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Pneumatic Balancing Mechanisms in Control Education

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The paper presents three balancing mechanisms, which have been utilized as experimental systems in the control education of mechanical engineering students. Their uniqueness is the pneumatic drive, which makes them more affordable, simpler and more interesting to control. These balancing mechanisms are the inverted pendulum, the inverted wedge and the ball and beam, while the pneumatic infrastructure includes a variety of valves. This paper describes these experimental systems and some methods applied to control them.

Keywords: control education; experimental systems; mechatronics; pneumatics

INTRODUCTION

FEEDBACK CONTROL is one of the most theoretical and abstract of engineering subjects. On the other hand, mechanical engineering or naval architecture students are often less open to abstract considerations, mostly as a result of their previous training, which is certainly a drawback that should be addressed in practicing control education. Therefore it is particularly important to demonstrate possibly abstract concepts using a familiar, but interesting physical system; some of these concepts can only be fully accepted through hands-on experience [1]. There is an overall consensus that it is important that students should be involved in control laboratory experiences as an essential part of control education [2]. Some of the objectives that a control laboratory system should have are to validate and demonstrate analytical concepts and introduce real world modeling and control issues. The example exercises and case studies in control education were also discussed at the Workshop on Future and Emerging Control Systems organized by the European Commission [3].

Laboratory exercises of some familiar courses such as Automatic Control, Mechatronics, Robotics and Fluid Power have taken place in the Laboratory for Automation and Robotics at the Faculty of Mechanical Engineering and Naval Architecture on the University of Zagreb. The Laboratory has diverse experimental systems that expose students to the main issues of feedback control and related disciplines. This paper describes three different balancing mechanisms driven by pneumatics that have been used in control education. These are the inverted pendulum, the inverted wedge and the ball and beam. The feature that distinguishes them from usual balancing mechanisms is their pneumatic drive, which makes them exceptional, simpler and more affordable once you have a pneumatic infrastructure. These were the exact arguments used to develop pneumatic mechanisms described here. In addition, the research into modeling and advanced control methods applied on pneumatics gave an initial momentum to the development of the pneumatic infrastructure (the results can be seen in [4–6]), which has been extended over time.

The balancing mechanisms were designed and constructed throughout the student projects, mainly within the Mechatronics course. The teaching of mechatronics using the description of the design of the pneumatic inverted pendulum is given in [7].

The paper is organized as follows: in the next section the necessary pneumatic and control infrastructure is described. This is followed by a description of the mechanisms, and the applied control methods and related issues are then discussed. The last section gives a description of the educational experiences.

PNEUMATIC AND CONTROL INFRASTRUCTURE

These balancing mechanisms require a pneumatic infrastructure, which they share, making the manufacturing of an experimental system cheaper and simpler. The variety of valves available offers plenty of diverse control options with different characteristics, and at different prices. The pneumatic infrastructure with its basic control elements is showed in Fig. 1. It consists of a compressor, units for preparation and distribution of pressurized air, different types of valves (1) that control the motion of a pneumatic actuator (2),

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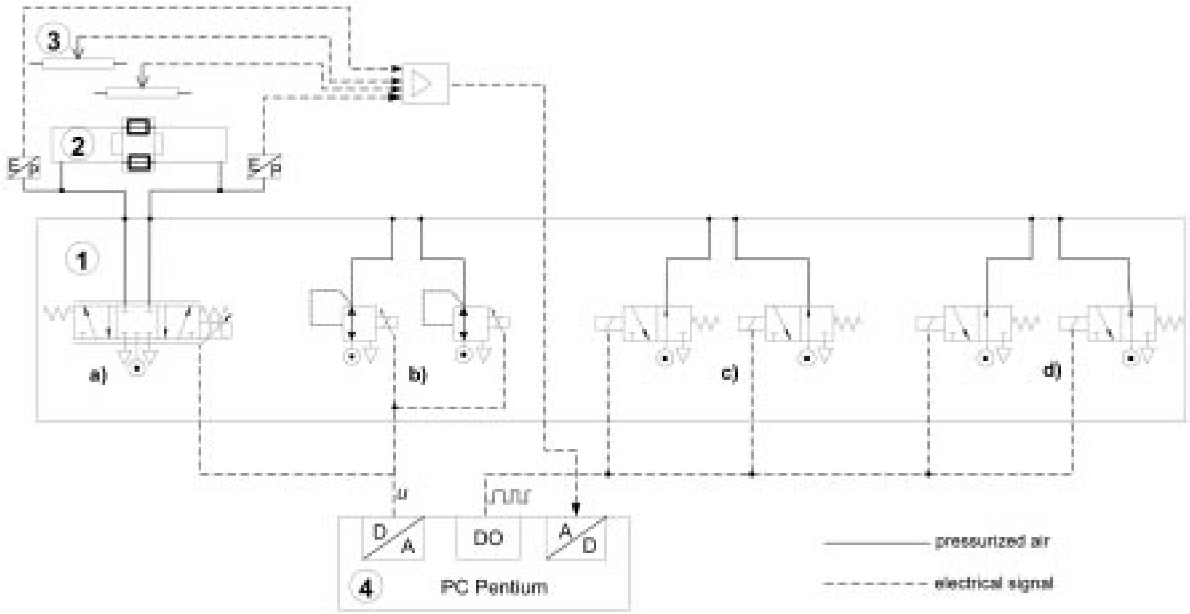

Fig. 1. Pneumatic scheme with control elements.

which is a constructive part of any balancing mechanism. The balancing mechanisms also comprise potentiometers (3) (or possibly other types of transducers), which measure the movement of the elements of the mechanism. Pressure transducers (E/P) measure the air pressure of the supply, and the air pressure in the actuator's chambers. This enables an accurate estimation of the force or acceleration of a piston. A personal computer (4) with associated electronic cards and software (Matlab/Simulink with Real Time Workshop and dedicated program in C-code), serves as the control unit. The applied valves (1) are:

a) the proportional directional 5/3 valve;
b) the pair of proportional pressure reducing valves;
c) the pair of simple on–off 3/2 valves;
d) the pair of fast on–off 3/2 valves.

The balancing mechanisms can be controlled by any of these four types of valves. However, the closed-loop behavior differs because of the diverse characteristics of the applied valves. Basic data for the applied valves are listed in Table 1. The proportional directional valve gives the best performances, and it has a continuous nature that is suitable for application in many control methods, therefore it is mainly used in the laboratory exercises and demonstrations. On the other hand, the proportional pressure reducing valves are quite slow, which reflects considerably on the control properties of the balancing mechanisms. More extensive comparisons of the applied valves are given in [4]. The pneumatic actuators (rodless cylinders or rotational actuators) are considered to be part of the mechanisms, and they are described in the next section.

BALANCING MECHANISMS

Translation or rotation of the pneumatic actuators balances the mechanisms. The described mechanisms, according to the Lagrange formulation, have two degrees-of-freedom (DOF), and they can be treated as planar robot arms. They are controlled by just one actuator, or they have just one control input (hence they are 'underactuated'). A schematic diagram of the balancing mechanisms is given in Fig. 2. This shows the

Table 1. Applied valves

	Producer and type	Solenoid	Command voltage (V DC)	Max. switch. frequency (Hz)	Pneumatic connection	Nominal flow (l/min)	Price ratio[1]
a	FESTO MPYE-5 1/8 HF-010B	Proportional	0–10	100	G 1/8	700	1
b	SMC VY1A00-M5	Proportional	0–5	5[2]	M5	400	2.2
c	SMC EVT307-5D0-01F	On–off	24	10	G 1/8	200	0.3
d	FESTO MHE2-MS1H-3/2O-QS-4	On–off	24	330	4 mm	100	0.28

[1] Approximated price, in respect to the ratio to the proportional directional 5/3 valve. For others, the pair of valves is considered.
[2] Not indicated, but it is experimentally estimated to 5 Hz.

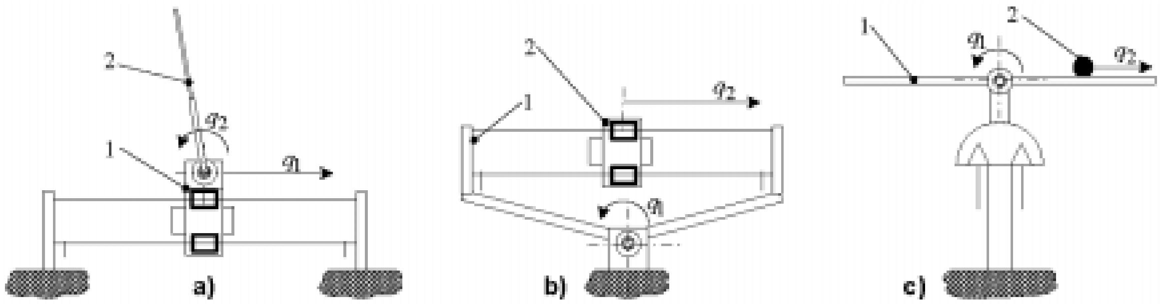

Fig. 2. Balancing mechanisms: (a) inverted pendulum; (b) inverted wedge; (c) ball and beam.

inverted pendulum (a), the inverted wedge (b), and the ball and beam (c). They are shown in Figs 3 and 4. The pneumatic outfitting can also be seen. The basic parameters of the mechanisms, as well as the applied equipment, are given in Table 2. More details of each mechanism are listed below.

1. Inverted pendulum

The pneumatic rodless cylinder is fixed at the base, and the motion of the slider (piston with the joint of the pendulum) (1) maintains the attached pendulum (2) in balance. The length of the pendulum is variable (telescopic), and by varying it one can clearly demonstrate the influence of the changes in parameters on the behavior of the controlled system. The motion of the slider (variable q_1) is measured by the linear potentiometer, while the angle of the pendulum (q_2) is measured by the rotational servo-potentiometer. A more detailed description of the inverted pendulum, including the nonlinear and the linearized mathematical model of dynamics, is given in [7].

2. Inverted wedge

The pneumatic rodless cylinder is a part of the frame (1) that can turn around the point of rotation (variable q_1). The motion of the slider (piston) (2) balances the frame. The inverted wedge has a nonminimum-phase characteristic, which is the result of the effect of the reactive force. In fact, pressure in one chamber not only pushes the piston, creating a useful torque that stabilize the frame, but it also pushes the cylinder in the opposite direction, thus producing a reactive torque which has a detrimental effect on the stability. That can also be seen from the mathematical model and pole-zero map of the system, which is described in [8]. The angle of rotation of the frame (variable q_1) was measured by the rotational servo-potentiometer, and the motion of the piston (q_2) was estimated by the observer [8]. In order to improve the control results, an additional rotational servo-potentiometer was added later, and it was connected to the slider by a wire, so its movement could be directly measured (variable q_2). This is described in [9].

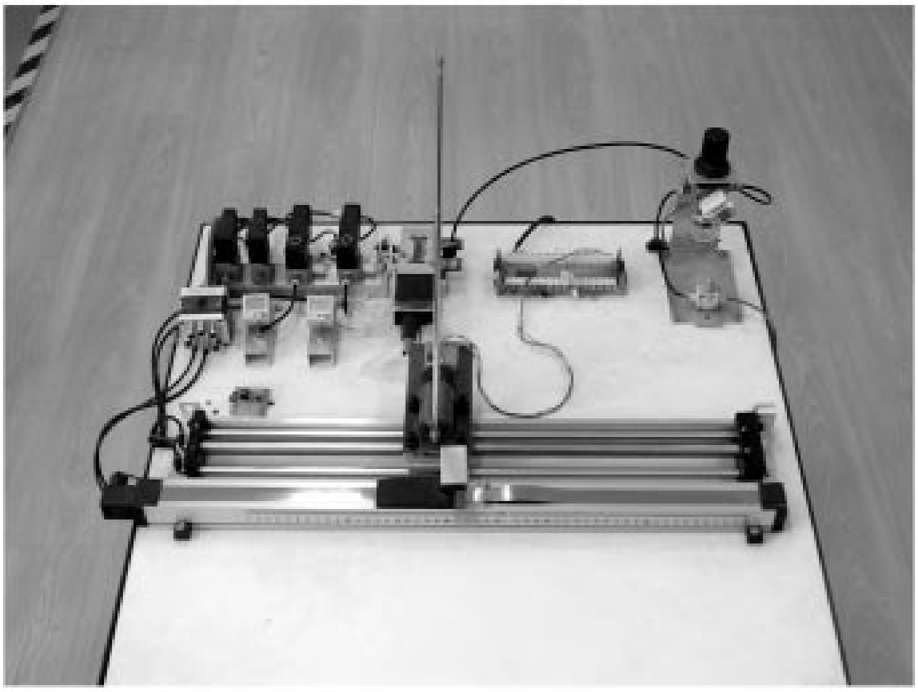

Fig. 3. Photograph of inverted pendulum.

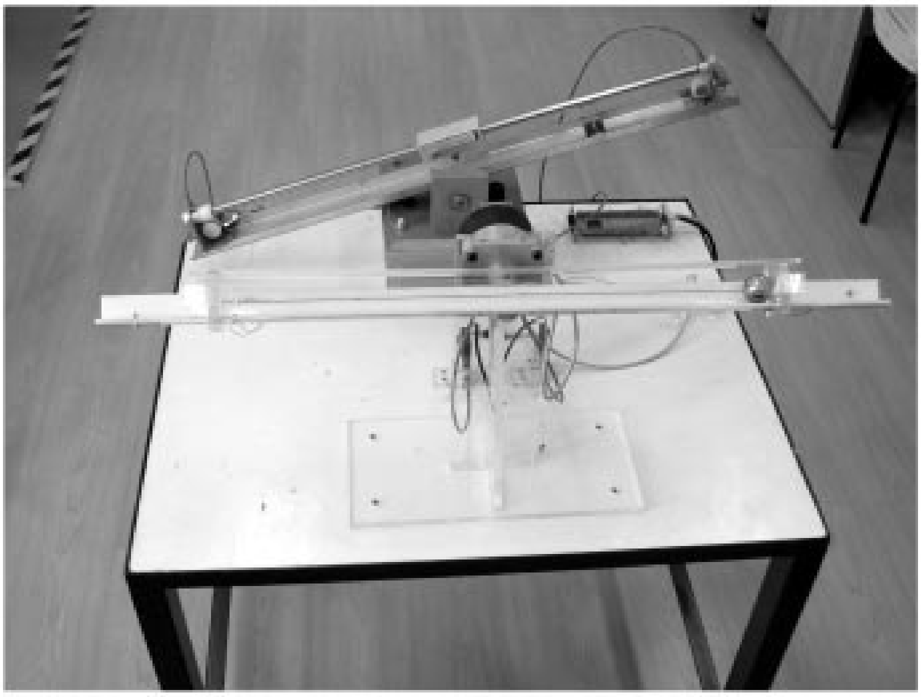

Fig. 4. Photograph of ball and beam and inverted wedge (at the back).

3. Ball and beam

The pneumatic semi-rotary actuator with a limited angle of rotation controls the rotation of the beam (variable q_1), which keeps the ball in the desired position (q_2). The angle of rotation of the beam (q_1) was measured by the rotational servo-potentiometer. Initially, the motion of the ball (q_2) was measured by the ultrasonic transducer (Pepperl-Fuchs UC 500-30GM-IU-V1-R) set at the end of the beam, but the results were not satisfactory because of the relatively short measuring range (approximately 35 cm) owing to the small measured area of the ball and its spherical form. Later, resistant wire was used because of its affordability (it was taken from a cheap rotational potentiometer and glued to the beam, and the associated electronics were custom made). The steel ball closes electric circuit, and the resistance changes according to its position. The dynamics of the ball and beam are very interesting, and it has become a benchmark for some advanced control methods applications (for example in [10], and many works later). Here, the centrifugal force provides a strong positive feedback and can lead to a peaking phenomenon. If the beam angle is not controlled well, the ball may jump off the beam, so inducing a feedback signal giving an incorrect position of the ball. The mathematical model of

Table 2. Parameters of mechanisms and applied equipment

Inverted pendulum	
Rodless cylinder	SMC CDY1S15H-500; stroke = 500 mm; Ø = 15 mm
Linear potentiometer	FESTO MLO-POT-500-TLF
Rotational potentiometer	Spectrol, servo quality
Slider (1)	mass = 1.5 kg; viscous friction[1] = 65 Ns/m
Pendulum (2)	mass = 0.06 kg; gravity center = variable
Inverted wedge	
Rodless cylinder	FESTO DGO-12-600-P-A-B; stroke = 600 mm; Ø = 12 mm
Rotational potentiometers	Spectrol, servo quality
Frame (1)	mass = 1.1 kg; gravity center = 30 mm; viscous friction[1] = 0.05 Nms
Slider (2)	mass = 0.25 kg; height = 62 mm; viscous friction[1] = 45 Ns/m
Ball and beam	
Semi-rotary actuator	FESTO DSM-25-270-P-CC, swivel type
Rotational potentiometer	Spectrol, servo quality
Ball position measurement	resistant wire, length = 530 mm; resistance = 50 kΩ
Beam (1)	V profile; mass = 0.45 kg; length = 800 mm; visc. friction [1]= 0.1 Nms
Ball (2)	mass = 0.12 kg; Ø = 30 mm; roll friction = 0.7 Ns/m

[1] Friction values are estimated experimentally.

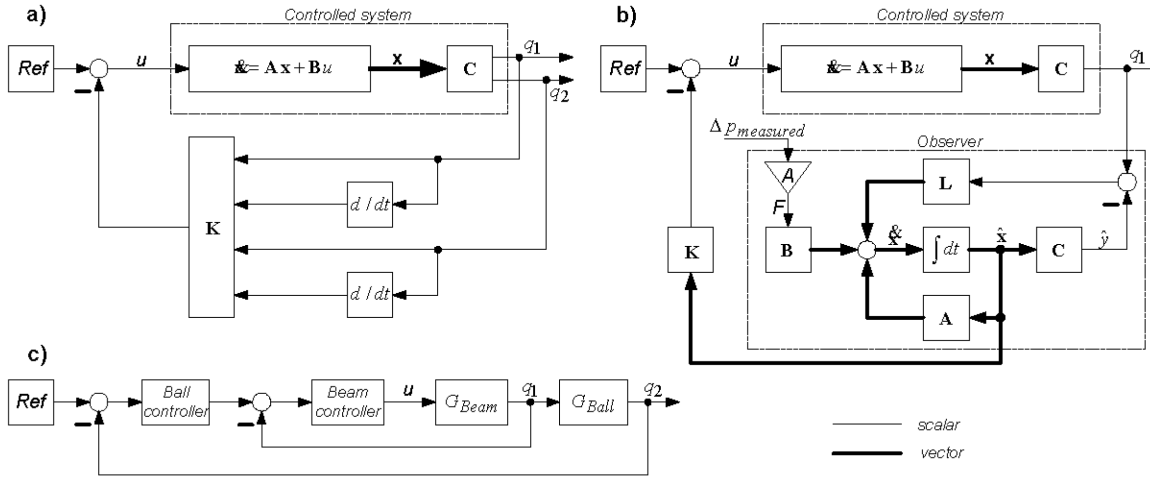

Fig. 5. Control schemes: (a) state-variable feedback; (b) state-variable feedback with observer; (c) cascade compensation.

the dynamics of the ball and beam, and a more thorough description of the laboratory system is given in [11].

APPLIED CONTROL METHODS

Pneumatic balancing mechanisms offer many opportunities for the application of feedback control. They are inherently unstable, some of the attributes that concern control have been mentioned (underactuation, nonminimum-phase, peaking), and this certainly makes their control an interesting task. A sample with a simple PD or PID controller acting on the output variable of the inverted pendulum can demonstrate this. It can successfully hold the pendulum upright, while the slider moves to infinity. So it is useless here, as well as for control of other two mechanisms. This can be proved both experimentally and theoretically, by analyzing closed loop roots. Therefore some other control methods were used (shown in Fig. 5): state-variable feedback with linear quadratic regulator (LQR) optimal design (a); the same control with the observer (for the inverted wedge) (b); and the cascade compensation (applied on the ball and beam) (c). These control methods have also been combined with the pulse-width modulation (PWM), which is particularly appropriate for control the valves with on–off solenoids.

4. State-variable feedback

State-variable feedback has been applied with the LQR optimal design. It requires a knowledge of the mathematical model of the system. The weighting matrix **R** has been kept equal to the identity matrix, while the initial value of weighting matrix **Q** was equal to **C'C**. They were adjusted after analysis of the closed loop poles and after computer simulations. The final adjustments were made after experimental trials, which emphasizes the importance of hands-on experience. Properly designed, the state-variable feedback was successful in the control of any balancing mechanisms.

5. State-variable feedback with observer

Since the initial experiments on control of the inverted wedge were made without measuring the slider position (variable q_2), the full-order observer was added in order to estimate q_2. A discussion on the design of the observer, about the effects of its gains and about the influence of the added integral action, is given in [8]. The results were not quite satisfactory, so an additional potentiometer was added, which can measure the slider position directly, thus making the observer unnecessary. Control results in this case were excellent, and are described in [9].

6. Cascade compensation

This has been applied only to control the ball and beam, although it can certainly be used for other mechanisms by. Two feedback loops were required—the inner, to control the angle of the beam, and the outer, to control the motion of the ball. Both the controllers were simple PDs, and the control results were reasonably good (the semi-rotary actuator of the ball and beam is relatively large and, coupled with the existing valves, it cannot reach an adequate speed). More details about cascade compensation applied to the ball and beam are given in [11].

7. Pulse-width modulation

The control methods already mentioned can be combined with the PWM signals, which are suitable for control the valves with on–off solenoids, since they do not need to be demodulated and have better energy efficiency. However, because of the solenoid's dead time, attention has to be paid to the frequency of the PWM signal, which should be specified according to the valve switching frequency (discussion given in [12] and [4]).

The pneumatic balancing mechanisms that have

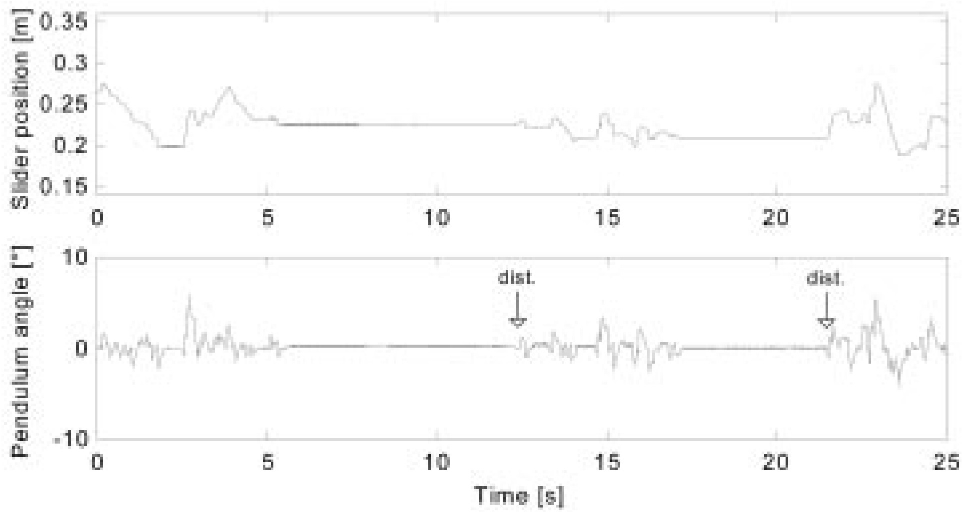

Fig. 6. Slider position and pendulum angle of inverted pendulum.

been described also provide consideration and demonstration of many other important practical control and modeling issues, such as the influence of parameter changes, sensor choice and position, signal noise and filtering, and the influence of actuator dynamics and its integration in model and control. This is considered in more details in [7–9, 11].

One example of the responses of the inverted pendulum controlled by the state-variable feedback is given in Fig. 6. The figure shows the slider position (q_1) and pendulum angle (q_2), the denoted disturbances were impulses given to the pendulum using a fingertip. It can be seen that the pendulum was efficiently calmed after about 5 seconds.

EDUCATIONAL EXPERIENCES

The complete educational experience involving classical and modern control theory as well as practical applications and comparative analysis of different control techniques are recognized by educators in universities and control laboratories around the world. The teaching areas that can benefit by using pneumatically based experimental models described in this paper are: influence of mechanical parameters to the system characteristics, mathematical description of the system, parameter identification of the process, simulation and analysis of nonlinear and linearized models of the system, consideration of different control techniques and their experimental verification. In this way, the courses that relate to control education and mechatronics can additionally improve practical-oriented experiences in the mechanical engineering curriculum. Different system designs can be quickly assembled, enabling students to test their control algorithms on real systems. Through this laboratory-based course, students were introduced to basic system modelling procedure, simulation and conventional control methods up to modern and intelligent control theory. This approach is consistent with the context-based learning models, described in [13], which additionally attract students' interest in the matter of control, and with the interdisciplinary approach to the control education, which is stressed in [14]. There the mechatronics impact on control education is assumed to be particularly valuable.

The feedback from the students has been very good, and they pointed out that laboratory-oriented teaching activities allowed them the opportunity of practical realization of control systems, experience with different electric and pneumatic components, a physical insight into the mathematical model of the system and also gave them a perception of the imperfect nature of real systems in their operation as opposed to the theoretical ideal, which is often used in system analysis and simulations. Thus, the students generally had positive attitude towards laboratory-oriented lectures: they can implement real-time control algorithms, which give them a better understanding of more complex industrial systems. In addition, several students have written their diploma thesis based on modern and intelligent control techniques using the experimental models described in this paper.

CONCLUSIONS

The paper presents three balancing mechanisms, which have been used for hands-on experience in the control education of mechanical engineering students. Their uniqueness is the pneumatic drive. This makes them more affordable to manufacture once one has a pneumatic infrastructure, and the wide variety of pneumatic valves offers different opportunities in application and comparison of diverse control methods. The mode of operation of pneumatic elements is obvious to the mechanical engineering students, so the effects of the controls can be more easily experimentally demonstrated and explained.

The applied control methods used state-variable feedback, as well as employing a full-order observer, and cascade compensation. The PWM signals were also applied. Some important practical control and modeling issues, such as the influence of parameter changes, sensor choice, signal noise and filtering, influence of actuator dynamics and its integration in model and control, can be easily and effectively demonstrated using these experimental systems.

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