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Laboratory real-time systems to facilitate automatic control education and research

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Abstract—**The paper is an attempt to interest the reader how to control real-time mechatronic systems under the MS Windows operating system. The authors refer to solutions that combine a software part and a hardware using the FPGA technology, together forming a comprehensive platform for the control purposes in the real-time. The main emphasis is placed on the authors' own designs and constructions. Lectures and laboratory experiments must be conducted hand in hand. Such is the message to facilitate the *Automatic Control* education. Research works have been carried out in the Department of Automatics at the University of Science and Technology (AGH).**

I. Introduction

THE paper presents important aspects of education provided with the use of laboratory experiments. How to facilitate the teaching of control theory which can not go without a control experiment performed in the real-time? Researcher, scientist, teacher, engineer should use the laboratory computer controlled systems. That is the systems that we create and by which we teach young people. These systems are the subject of further considerations. The work focuses on:

❍ development of software to enable a control in real time involving a popular MS Windows operating system,
❍ construction of simple and also advanced mathematical algorithms for control purposes in the real-time,
❍ implementation, verification and tests of the developed algorithms in the self-designed and constructed complete mechatronic systems such as: the gantry crane, tower crane, magnetic levitation, magnetic bearings, anti-lock braking system, pendulum on a cart, the multi tank, etc.,
❍ usability of the same software and hardware platform to perform simulations and real-time experiments.

While teaching the automatic control it is reasonable to intertwine lectures and laboratory experiments. In particular this field of knowledge requires to be exposed through demonstrative laboratory tools. A prominent pedagogue equipped only with chalk and his knowledge can be under a misapprehension that a pure theory presented at the lecture is just what was expected by the audience. In fact, such a lecture may become as interesting as watching grass grow. One has to be far from impression that he is just presenting electro-mechanical toys in motion even quite complex due to involved preprogrammed control algorithms. In fact, one may notice a smell of mechatronic systems and it is not bad. However, our address has a different goal, namely how to facilitate the automatic control education.

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II. Real Time Control

A. Real-time services in MS Windows systems

MS Windows can not be considered as robust hard real-time operating systems. However some features of the system can be applied to develop a soft real-time platform. The main parameter of the real-time control systems is the sampling time period – its maximum frequency and accuracy. The timing services built into the MS Windows systems are:

❍ system timer message (WM_TIMER),
❍ multimedia timer events,
❍ kernel mode services. The RTWT kernel driver is considered in this comparison.

The system timer is posted to a thread's message queue when a timer expires. The minimum sampling period of this service is 1 millisecond. In fact, the system processes the WM_TIMER message at low priority influencing the performance. Also, the minimum sampling in multimedia services is 1 ms. But the performance, considered as the timer jitter, seems to be much better. The best performance, both in the sampling period and the jitter, is achieved by kernel mode services.

Fig. 1, presents the histograms of three services. In all cases a 10 millisecond timer event has been started. The horizontal axis presents the duration of the sampling period. The duration was measured by a hardware timer with a 25 ns resolution. The vertical axis shows the number of sampling periods of a given duration.

One can observe that the WM_TIMER service behaves in a very poor way. The period was set to 10 ms but most of the sampling periods last much longer. Even a 260 ms period was observed. It is unacceptable for electrical and mechanical control systems. On the opposite side of the time regimes appear the RTWT service. Here the accuracy and jitter of the sampling periods i less then 15 ms. The multimedia timer can be located as an in-between solution. The average value of the sampling period follows the timer period setup, but a few millisecond jitter can be observed as well.

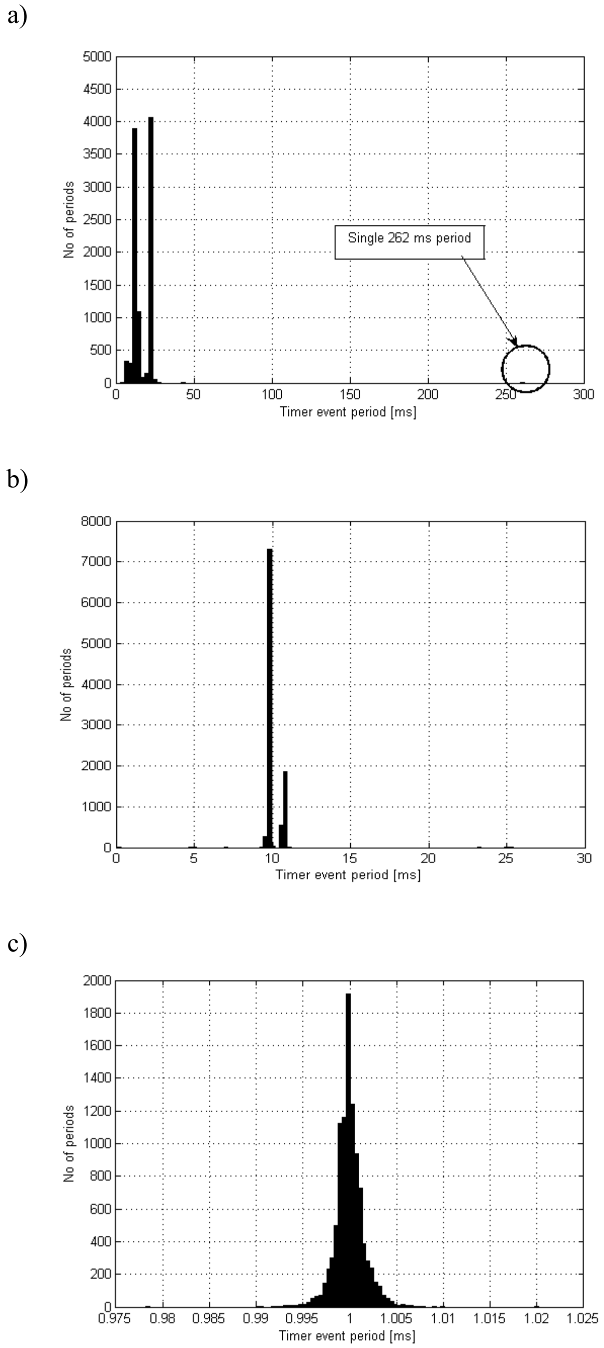

Fig.1. Histograms of the durations of the timing services: a) WM_TIMER, b) multimedia, c) RTWT timer

The timer services are executed in interrupt mode between operating system services and usually are not allowed to call all operating system functions. In the investigated timers the exception is the WM_TIMER procedure, where any OS call can be executed. The multimedia service disallows call only to a very limited set of OS functions. Such API functions like file I/Os, network functions or access to the USB stack, which are crucial to applications of measurement and control systems, can be executed in a timer service routine. The most restricted policy enforces RTWT timer. In this case the timer routine is executed at the kernel level and most of the OS API function may crush the system. The RTWT platform can be applied to cooperate with I/O boards plugged-into PCI or ISA buses but Ethernet or USB devices are unavailable.

Some functions of the control system may require a reaction faster than the response time of the presented timers. An interface to incremental encoder of safety functions can be given as an example. In such a case an additional hardware has to be used. The FPGA technology seems to be an ideal solution due to its flexibility.

III. Hardware implementation

A. *RTDAC-Board*

Standard PC computers are used most often as a control hardware in educational field. This solution has some advantages and disadvantages. The most important disadvantage is that PC hardware is not dedicated for control application. In most cases an additional hardware is needed. A control and/or measurement PCI or USB board is a good choice for educational usage. Control and measurement board should provide some basic features like analog inputs, analog outputs, digital inputs, digital outputs and communication with computer operating system. Some extra features e.g., incremental encoders counters are necessary for special mechatronic system like Inverted Pendulum or Crane.

Typically control and measurement hardware is used with many dynamical systems. This is the reason, that some kind of reconfigurability of the measurement board is necessary. This feature can be provide by using FPGA techniques. One of the FPGA control board is RT-DAC4/PCI [5] presented in Fig. 2.

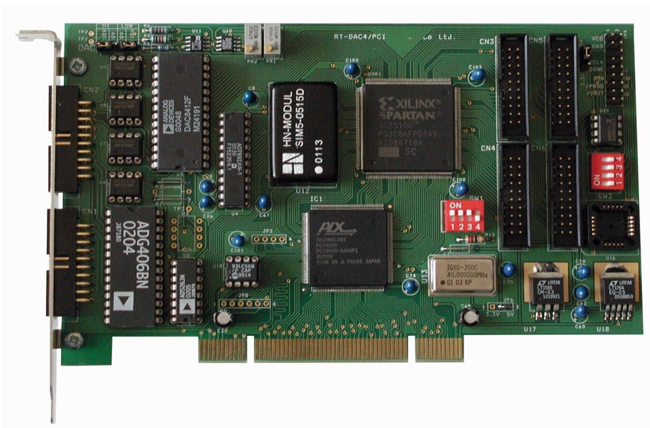

Fig. 2. RT-DAC PCI I/O board

The block diagram of this board is presented at the Fig. 3. The FPGA circuit can be reprogrammed from the PC computer level. This unique function guarantees flexibility of the device and a whole control system. User can manage configuration of the FPGA circuit by special software executed in the PC computer. Hardware functions can be modified by changing FPGA configuration.

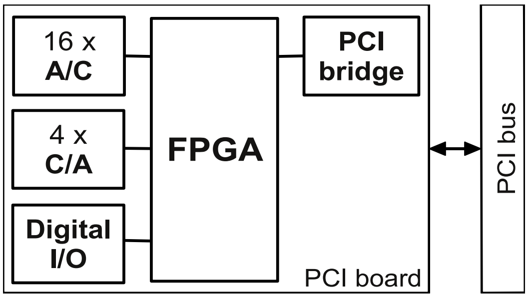

Fig 3. RT-DAC4/PCI block diagram.

FPGA control and measurement boards can work in three main modes that can be changed by reprogramming FPGA.

1. Basic mode. In this mode the board is equipped only with elementary functions. They support only simple operations with analog to digital and digital to analog converters and digital I/Os.
2. Advanced measurement mode. In this mode, the board is equipped with analog I/O operation functions, digital I/O operation functions, and some advanced measurements and control signal operation functions like incremental encoder counters, PWM functions, digital filter blocks, linearisation operation for analog signals. The control loop is closed by PC computer in this case. A designer can save additional processor time for calculations of the most advanced control algorithms in the computer by moving some operations from the software layer (PC computer control task) to the hardware layer (FPGA circuit).
3. Hardware control mode. In this type of operation the hole control task is located in the hardware layer. This is useful for time-critical dynamical systems. A high-speed control system is necessary in this case and PC computers are to slow to execute control tasks [9][8]. In this mode, only monitoring and supervisory operations are performed in a PC computer. Hierarchical high-speed control system can be also build with measurement and control board equipped with FPGA circuit. Direct control algorithms can operate in a hardware layer (FPGA) and optimisation or adaptation algorithm can operate in a software layer (PC software).

B. Power Interface

The power interface is an electronic device that provides connections between mechanical system and the controller (computer, PLC, microcontroller etc.). The typical structure of the power interface is shown in Fig. 4. It contains:

- ❍ power controller to activate the actuators,
- ❍ electronics for measurement signal conditioning,
- ❍ other electronics including optical insulation, protection against overvoltage and short circuit.

The main function of the power controller is to guarantee the required current and voltage range for actuators (DC motors, valves). The power controller operating in the PWM mode utilizes integrated bridge circuits supported by a control logic and protection system. Current and temperature are measured by integrated sensors. Depending on the controlled systems is used from one (the cart & pendulum case) to four (the tanks case) power modules. The power module provides required by the actuators voltages in the 12-24 V range and currents up to 16 A (the ABS case).

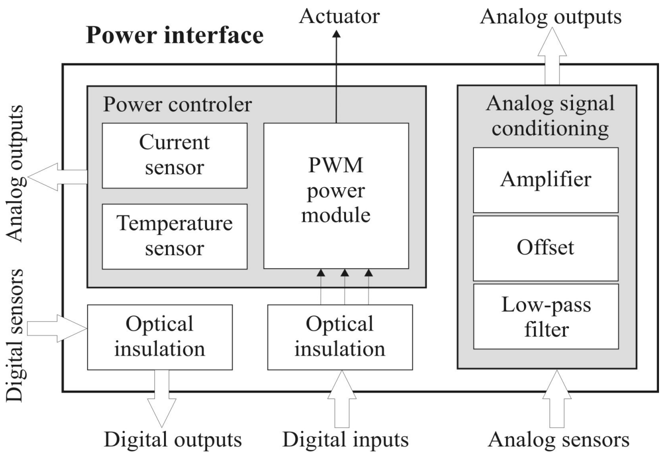

Fig. 4. Structure of the power interface

The analog sensors are connected to conditioning analog circuits. They provide the required measurement signal properties for a high quality A/D conversion. The analog signal conditioning block has an independent bipolar stable supply. Analog output signals from the conditioning block can be established as a unipolar or bipolar in the 0-10 V or ±10 V range respectively. These circuits are utilized to:

- ❍ increase or decrease the amplitude of the signal,
- ❍ filter the signal,
- ❍ decrease the signal output impedance,
- ❍ reduce the measurement signal bandwidth,
- ❍ provide a variable gain and offset control.

Optical insulation is used to protect the external I/O interface from overvoltage and overcurrent. It also provides a matching voltage levels.

In addition to these electronics circuits, power interface may also contains circuitry to handle voltage, pressure and strain gauge sensors.

The following sections present implementations of mechatronic systems that use the hardware just described.

IV. One Rotor Aerodynamical System (ORAS)

ORAS shown in Fig. 5 is a laboratory set-up designed for control experiments performed in the real-time. In certain aspects its behavior resembles the special type of one rotor helicopter. From the control point of view it exemplifies a high order nonlinear system with significant cross-couplings. ORAS consists of a beam pivoted on its base in such a way that the beam can rotate freely both in the horizontal and vertical planes.

At the end of the beam there is the rotor driven by a DC motor. The rotor position can be changed by the geared DC motor (see Fig. 6 and 7).

The state of the beam is described by four process variables: horizontal and vertical angles measured by encoders, and two corresponding angular velocities. Two additional

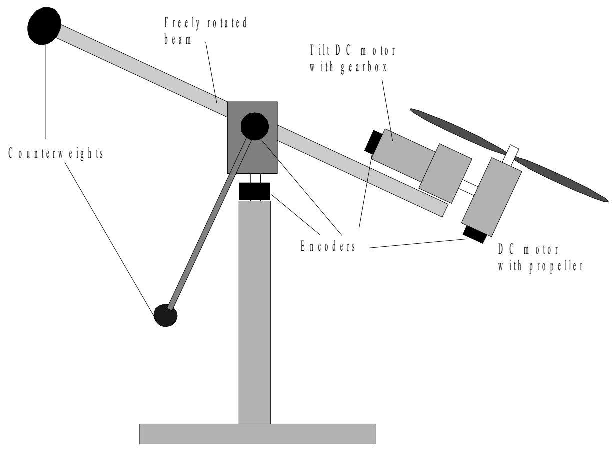

Fig.5 **O**ne **R**otor **A**erodynamical **S**ystem

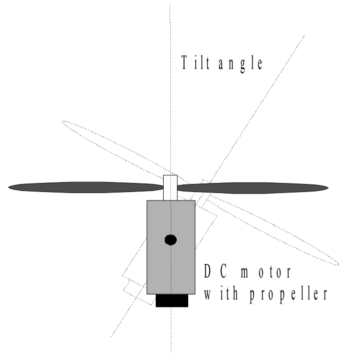

Fig. 6 Propeller tilt angle

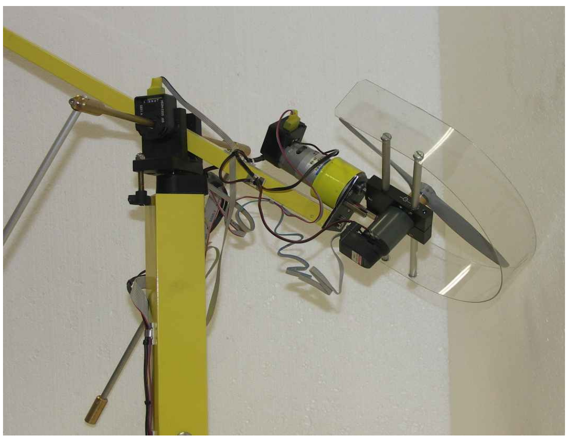

Fig.7 Laboratory set

state variables are the angular velocity of the rotor and the tilt angle. The ORAS system has been designed to operate with an external, PC-based digital controller. The control computer communicates with the position, speed sensors and motors by a dedicated I/O board and power interface. The I/O board is controlled by the real-time software which operates in the MATLAB/Simulink RTW/RTWT environment.

V. Tower Crane

Fig. 8 illustrates a general view of the model. The crane may hoist or lower a suspended payload and also move the payload along the rail and around the basis. The crane is controlled in the real-time in the MATLAB & Simulink environment [6][7].

Fig. 8 General view of the tower crane

A PC computer is equipped with an analog-digital board (RT-DAC USB [5]) to transfer data between the tower crane and a controller running on the PC. Digital outputs of RT-DAC are connected to the crane power interface, where the calculated by the control algorithm value of control is converted into a PWM type voltage signal and then distributed to one among three DC-gear motors.

There are two encoders mounted on the shafts to measure rotary positions. Subsequent two encoders are placed in the trolley mechanism for measuring a deviation of the rope from the vertical position. The measurements are performed in two planes (see Fig. 9). The third gear motor is placed directly inside the crane body. The shaft that transfers the motor torque is equipped with the next encoder that measures rotary position of the crane arm with respect to the basis. The Simulink driver has three inputs: XPWM, TPWM and ZPWM to control three motions: a trolley progressive, crane rotary and payload up or down. The control values may vary from 0 to 1. The value 0 refers to no control, value 1 means full control. The control is the PWM type. A value between 0 and 1 refers to the duty cycle of the control square wave. The switch “Reset” sets the encoder counters to value 0. It is used for calibration purposes.

There are five outputs: *X Position* is the trolley position related to the jib length, *T Angle* is the jib angular position related to the crane basis, *Z Position* is the rope length of the suspended payload, *X Angle* is the angle deviation of the

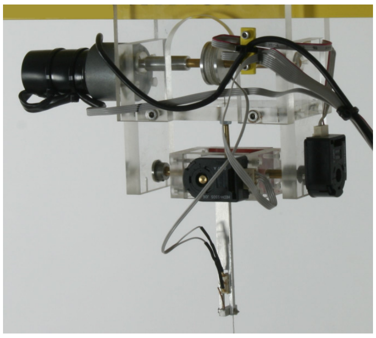

Fig. 9. Tower crane trolley

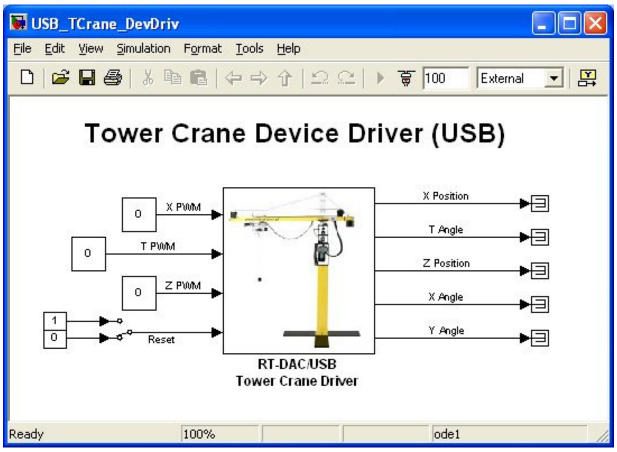

Fig. 10. Tower crane Simulink device driver

payload in the jib plane, *Y Angle* is the angle deviation of the payload in the plane, directed perpendicularly to the jib.

The laboratory model is not a copy of any existing industrial tower crane. It is a tool for research to examine phenomena that occur during motion of a suspended payload and to design control algorithms assuring a safe transport.

VI. Active Magnetic Levitation Systems (AMLS)

AMLS [14] represent structurally unstable systems where the system dynamics is adjusted by the operating controller. The performance of the controlled AMLS depend on the applied hardware and realized control strategy. A key point is to satisfy real-time conditions that allows to close the control loop with frequencies higher than 200Hz depending on the applied hardware and control tasks. Nowadays, AMLS are controlled in the digital form usually, where a number of hardware-software architectures is used, to satisfy mentioned requirements. The real-time controller processing time, computational effort and numerical representation of the processed digital system must be considered for the real-time application.

The AMLS candidates are available now in two designs: single and dual electromagnet (Fig. 11). Both of them contain the electromagnet, ferromagnetic object, position sensors, signal conditioning unit and power interface. The electromagnetic actuator is driven by PWM or current controller. In the first case the high frequency voltage signal is applied to the coil, while in the second one the coil current is kept at the desired level by the hardware current feedback. Both solutions affect the real-time control architecture. For the current driven systems the lower sampling frequency (200-400Hz) allows to control the AMLS using UBS based board [5]. The AMLS are connected to the PC via PCI based board usually equipped with the FPGA unit where the custom logic is implemented [5]. For the real-time control purposes the parallel signal processing board has been developed. The real-time control system performance can increase due to the parallel sampling. [10].

The basic principle of AMLS operation is to control an electro-magnet to keep a ferromagnetic object levitated. The object position is determined through a distance sensor or state observers. The equilibrium stage of two forces (the gravitational and electro-magnetic) has to be maintained by the controller to keep the sphere in a desired distance from the magnet. A number of real-time controllers has been developed to realize stabilization, program system dynamics (see Fig. 13), tracking and satisfy robustness.

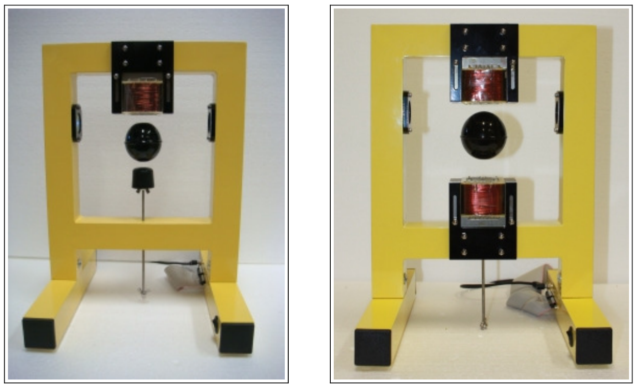

Fig. 11. AML Systems in a single and dual electromagnets versions [3].

From the real-time control point of view a time slot reserved for the application controller vary with respect to the controller architecture. The computational effort, control algorithm structure and numerical representation limit the execution time. For example a nonlinear robust fuzzy based controller [12] consumes more processing power that self tuning neural controller [11] and optimally tuned PID. The dual electromagnets AML can be used to check performance of the real-time controller. The lower electromagnet suits as an extra excitation signal (see Fig. 13) or increases the electromagnetic forces to speed up the system dynamics. The digital hard real-time realized in the form of custom FPGA embedded PID controller is mostly limited by the A/D converters speed. For the analog sampled hard-real time control the Dynamically Programmable Analog Signal Processor has been applied [13]. This solution allows to process sampled analog signals with tunable option of gains fast sampling rate up to 2MHz limited by the controller architecture.

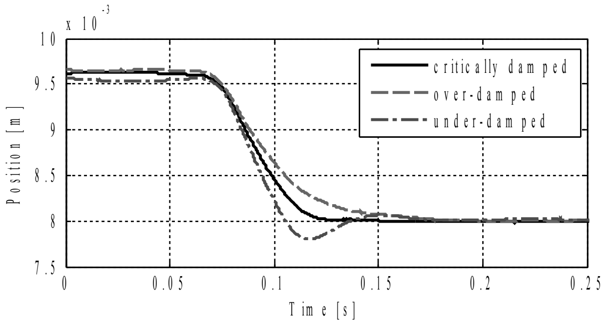

Fig. 12. Programmable dynamics of the AML System

AMLS are one of best tools to learn the control theory and real-time control due to the time-critical execution requirements of AMLS and its dynamics programming ease. Note, that limits of the real-time control systems or limited sampling frequency could make the system unstable.

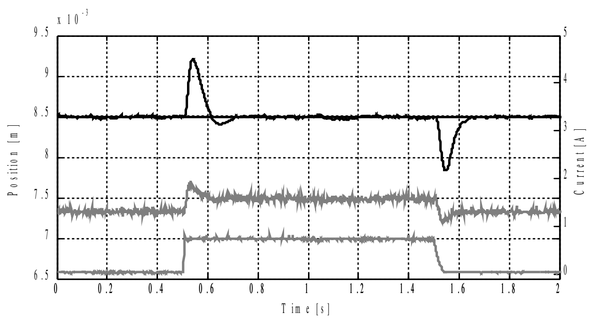

Fig. 13. Object stabilization at external square pulse excitation realized by the lower electromagnet [11]

For more information visit www.maglev.agh.edu.pl.

VII. Multitank system

The Multitank System consists of three water tanks placed above each other (Fig. 14). The uppermost tank is rectangular, the middle one is prismatic and the lowest is a quarter of a cylinder. The first tank thus has a constant cross section, while the cross sections of the two others vary with the water level. Water is pumped into the upper tank from a supply tank by a pump driven by a DC motor. The water flows out from the tanks only due to gravity. The orifices act as flow resistors. The outflow rate from each tank can be adjusted by a manual valves or proportional.

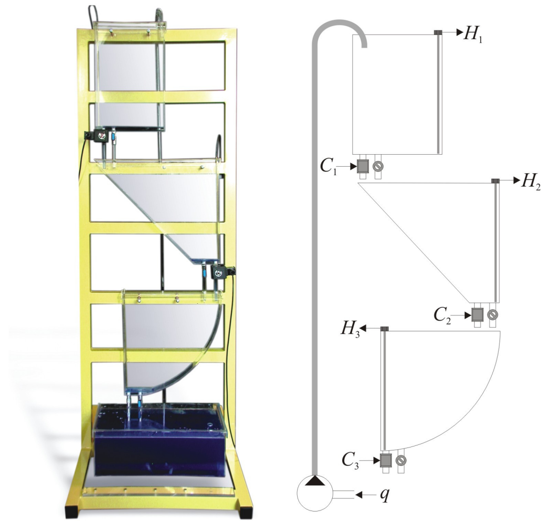

Fig. 14. General view of the tanks system

The levels in the tanks are measured with pressure transducers, which offers analog (0-10) V or digital interface (frequency signal from 100-200 kHz). The speed of the pump motor and proportional valves are controlled by PWM signals via power interface [4].

The goal of the Multitank System design is to study and verify in practice linear and nonlinear control methods. The general objective of the control is to reach and stabilise the level in the tanks (mainly the lower tank) by an adjustment of the pump operation or/and valves settings. The other control problems are: minimizing of the fluid level oscillations and stabilization of the outflow from the tank. These control problems can be solved by a number of level control strategies ranging from PID to adaptive and fuzzy logic controls [1][2].

The Multitank System has been designed to operate with following hardware control platforms:

- PC-based equipped with dedicated I/O board,
- PLC/PAC controller provided with PWM generator and analog (or high-speed counter) input modules,
- other FPGA/microcontroller based platform able to measuring analog or high-speed frequency signals and generating PWM signals.

Such a platform works as an external controller. The control system communicates with the level sensors, valves and pump by a dedicated I/O interface and the power interface.

The mathematical model of the process can be obtained by means of mass balance [15]:

$$\frac{dH_1}{dt} = \frac{q - C_1\sqrt{H_1}}{\beta_1(H_1)} \tag{1}$$

$$\frac{dH_2}{dt} = \frac{C_1\sqrt{H_1} - C_2\sqrt{H_2}}{\beta_2(H_2)} \tag{2}$$

$$\frac{dH_3}{dt}=\frac{C_2\sqrt{H_2}-C_3\sqrt{H_3}}{\beta_3(H_3)} \tag{3}$$

where: H_1, H_2 and H_3 are the water levels; $\beta_1(H_1)$, $\beta_2(H_2)$ and $\beta_3(H_3)$ are the cross sectional area of the tanks; C_1, C_2 and C_3 are the outflow coefficients and q is the flow into the first tank (control variable). The tank cross sectional areas are:

$$\beta_1(H_1)=a\cdot w \tag{4}$$

$$\beta_2(H_2)=w\left(c+b\frac{H_2}{H_{2\max}}\right) \tag{5}$$

$$\beta_3(H_3)=w\sqrt{R^2+(H_{3\max}-H_3)^2} \tag{6}$$

where a, b, c, w, $H_{2\max}$, $H_{3\max}$ and R are constants. The control and state components are bounded:

$$0\leqslant q(t)\leqslant 200\,cm^3/s \tag{7}$$

$$0\leqslant H_1(t), H_2(t), H_3(t)\leqslant 40\,cm \tag{8}$$

For the model (5), for fixed q=q_0 we can define an *equilibrium state (steady-state points)*, given by:

$$q_0=C_1\sqrt{H_{10}}=C_1\sqrt{H_{20}}=C_1\sqrt{H_{30}} \tag{9}$$

Figure 15 shows the equilibrium states for the real tank system.

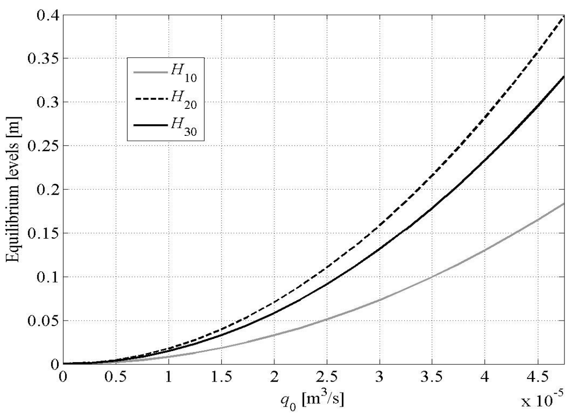

Fig. 15. Equilibrium levels for real system

Several issues have been recognised as potential difficulties for a high accuracy control of the tanks level or flow:

❍ nonlinearities caused by the tank shapes, the valve geometry and flow dynamics, the pump and valves input/output characteristic curve,

❍ state constraints, introduced by the maximum and minimum allowed levels in the tanks.

VIII. Pendulum on a cart system

A favourite laboratory system is the pendulum on a cart (see Fig. 16). We may have a lot of fan while experiment with it.

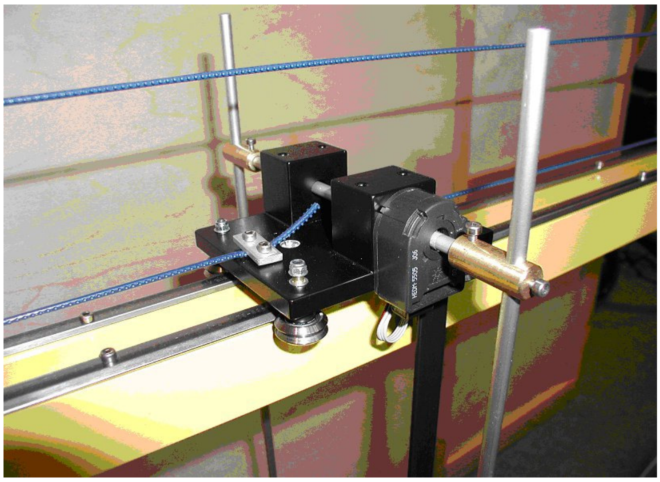

Fig.16 Pendulum on a cart system

To swing and to balance the pendulum the cart is pushed back and forth on a rail of limited length. The purpose of the control algorithm is to apply a sequence of forces of constrained magnitude to the cart such that the pendulum starts to swing with an increasing amplitude and the cart does not override the ends of the rail. The pole is swung up to achieve a vicinity of its upright position. Once this has been accomplish, the controller is maintaining the pole vertical and is bringing the cart back to the center of the rail. The pendulum in its upright position behaves as a circus acrobat. We have to be aware also that this non-trivial fourth order, unstable mechanical system can be used to conduct very serious research corresponding to the complex time-optimal control algorithm. To facilitate education does not mean to give a facile example. Hence, a short presentation of time-optimal and rule-based controls is shown.

The time-optimal controller requires analysis and synthesis based on a mathematical model [16][17]. The approach is laborious and time consuming. However, the good quality of control can be a reward. The so called canonical equations – state (forward) and conjugate (backward) – are solved. A variable parameter optimization method is used. The horizon, a number of switchings and the sign of the first "bang-bang" control are the variables of the quadratic performance index. A final snapshots of the state trajectories, control and anti-gradient of the performance index corresponding to the numerical optimization are shown in Fig. 17. The numbers correspond to the following variables: 1 → x_1 is the cart position with respect to the rail center, 2 → x_2 is the angle between the vertical upright direction and a current angular position of the pendulum, 3 → x_3 is the cart velocity, 4 → x_4 is the pendulum angular velocity, 5 → u is the control force acting horizontally on the cart and 6 → ψ is the anti-gradient of the performance index.

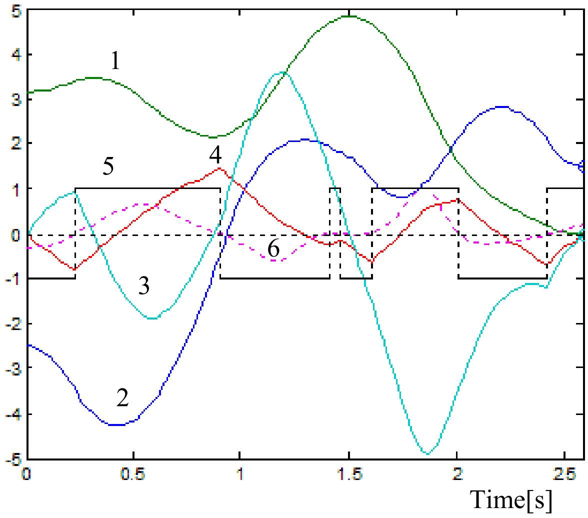

Fig. 17 The state trajectories, control and anti-gradient of the performance index at the end of the numerical optimization

The rule-based controller in a simple form is shown below.

Stabilization

If $|x_2|-S<0$ *Is pendulum in the stabilization zone?*

then $u_r=K_1(x_1-x_1^f)+K_2x_2+K_3x_3+K_4x_4$

Calculate an auxiliary linear control u_r.

if $|u_r|+F_s>u_{max}^{STAB}$ *Does the auxiliary control plus friction exceed the limit?*

then $u=u_{max}^{STAB}\operatorname{sign}u_r$ *Calculate the ultimate control that attains the limits.*

else $u=u_r+F_s\operatorname{sign}u_r$ *Calculate the ultimate linear control contained in the limits.*

end

Enlarging magnitude of the pendulum

elseif

$\frac{1}{2}x_4^2+9.81\cdot 3.2(\cos x_2-1)>0$ *Is pendulum kinetic energy larger then potential energy?*

then u = 0 *Set control to zero – perform soft landing in the stabilization zone.*

else

$$u=-u_{max}^{POST}\operatorname{sign}\left[x_4\left(|x_2|-\frac{\pi}{2}\right)\right]$$ *Apply the „bang-bang" control to enlarge oscillations.*

end

where: K_1, K_2, K_3, K_4 are constant gains, x_1^f is the final cart position, F_s is the static friction force and u_r is the auxiliary control.

Alas, rule-based control cannot predict the time-optimal strategy. In turn the time optimal control is sensitive to disturbances and without the soft landing (the control is set to zero when there is an excess of kinetic energy of the pendulum) it would be difficult to achieve the control goal.

IX. Conclusions

There are several critical terms to become an effective educator in the *Automatic Control* field. One must has access to facilities generally called mechatronic systems. Algorithms constructed on the basis of mathematical simulation models should be used in the same software environment to control the actual devices. It is a known complication of such a transfer, namely the real-time control regime. This is the biggest challenge in the education of engineers. It is satisfied mainly due to parallel (FPGAs) and software extensions.

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