range from 0 to 10 V. When the control signal is applied, the pressure output from the regulator can take a value from 0.005 to 0.9 MPa. A standard FRL group is installed at the inlet of the pneumatic system, which contains a direct operated 3/2 solenoid valve for supplying compressed air into the system.

Electrical part of the system. The control device of the system is a CONTROLLINO MAXI controller, and it was chosen because of the large number of input and output pins, the device contains analogue outputs and has the ability to receive signals from sensors. The digital outputs are galvanically isolated and have a high output voltage of 24V so they can operate at standard industrial voltages. All input-output connectors have ESD protection, which indicates that Controllino device is an industrial computer that combines the advantages of open source and programming methods with standard PLCs. A force sensor is used to measure the applied force on the cylinder piston. The main requirement for the sensor is the ability to measure the force in a compressive and tensile range with high accuracy. The selected sensor type HBM U10 enables precise measurements of accuracy class 00 according to ISO 376, and has a measuring range from 50 N to 10kN. The main features of this sensor are overload protection, TEDS (Transducer Electronic Data Sheet) and long life. For proper operation of the force sensor, a 1-channel amplifier of the same accuracy class, type HBM-BM 40, was also selected. All amplifier settings such as signal filtering options and sampling time can be set via a web browser.

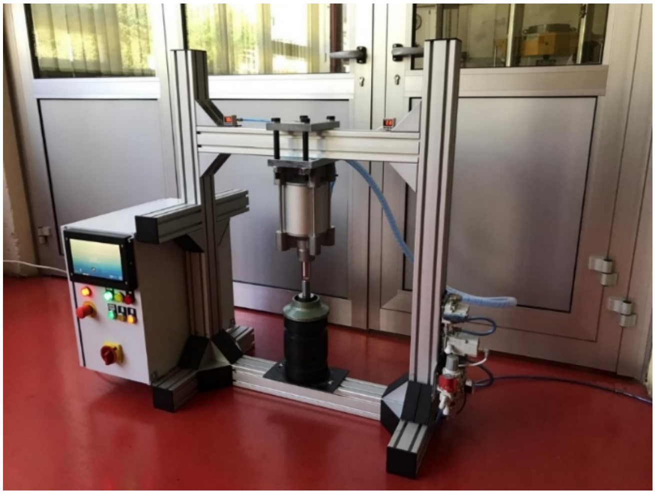


Figure 6: Pneumatic device for testing dynamic strength of materials.

The 9 inches LCD screen is selected for communication between the system and the operator. The screen size is suiTable for simply entering the required parameters of the test process and to display graphs of measured values from the sensor. The HMI system type SK-90DT from 4DSystems enables easy communication and data transfer with the control unit. The programming process is done in the Workshop software from 4Dsystems, while the program uses a combination of a graphical interface and the C programming language. The constructed pneumatic device for testing the dynamic strength of materials is shown in Figure 6.

4 Pneumatic system for products sorting

Transporting products on the conveyor belt and sorting them according to different characteristics is a very common task in automated production lines. The technology of marking and identifying various objects has long been used, and one widespread way of marking products intended for automatic detection is barcode, which can be read using a reader with a photo diode and a decoder, but with the involvement of a human operator. Using a camera to capture items on the conveyor belt and sort according to specific product features, the sorting process could be automated. Therefore, the practical implementation of an educational model using a vision system for sorting products marked with a barcode can be useful in teaching automatic control and vision systems [9].

Through years of research and development, computer vision systems have become more efficient in terms of image perception, detection, and processing [10]. Today they are used in many branches of industry, trade, medicine, and transport. Furthermore, vision systems are increasingly used in security systems, face recognition, fingerprint, and other applications. A barcode is a way of marking a product through a series of dark and light lines. This code is easy and simple to read using a camera or laser, so it is widely utilized in product recognition. Most often the bar code is added to the products after the production process is completed and after the product leaves the production line. Consequently, each product has its own unique code that is easy to read and follow up over a lifetime.

The designed conveyor belt has a drive drum powered by an electric motor, and a driven drum at the other end of the conveyor belt. The gravity tank contains the products with barcode to be sorted. The products are arranged vertically, and at the bottom of the tank a pneumatic cylinder (SMC CJ2B10-60) pushes objects one after another onto the conveyor belt. After one operation is performed, the cylinder rod is retracted, the next product falls into the position of the previously pushed object and the procedure is repeated. The operation of the vision system is based on a camera that reads a 2D barcode. The collected data is sent to the Raspberry Pi2 module Due to compatibility with the control unit, an 8-megapixel Raspberry Pi V2.1 camera from the same manufacturer is used, because the motherboard of the control unit contains the original connector for this camera. In the terminal software of the Raspberry Pi it is necessary to install the SimpleCV module which allows barcode reading and image processing. Another module that must be installed is Zbar which processes barcodes. If the camera is properly installed and if its operation is enabled in the Raspberry Pi software terminal, the bar code is read when the object comes into the camera's detection field. After the camera detects the barcode, that code is saved and compared in the program with the code values from the database. During the testing of the operation of the conveyor belt, the moment of activation of an individual cylinder was determined after the barcode was detected on a certain type of product. This setup can sort three types of products, so two cylinders (SMC CD85F25-160-B) are used to push the product off the belt into separate containers, and a third type of product falls into the container at the end of the belt. Three monostable 4/2 solenoid valves (SMC VQD1121) are used to control the movement of the cylinders. The air pressure at the system inlet is adjusted using the pressure regulator (SMC-AR20-F02H-N).

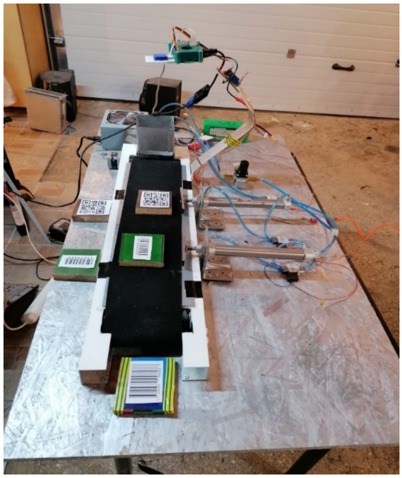


Figure 7: Pneumatic conveyor belt for products sorting.

A support pole is attached to the conveyor belt, which carries the camera and the control unit. The computer power supply is used to operate the conveyor, control unit and relay, while the valves are connected to a separate 24 V power supply. The Python programming language is used to program the control unit. Figure 7. shows the developed pneumatic conveyor belt system for sorting products using a vision system.

5 Position control of a hydraulic cylinder using cartridge valves

Cartridge valves can be used to obtain various functions in the hydraulic circuit which are usually achieved by using traditional valves to control the pressure or flow of the working fluid [11]. By using cartridge valves it is possible to realize cheaper hydraulic systems, which are more compact and require less installation space, they have a shorter switching time than classic solenoid valves, less fluid leakage, less sensitivity to oil contamination, require less assembly time and enable construction of compact hydraulic systems because they are installed in a drilled aluminium block or manifold. In order to use these valves properly, a good understanding of their operation is required. Therefore, the design of a hydraulic servo system that uses cartridge or logic 2/2 valves to achieve precise positioning of the hydraulic cylinder could clearly demonstrate the possibilities of application of these valves in mobile systems and industrial plants. Cartridge valves are usually built into drilled manifold but they can also be available in individual bodies and currently they play an important role in many fluid power systems across a broad spectrum of industries. Valve cartridges can be thought of as bodyless-valves without an integral housing, until they are inserted into a suiTable housing. There are two types of cartridge valves: screw-in catridges and slip-in catridges. Directional screw-in cartridge 2/2 valves were used to make a functional hydraulic circuit on a realized experimental setup. The use of cartridge valves is common in mobile machines where built-in valves are an integral part of the working hydraulic circuits. In the process of designing machines, there is often a requirement for the compactness of hydraulic systems, so hydraulic integrated circuits (HIC blocks) are performed. By using different types of cartridge valves such as directional control valves, pressure and flow control valves, load holding valves or sequential valves, complex HIC blocks can be realized that enable multi-actuator operation.

Figure 8 shows a functional diagram of a developed system for controlling the position of a hydraulic cylinder using cartridge valves. By activating the 2/2 valve (position 1.12) and the flow control valve set in the bypass (position 1.7), the flow towards the control valves can be changed. The system is unloaded by activating the 2/2 valve (position 1.10) in the second bypass line.

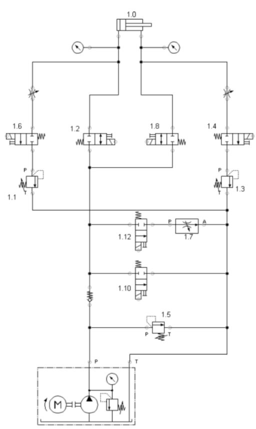


Figure 8: Functional diagram of hydraulic cylinder controlled with cartridge valves.

Figure 9: Experimental setup of a hydraulic cylinder controlled with cartridge valves.

The Controllino Maxi controller was used as a control device. It combines the flexibility and advantage of an open source program like the Arduino with the security and reliability of a PLC as a standard industry component. The

Controllino device enables USB communication, the use of analogue and digital inputs or outputs to activate the cartridge valves, and can receive signals from the encoder. The encoder and the program code constantly monitor the current position of the cylinder piston also during manual control so that the program has information about the position of the cylinder at the time when the user activates the switch for automatic mode. When the automatic mode is started, the program already has the value of the piston position obtained from the encoder. This current position will in almost all cases be different from the setpoint value, so a control error is calculated and then it is determined which cartridge valves must be activated to achieve the desired position. The program then determines whether the difference is positive or negative, two cartridge valves with a higher nominal flow (positions 1.2 and 1.8) are activated and the movement of the cylinder piston starts. When the piston comes close to the set position (according to the program, this is the range between 13 and 25 pulses), a logic valve (position 1.12) is activated which slows down the movement of the cylinder piston. Furthermore, when the piston comes very close to the desired position (the range between 1 and 13 pulses), cartridge valves (position 1.4 and 1.6) with lower nominal flow are activated (and at the same time valves with higher flow are deactivated). This ensures a low cylinder piston speed and thus the cylinder reaches the desired position with high precision. The control program does not stop after only one positioning, because at the end of the program a new desired position is set which the cylinder should reach. In this way, the program code will be executed as long as the switch is deactivated, the automatic mode will be stopped and the user can continue working in manual mode. However, as mentioned earlier, after the automatic mode is interrupted, the generated pulses from the encoder are still collected in case the user decides to return to the automatic mode.

The experimental setup made to demonstrate the position control of the hydraulic cylinder using cartridge valves is shown in Figure 9. The developed experimental system is an interesting educational setup where the capabilities of cartridge valves in hydraulic cylinder positioning tasks can be demonstrated. Also, various terms in the field of electrohydraulics and programming process can be explained. The system also has great potential for further development and upgrades.

6 Conclusion

The paper has presented four experimental systems powered by pneumatic or hydraulic drive. These systems have been designed in the Laboratory for Automation and Robotics at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb as projects within student undergraduate and graduate theses. The systems can be used as test models within the field of fluid power drives and automatic control education of mechanical engineering students. The complete educational experience involving theoretical and practical applications of different control techniques applied to different implementations of fluid power systems provide a realistic insight into the actual behavior of the system.

The article was first introduced an example of a pneumatic motor speed and position control using a proportional directional control valve. This project is largely based on experiences from past activities in our Laboratory, which has resulted in several successfully implemented experimental systems in the field of mechatronic systems actuated by pneumatic actuators [12, 13]. Then the paper has described the design and control of a test device with pneumatic drive for determining the dynamic strength of materials, on which the fracture mechanics of materials due to the action of dynamic stress can be experimentally demonstrated and the resistance of materials to cyclic stress can be analyzed. Then the article has presented the design, construction and control of a pneumatically driven system for sorting products marked with a bar code using a vision system. Finally, the article has presented an experimental setup for precise position control of a hydraulic cylinder using 2/2 cartridge valves, which can clearly demonstrate the application possibilities of these valves in industrial plants and mobile systems.

By using these experimental systems students have the opportunity to learn about mechanical systems construction and control of practical systems built from real industrial components.

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