

## MAGNETIC LEVITATION SYSTEM IN CONTROL ENGINEERING EDUCATION

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**Abstract.** *This paper deals with the magnetic levitation control system of a metallic sphere, which is an interesting and visually impressive equipment for demonstrating many intricate problems. In order to stimulate future research, after short description of the system operation in analogue and digital mode, several open problems in areas of electrical and control engineering are offered. Also, the paper presents some initial outcomes in creating a laboratory environment for remote monitoring of the magnetic levitation equipment.*

**Key words:** *magnetic levitation equipment, control engineering education, control in MATLAB® environment, real time control, remote control*

### 1. INTRODUCTION

The portable magnetic levitation system (MagLev), whose photograph is given in Fig. 1, is a laboratory set-up designed mostly for control experiments. The suspended body of this single-axis magnetic levitator is a hollow steel ball of 25mm diameter and 20g mass. This equipment was purchased in order to support automatic control learning at the Faculty of Electronic Engineering in Niš. The complete purchase of MagLev System 33-006 [1] was enabled by WUS–Austria [2] under the Grant CEP N°.115/2002. Due to its nonlinear and unstable nature, this attraction-type levitator system is a very challenging plant [3]-[5].

The layout of the paper is as follows: in Section 2 we give a brief review of the didactic magnetic levitation system, as well as its control in both analogue and digital mode; Section 3 addresses several challenging and interesting open problems in magnetic levitation system identification and control in order to motivate future research with respect to this equipment. Section 4 contains an overview of some initial steps in design and establishing a remote laboratory of automatic control at the Faculty of Electronic Engineering in Niš, where the MagLev system is one of the offered experiments.

## 2. DIDACTIC MAGNETIC LEVITATION SYSTEM

## 2.1. System Description

The control goal of the system given in Fig. 1 is the steel body levitation by means of the electromagnetic field counteracting the force of gravity. The applied control is voltage, which is converted into the current via a driver embedded within the unit. The current passes through an electromagnet, which creates the corresponding magnetic field in its vicinity. The sphere is placed along the vertical axis of the electromagnet. The measured position is determined from an array of infrared transmitters and detectors, positioned in such a way that the infrared beam is intersected by the sphere. The infrared photosensor is assumed to be linear in the required range of operation. To avoid the problem of phase compensation due to the high inductance of the electromagnet, the active drive to the electromagnet is current. Namely, the control voltage is linearly converted into the current by the internal circuit within the MagLev system.

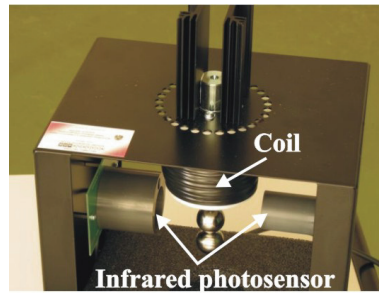


Fig. 1 Photograph of stable levitation of two metal spheres

Using the fundamental principle of dynamics, the behavior of the ferromagnetic ball is given by the following electromechanical equation

$$m \frac{d^2 x}{dt^2} = mg + f(x, i), \quad (1)$$

where  $f(x, i)$  is the magnetic control force given by

$$f(x, i) = -k \frac{i^2}{x^2}. \quad (2)$$

In previous relations  $m$  is the mass of the levitated ball,  $g$  denotes the acceleration due to gravity,  $x$  is the distance of the ball from the electromagnet, and  $i$  is the current through the coil. In addition to that,  $k$  is a constant related to the mutual inductance of the ball and coupling coefficients.

Note that both analogue and digital control solutions can be implemented. All this results in a visually attractive system with convenient time constants suitable for testing user-defined control strategies.

## 2.2. Magnetic Levitation Control System in Stand- alone Analogue Mode

Recall that the considered equipment is with a built-in power supply and in the analogue mode is capable of stand-alone operation without any computer control software. As shown in Fig. 2, to perform experimentation in analogue mode, it is necessary to connect the convenient sockets, which are located on the enclosure panel and marked with *Control Output* and *Drive Input*. Also, after inserting  $R$  and  $RC$  networks correctly, it is possible to change analogue controller gain, as well as compensation components quickly.

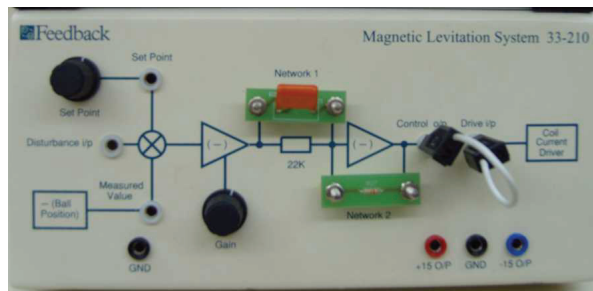


Fig. 2 Front panel of magnetic levitation system

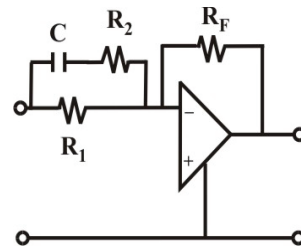


Fig. 3 Scheme of lead network

It is well known that the lead network acts mainly in order to modify the dynamic response by raising the bandwidth and decreasing the transient overshoot. Recall that the physical realization of a lead network can be accomplished in many ways. The most common method is by means of an operation amplifier, whose example is shown in Fig. 3. This kind of compensation is exactly applied in analogue control mode of the considered levitator. The bandwidth of the lead compensation may be changed, as well as the stability and response time investigated. The transfer function of the circuit of Fig. 3 is easily shown to be

$$W_d(s) = -\frac{R_F}{R_1} \frac{(R_1 + R_2)Cs + 1}{R_2Cs + 1}. \quad (3)$$

If we replace the actual parameter values of the supplied  $R$  and  $RC$  networks,  $R_F = R_1 = 22\text{k}\Omega$ ,  $R_2 = 100\Omega$  and  $C = 1\mu\text{F}$ , the transfer function becomes

$$W_d(s) = 221 \frac{s + 45.25}{s + 10000}. \quad (4)$$

Therefore, the system is configured for a real proportional derivative (PD) feedback control loop with the proportional gain set by the resistor network and the derivative gain set by the  $RC$  network. Note that some other user-defined analogue controllers may be also tested.

To demonstrate the efficiency of the lead compensation of the proposed structure (4), the set-point transient response of the control system with the considered unstable object is recorded and shown in Fig. 4. Moreover, the position of the sphere may be adjusted by using the set-point control, whereas the system stability may be varied by gain control. Namely, by changing the set-point control gradually, a control zone may be defined as a maximum distance where the sphere remains still under control.

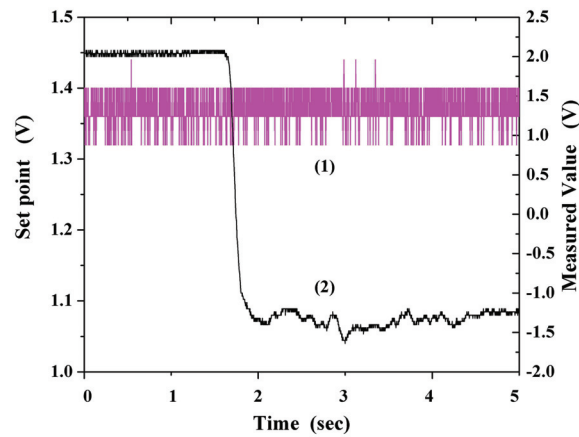


Fig. 4 Set-point (1) and measured signal (2) as time functions

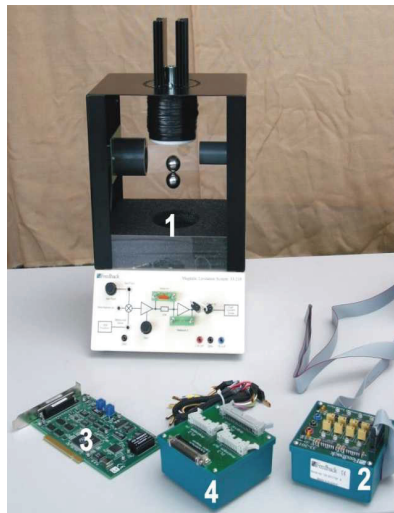


Fig. 5 Photograph of the dedicated magnetic levitation system

### 2.3. Magnetic Levitation Control System in Digital Mode

In the digital mode, the MagLev system operates with MATLAB<sup>®</sup>/Simulink software. The Magnetic Levitation Unit and the Interface Module (denoted with 1 and 2 in Fig. 5) should be linked to each other with lead connections. The Advantech PCI1711 Card (component 3 in Fig. 5) is also inserted into a computer PCI slot, and connected with the Feedback SCSI Adapter box (component 4 in Fig. 5) using the SCSI cable. Feedback Software for Simulink is provided for the implementation of control algorithms and interfacing between the PC and the MagLev system hardware. Thus, the system operates within a MATLAB<sup>®</sup> environment which allows the system parameters to be determined and the system to be modeled.

The steps necessary to obtain the executable file from a controller model are shown in Fig. 6. Namely, in addition to MATLAB<sup>®</sup>/Simulink and Control Toolbox, the digital controller, implemented on a PC, uses Microsoft Visual C++ Professional, as well as some other software tools from Mathworks Inc. like Real Time Workshop (RTW) and Real Time Windows Target (RTWT). Therefore, MATLAB<sup>®</sup> acts as the application host environment, in which the other Mathworks products run, and offers extensive state-of-the-art control design toolboxes. Simulink provides a user friendly well structured graphical interface for implementation of the control law. A close interaction between MATLAB<sup>®</sup> and Simulink indicates the efficient interpretation and analysis of simulation and experiment results, in order to make the development cycle shorter.

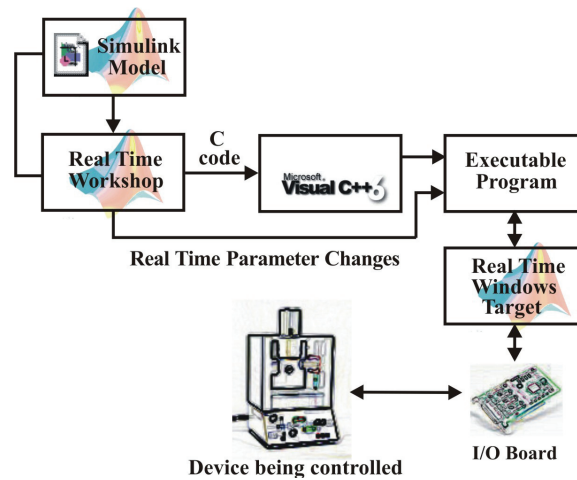


Fig. 6 Integrated set of tools for control system design and experimental validation

Thus, MATLAB<sup>®</sup>/Simulink and Real-Time Workshop (RTW) are used for control algorithm development, simulation, and rapid executable code generation. Digital controller with determined parameters can be used to run the hardware and the results of the actual control performance can be seen and analyzed. Various control algorithms, additionally developed by students, may be also easily implemented and tested. Moreover, in the case of the web-based laboratory experiments, the final goal is to offer special possibilities for students to build their own experiment from home [5].

To demonstrate the efficiency of the standard PD controller of the form

$$u = K_p(x_d - x) + K_d \frac{d}{dt}(x_d - x) + GravityBias, \quad (5)$$

as well as to verify the usefulness of the integrated set of tools given in Fig. 6, the experiment with the MagLev system in MATLAB<sup>®</sup> environment has been performed and the obtained results are visualized in Fig. 7. Note that the values used in the implemented control algorithm (5) can be modified in real time by entering new values into the Simulink<sup>®</sup> model. Also, the desired position for the metal sphere  $x_d$  may be set in real time. The

quality of transient response given in Fig. 7 is matched by the following parameter values:  $K_p = 6$ ,  $K_d = 0.3$ , and  $GravityBias = 0.4$ .

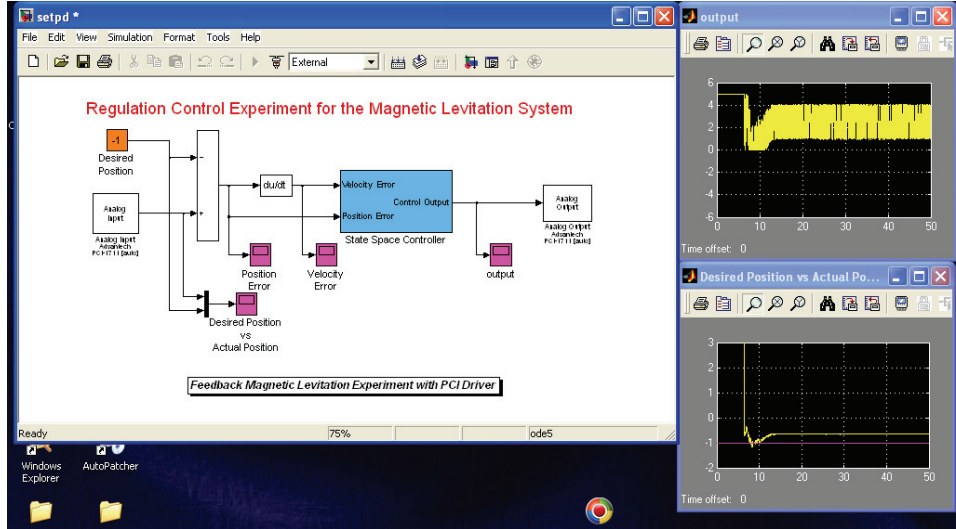


Fig. 7 Simulink® model with experimental results

### 3. SEVERAL OPEN PROBLEMS

This section offers a brief discussion about three, until now unsolved problems, which relate to the questions of the identification and control of the considered magnetic levitation system under the real circumstances.

#### 3.1. Determination of Characteristics of Position Sensor and Current Driver

The sensor of ball position in Fig. 1 is infrared photo-sensor and can be considered as static, since its response speed is much greater than that of the other system components. Its static characteristic is nonlinear, especially near its bounds. However, the infrared photosensor is assumed to be linear in the required range of operation with a voltage  $V$  that is related to distance  $X$  as

$$V = \gamma X + \bar{V}, \quad \gamma > 0, \quad (6)$$

where  $\bar{V}$  represents set of constants such that  $|V| < 2V$ . Also, the coil current  $I$  is regulated by an inner control loop [1] and is linearly related to input voltage  $U$  as

$$I = \rho U + \bar{I}, \quad \rho > 0, \quad (7)$$

where constant  $\bar{I}$  is the current that would be required to keep  $V = \bar{V}$ . Note, that various partial results are reported in [6].

### 3.2. Determination of the Levitation System Model

The force/current/displacement relationship in the considered equipment given in Fig. 5 is extremely difficult to determine using an analytic method. Moreover, the obtained approximate analytical expression  $f(x, i)$  is very complex for the further experimental purpose [3]. However, the magnetic force characteristics may be experimentally calibrated as a function of the applied current  $I$  and the ball position  $X$ . Namely, the experiment could be consisted of resting the levitation metallic sphere on a non-magnetic stand directly under the electromagnet. This special kind of  $xyz$ -stage (some solutions are shown in Fig.8(a)-(c)) should be capable, for example, of 1mm incremental positioning and determining the minimum current required to pick up the ball at various heights. Then the model of the force/distance relationship can be determined by means of least squares fitting. Note, that the validity of such obtained curve is limited to some range  $X_{\min} \leq X \leq X_{\max}$ . At the moment, in the Laboratory of Automatic Control at the Faculty of Electronic Engineering in Niš, the problem of the remote placement of the steel sphere among the vertical axis of the electromagnet is still not realized adequately. Hence, this is one of the basic problems in remote control of MagLev system in the underdeveloped web-based laboratory at the Faculty, which was established in order to support learning in automatic control. For now, as shown in Fig. 8, it is expected that the ball be placed along the electromagnet vertical axis by the laboratory technician.

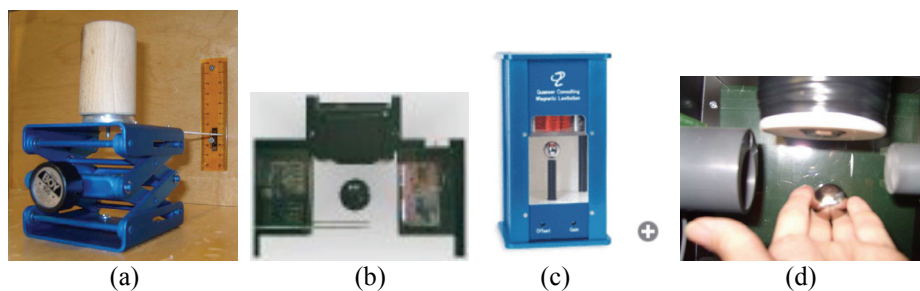


Fig. 8 Some solutions of the body rest: (a) The Institute of Automation and Computer Control at the Ruhr-University of Bochum [7]; (b) The Automatic Control Telelab (ACT) at the University of Siena [8]; (c) The Department of Mechanical Engineering at the Polytechnic University NY; (d) The Department of Automatic Control at the Faculty of Electronic Engineering Niš

### 3.3 Levitation: Stable or Unstable

During numerous experimentations, it is observed that, in the case of a stable levitation, a thin steel tile is placed along the electromagnet vertical axis in the manner, as shown in Fig. 9(b). This problem is offered with the intention of generating an analytical confirmation of this kind of thin tile behavior in the magnetic field of the considered equipment. Recall that the magnetic field in the electro-magnet vicinity introduces a magnetic dipole in the sphere which itself becomes magnetized. We assume that the sphere is magnetized within the linear part of the magnetization curve and does not reach saturation. The force acting on the sphere is then composed of gravity and magnetic force acting

on the introduced dipole. As shown in Fig. 10, the location of the dipole within the sphere is such that each pole is at the center of mass of its respective hemisphere. Obviously, the forces on the sphere due to the magnetic field are an attractive force on the North Pole, and a repulsive one on the South Pole. The applied magnetic field strength at the top of the sphere must be greater than the strength at its bottom. In other words, the lines of the flux must diverge horizontally as the distance from the electromagnet increases.

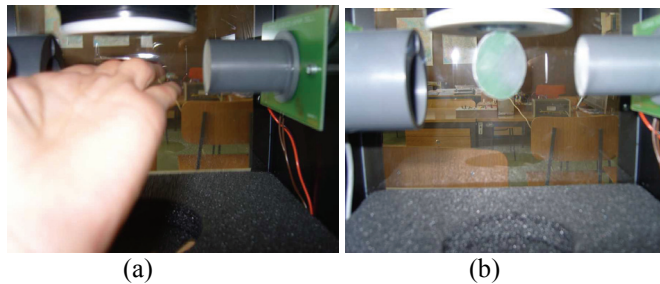


Fig. 9 A steel tile in electromagnet vicinity:  
(a) unstable equilibrium; (b) stable equilibrium

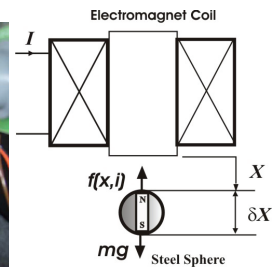


Fig. 10 Scheme of the sphere levitation

#### 4. REMOTE CONTROL OF MAGLEV SYSTEM IN CONTROL ENGINEERING EDUCATION LABORATORY

It is well known that effective learning in the field of engineering requires a combination of theoretical and practical exercises. Laboratory experiments play an important role in control engineering education, because a well-equipped laboratory represents a special link between the knowledge acquired in the classroom, and the needs of modern automated industry. Conventional laboratories, however, are with limited accessibility regarding space and time, and have high running costs. New technologies developed over the past two decades enabled practical laboratories to be supplemented with virtual and remote laboratories. Following one of the first remote laboratories that was developed in 1992 by Stanford Center for Innovations in Learning (<http://scil.stanford.edu>), a variety of different approaches have been proposed for developing remote laboratories in the field of control engineering education and robotics, particularly. The remote laboratories offer the opportunity for students to operate with the real systems from any location at their own time.

Some results of initial developing of a remote laboratory of automatic control at the Faculty of Electronic Engineering in Niš, which allows students to interact easily with a set of physical processes via the Internet, are presented in this paper. Figure 10 shows the screenshot of the ACEL laboratory homepage with the up to now offered experiments. Using the possibility of easy integration of other new processes for control experiments, the list of experiments could be extended. To perform a remote experiment in ACEL laboratory, the "LabVIEW Run Time Engine" and a standard web browser must be installed on a distant computer requiring access.





Fig. 10 Layout of the page <http://www.elfak.ni.ac.yu/~milica>

A web page created in LabVIEW environment for remote monitoring and control of the magnetic levitation equipment in stand-alone analogue mode is presented in Fig. 11. By using 'start' button on the top center part of the front panel, the application can be started. For now, when the initial procedure is completed and after the sound signal in the interface application, it is expected that the laboratory technician place the ball along the electromagnet vertical axis, as shown in Fig. 8(d). When the experiments are completed, the remote user can save some data of the relevant signals in ASCII data files, as well as pictures of the application window in JPEG format [5].

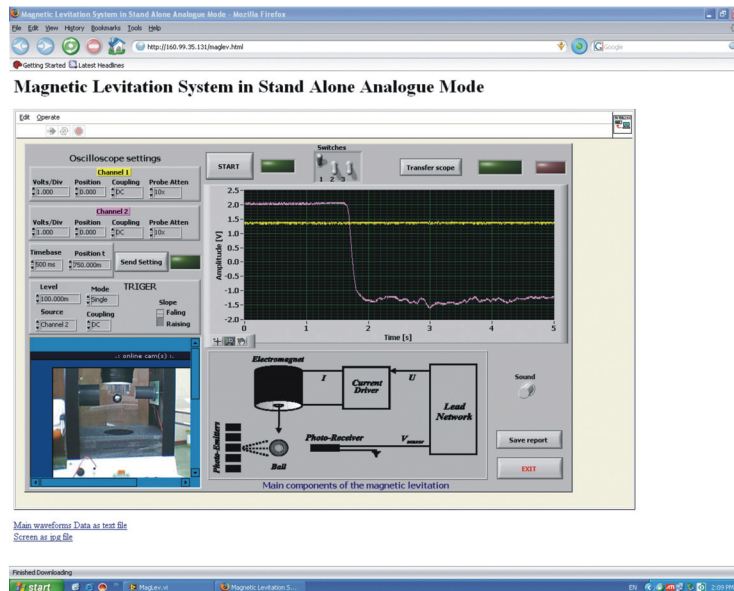


Fig. 11 Layout of classical web browser window for conducting remote experiments

## 5. CONCLUSION

As a teaching aid, the magnetic levitation system of a steel object enables the implementation of many basic and advanced approaches to both theoretical study and practical investigation of the nonlinear, unstable system control. We hope that the solution to any of problems, mentioned in this paper, would be of wide interest in the control engineering community. Moreover, in order to support learning of automatic control at the Faculty of Electronic Engineering, University of Niš, a web-based laboratory was established. The remote user is able to control the magnetic levitation equipment in stand alone analogue mode through an appropriately designed graphical user interface running on the client's computer. The current solution is based on an architecture that can be easily adapted to different remote control experiments.

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## SISTEM MAGNETNE LEVITACIJE U OBRAZOVANJU INŽENJERA AUTOMATIKE

**Milica B. Naumović, Boban R. Veselić**

*U radu je prikazan sistem magnetne levitacije metalne sfere koji predstavlja interesantnu i vizuelno impresivnu opremu za demonstraciju mnogih kompleksnih problema. U cilju stimulacije budućih istraživanja, posle kraćeg opisa rada ovog sistema u analognom i digitalnom modu, ukazano je na nekoliko otvorenih problema iz oblasti elektrotehnike i automatskog upravljanja.*

**Ključne reči:** *magnetni levitator, obrazovanje inženjera automatike, upravljanje u MATLAB® okruženju, upravljanje u realnom vremenu, daljinsko upravljanje*