CONTROL SOLUTIONS, SIMULATION AND EXPERIMENTAL RESULTS FOR A MAGNETIC LEVITATION LABORATORY SYSTEM

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Abstract

The paper presents two control solutions for the position control of a sphere in a Magnetic Levitation System with 2 Electromagnets. The nonlinear state-space mathematical model of the controlled plant was linearized around several operating points to enable for a low-cost control system design. Both control systems which are discussed, the state feedback control and the cascade control, are simple to design and easy to implement. Simulation and real-time experiments referring to the sphere's position and speed were conducted to validate the performance of the two control systems.

Keywords: Cascade control solution, Magnetic Levitation System with 2 Electromagnets, State feedback control solution, Simulation, Real-time experiments.

Presenting Author's biography

Claudia-Adina Dragoş. She received the Dipl.Ing. degree in systems and computer engineering and the M.Sc. degree in control systems from the "Politehnica" University of Timisoara (PUT), Romania, in 2007 and 2009, respectively. She is currently working toward the Ph.D. degree in systems engineering at the PUT. Her research interests include control structures and algorithms with focus on fuzzy, predictive and adaptive control. She is the coauthor of several papers published in journals and refereed conference proceedings. Ms. Dragos is a member of the Romanian Society of Control Engineering and Technical Informatics.

1 Introduction

The control of a metallic sphere levitating in an electromagnetic field is a classical benchmark control application. Since the controlled plant is nonlinear and unstable, the design of a good control solution is a challenging problem.

Several control solutions for magnetic levitation systems are reported in the literature: zero-power and PID controllers [1], a modified Elman neural networks-based decentralized control [2]. A robust PID controller tuning satisfying multiple H_∞ performance criteria is discussed in [3]. In [4] a disturbance observer is merged into the K-filter-based output-feedback controller to compensate the external disturbance and model mismatch. A networked predictive control method is employed in [5] using feedback linearization and direct local linearization models of nonlinear magnetic levitation systems. A high gain adaptive output feedback control to a magnetic levitation system is discussed in [6]. A combination of a pre-feedback compensator with an adaptive control and a robust stabilizing controller is proposed in [7]. A sliding mode controller is used in [8] to increase the robustness to model uncertainties and to reduce the disturbance responses.

We are using a Magnetic Levitation System with 2 Electromagnets (MLS2EM) [9]. This laboratory equipment is an attractive benchmark that allows for the convenient real-time Matlab - Simulink implementation of various control system structures and controllers.

Building upon our previous works [10,11] this paper discusses design details as well as simulation and physical experiment results for a feedback control solution and a cascade control solution for the position control of a sphere levitating in MLS2EM.

System modeling and simulation allow to refine the design of the control solutions which are then tested and validated by real-time experiments.

This paper is structured as follows. The mathematical model of the controlled plant and the control problem are presented in Section 2. Specific design aspects for two control solutions that are considered are discussed in Section 3. Simulation and real-time experimental results validating the two control solutions are presented in Section 4. The conclusions are presented in Section 4.

2 2 Mathematical model of the controlled plant and the control problem

The block diagram of the ML2SEM controlled plant is presented in Fig. 1 where and EM1, EM2 are the upper and lower electromagnet, *m* is the mass of the sphere, .F_{em1} and F_{em2} are the electromagnetic forces, and F_g is the gravity force.

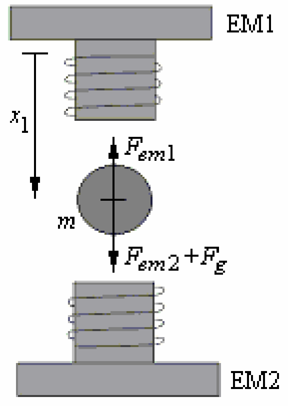

Fig. 1 Block diagram of controlled plant as part of ML2SEM

The nonlinear state-space mathematical model of ML2SEM is

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -\dfrac{F_{em1}(x_1, x_3)}{m} + g + \dfrac{F_{em2}(x_1, x_4)}{m}, \\ \dot{x}_3 = \dfrac{1}{f_i(x_1)}(k_i u_1 + c_i - x_3), \\ \dot{x}_4 = \dfrac{1}{f_i(x_d - x_1)}(k_i u_2 + c_i - x_4), \end{cases} \quad (1)$$

where the nonlinear functions are

$$\begin{aligned} &F_{em1}(x_1, x_3) = x_3^2 \frac{F_{emP1}}{F_{emP2}} \exp(-\frac{x_1}{F_{emP2}}), \\ &F_{em2}(x_1, x_4) = x_4^2 \frac{F_{emP1}}{F_{emP2}} \exp(-\frac{d - x_1}{F_{emP2}}), \\ &\text{for both actuators}: \ f_i(x_1) = \frac{f_{iP1}}{f_{iP2}} \exp(-\frac{x_1}{f_{iP2}}). \end{aligned} \quad (2)$$

x_1, $0 \le x_1 \le 0.016\,\text{m}$ is the sphere position, x_2 is the sphere speed, x_3 and x_4, $0.03884\,\text{A} \le x_3, x_4 \le 2.38\,\text{A}$ are the currents in the electromagnetic coil, u_1 and u_2, $0.00498 \le \{u_1, u_2\} \le 1$ are the control signals applied to EM1 and EM2, respectively, d is the distance between electromagnets minus sphere diameter, $F_g = m\,g$, g is the gravity acceleration, m is the sphere mass, the parameters k_i and c_i correspond the actuator dynamic analysis, and $f_i(x_1)$ are functions of x_1 for both actuators. The numerical values of the parameters in equations (1) and (2) are [9]

$$m = 0.0571\,\text{kg},\, g = 9.81\,\text{m/s}^2,$$
$$F_{emP1} = 1.7521 \cdot 10^{-2}\ \text{H},$$
$$F_{emP2} = 5.8231 \cdot 10^{-3}\ \text{m},$$
$$f_{iP1} = 1.4142 \cdot 10^{-4}\ \text{m s}, \quad (3)$$
$$f_{iP2} = 4.5626 \cdot 10^{-3}\ \text{m},$$
$$c_i = 0.0243\,\text{A}, k_i = 2.5165\,\text{A},$$
$$x_d = 0.075\,\text{m}.$$

As shown in Fig. 1 the ferromagnetic sphere is placed between EM1 and EM2. The main objective is to keep the sphere in levitation at the desired position set by the reference input.

The first two objectives of the control system are the stabilization and the tracking of constant reference inputs.

When both electromagnets are used, the control signal applied to EM2 can be used as an additional force leading to Multi Input-Multi Output (MIMO) control systems. This feature is also useful in robust applications. On the other hand the control signal u_2 can be considered as a disturbance input. Therefore a third objective of the control system is to ensure the regulation with respect to this kind of load type disturbance input.

The design of the control systems able to meet these three control objectives is quite complicated because of the nonlinearity of the controlled plant illustrated in (1) and (2). We are solving this problem by using a linearization around several operating points in order to enable the low-cost automation solutions. Accepting $u_2 = 0$ the following general linearized state-space mathematical model can be used in this context:

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\,\Delta\mathbf{x} + \mathbf{b}\,\Delta u_1,$$
$$\Delta y = \mathbf{c}^T \Delta\mathbf{x}, \quad (4)$$

where $\Delta u_1 = u_1 - u_{10}$ and $\Delta y = y - y_0$ are the differences of the variables u_1 and y with respect to their values corresponding to the operating point, u_{10} and y_0, respectively, $y = x_1$ is the controlled output, $\Delta\mathbf{x} = [\Delta x_1 \quad \Delta x_2 \quad \Delta x_3 \quad \Delta x_4]^T$ is the state vector, and the superscript T indicates the matrix transposition.

The matrices in equation (4) have the general expression

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & 0 & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & 0 \\ a_{41} & 0 & 0 & a_{44} \end{bmatrix}, \mathbf{b} = \begin{bmatrix} 0 \\ 0 \\ b_3 \\ b_4 \end{bmatrix}, \quad (5)$$
$$\mathbf{c}^T = [1 \quad 0 \quad 0 \quad 0],$$

with the parameters [10]

$$a_{21} = \frac{x_{30}^2}{m} \frac{F_{emP1}}{F_{emP2}^2} \exp(-\frac{x_{10}}{F_{emP2}}) +$$
$$+ \frac{x_{40}^2}{m} \frac{F_{emP1}}{F_{emP2}^2} \exp(-\frac{d - x_{10}}{F_{emP2}}),$$
$$a_{23} = -\frac{2x_{30}}{m} \frac{F_{emP1}}{F_{emP2}} \exp(-\frac{x_{10}}{F_{emP2}}),$$
$$a_{24} = \frac{2x_{40}}{m} \frac{F_{emP1}}{F_{emP2}} \exp(-\frac{d - x_{10}}{F_{emP2}}), \quad (6)$$
$$a_{31} = -(k_i u + c_i - x_{30})(x_{10} / f_{iP2}) f_i^{-1}(x_{10}),$$
$$a_{33} = -f_i^{-1}(x_{10}),$$
$$a_{41} = -(k_i u + c_i - x_{40})(x_{10} / f_{iP2}) f_i^{-1}(d - x_{10}),$$
$$a_{44} = -f_i^{-1}(d - x_{10}),$$
$$b_3 = k_i f_i^{-1}(x_{10}),$$
$$b_4 = k_i f_i^{-1}(d - x_{10}).$$

We adopted an operating point defined by [11]

$$x_{10} = 0.007\,\text{m},\ x_{20} = 0,$$
$$x_{30} = 0.754\,\text{A},\ x_{40} = 0.37\,\text{A}. \quad (7)$$

3 Control system designs

Starting with the linearized state-space model (4) the state feedback control system (SFCS) solution based on the control system structure presented in Fig. 2 was designed as the first control solution.

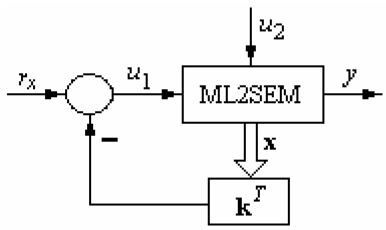

Fig. 2 State feedback control system structure

The signal u_2 in Fig. 2 represents the disturbance input, r_x is the reference input, $\mathbf{k}^T$ is the state feedback gain matrix, and the ML2SEM plant includes the actuators and sensors.

The nonlinear model (1) is simplified to the upper electromagnet only and is linearized at the selected steady-state point, considering that the coil current is fixed and actuator dynamics is negligible.

It is accepted that the process is controlled directly by the coil current $\Delta u_I = \Delta x_3$. The process is represented as by linear second order state-space model:

$$\begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ a_{21} & 0 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ a_{23} \end{bmatrix} \Delta u_I,$$
$$\Delta y_1 = [1 \quad 0] \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix}, \quad (8)$$

where $a_{21} = 1860$, $a_{23} = -24$, and the coordinates of the operating points have been omitted for simplicity but their role is not neglected. The closed-loop system poles (Fig. 2) are next imposed as $p_1 = -0.25$ and $p_2 = -240$. Therefore the pole placement method results in the state feedback gain matrix $\mathbf{k}^T = [40 \quad 5]$.

The fourth order model in equation (1) is next reduced to the following third order state-space model of the SFCS which is obtained in terms of neglecting the lower electromagnet:

$$\begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_2 \\ \Delta\dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1860 & 0 & -24 \\ 15024 & 1878 & -150 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 375.6 \end{bmatrix} r_x, \quad \Delta y_2 = [1 \quad 0 \quad 0] \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{bmatrix}. \tag{9}$$

The model presented in (9) is designed in order to ensure the zero steady-state control error which is not guaranteed by the SFCS in Fig. 2. This model leads to the transfer function of the SFCS

$$H(s) = -0.11/\mu(s), \quad \mu(s) = (1 + 0.2s)(1 + 0.0034s + 0.000023s^2). \tag{10}$$

Therefore the combined PID and SFCS structure is obtained as shown in Fig. 3, where e is the control error, r is the reference input and C is the PID controller.

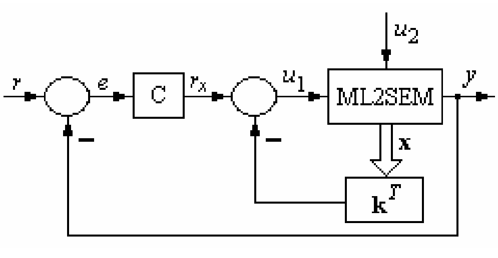

Fig. 3 Combined PID and state feedback control system structure

The frequency domain design is applied to design the PID controller. Imposing a phase margin of 60° the transfer function of the PID controller (with first order low-pass filter) becomes

$$C(s) = 10(1 + 0.0034s + 0.000023s^2) / /[s(1 + 0.001s)]. \tag{11}$$

4 Simulation and real-time experimental results

The two control solutions are tested using the results of simulations based on a detailed mathematical model (1) of the controlled plant, and then the results of real-time experiments. The real-time experimental results are conducted on the experimental setup implemented in the Intelligent Control Systems Laboratory of the "Politehnica" University of Timisoara, Romania (Fig. 4).

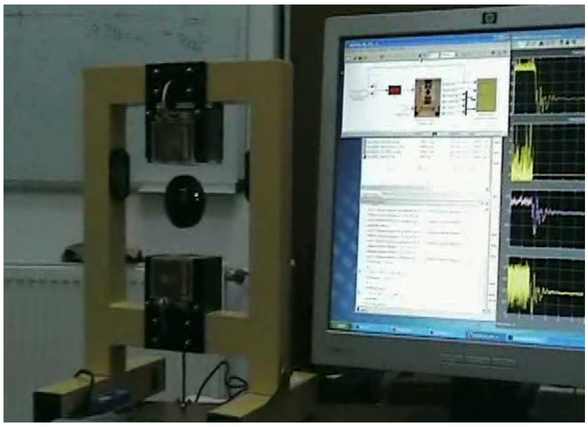

Fig. 4 Experimental setup

The experimental setup is built around the laboratory equipment ML2SEM [9]. It is very convenient because it allows running in real-time control algorithms developed in Matlab-Simulink [12] and the RTW and RTWT toolboxes. The control software includes several modules which enable the computer-aided analysis and design of the control solutions, as well as the real-time implementation of various controllers. Such solutions can be implemented easily in other control system structures and models [13,14,15,16,17,18,19,20,21,22, 23,24].

Simulation and real-time experimental scenarios are conducted for different step type modifications of the reference inputs r_x or r. However all results include the evolutions of the sphere position, sphere speed, control signals applied to EM1 and EM2, and currents in EM1 and EM2 versus time.

The simulation results and the real-time experimental results for the first control solution are presented in Fig. 5 and Fig. 6, respectively.

The simulation results and the real-time experimental results for the second control solution are presented in Fig. 7 and Fig. 8, respectively.

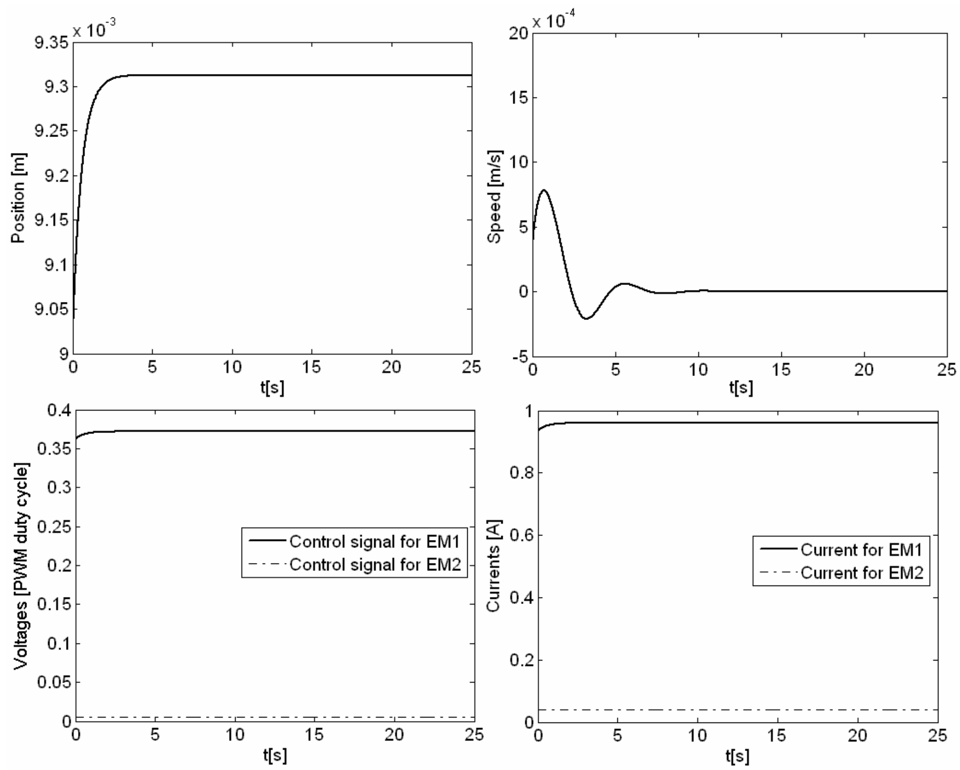

Fig. 5 Digital simulation results for the state feedback control system

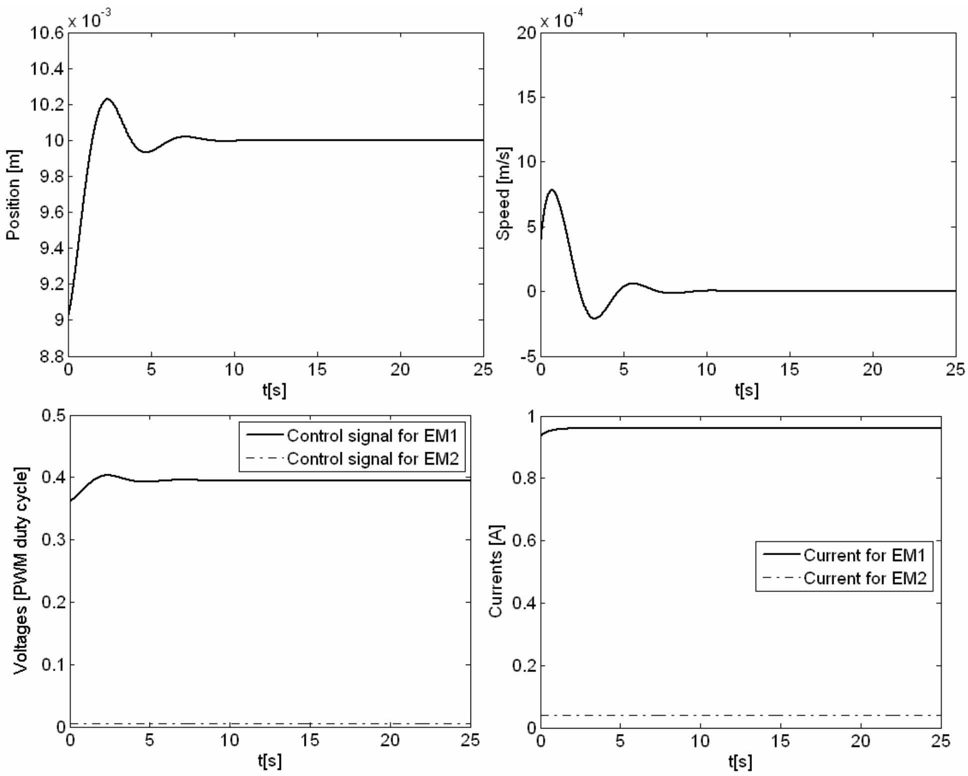

Fig. 6 Digital simulation results for the combined PID and state feedback control system

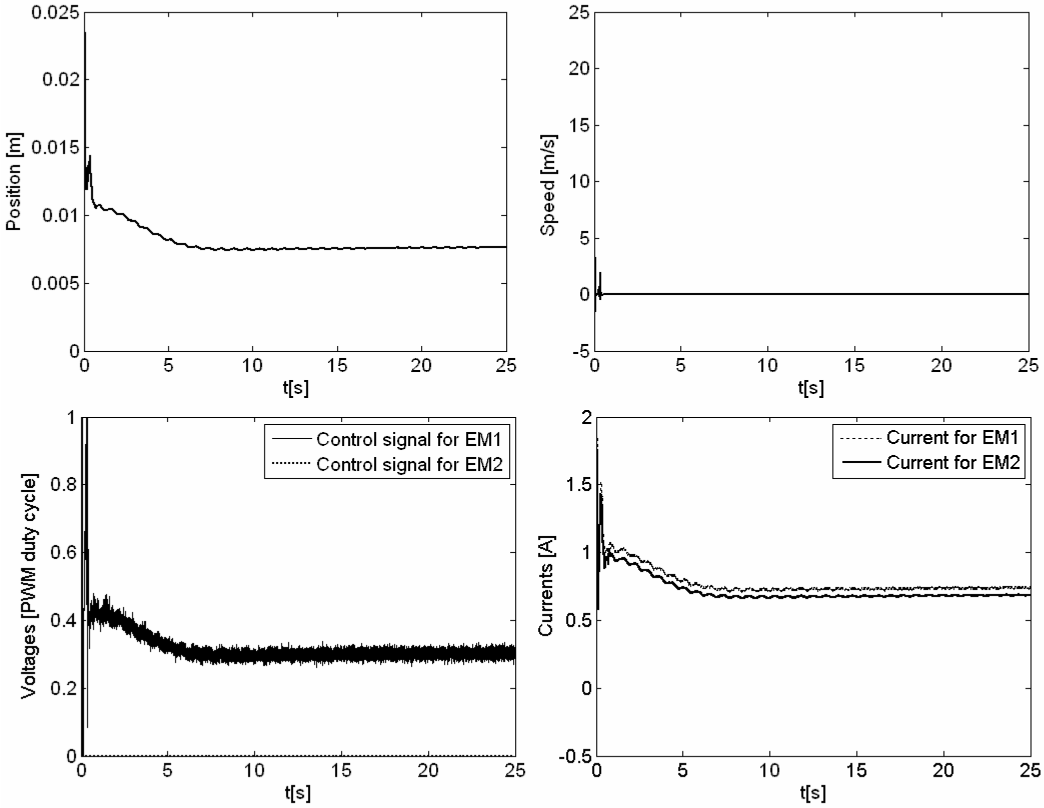

Fig. 7 Real-time experimental for the state feedback control system

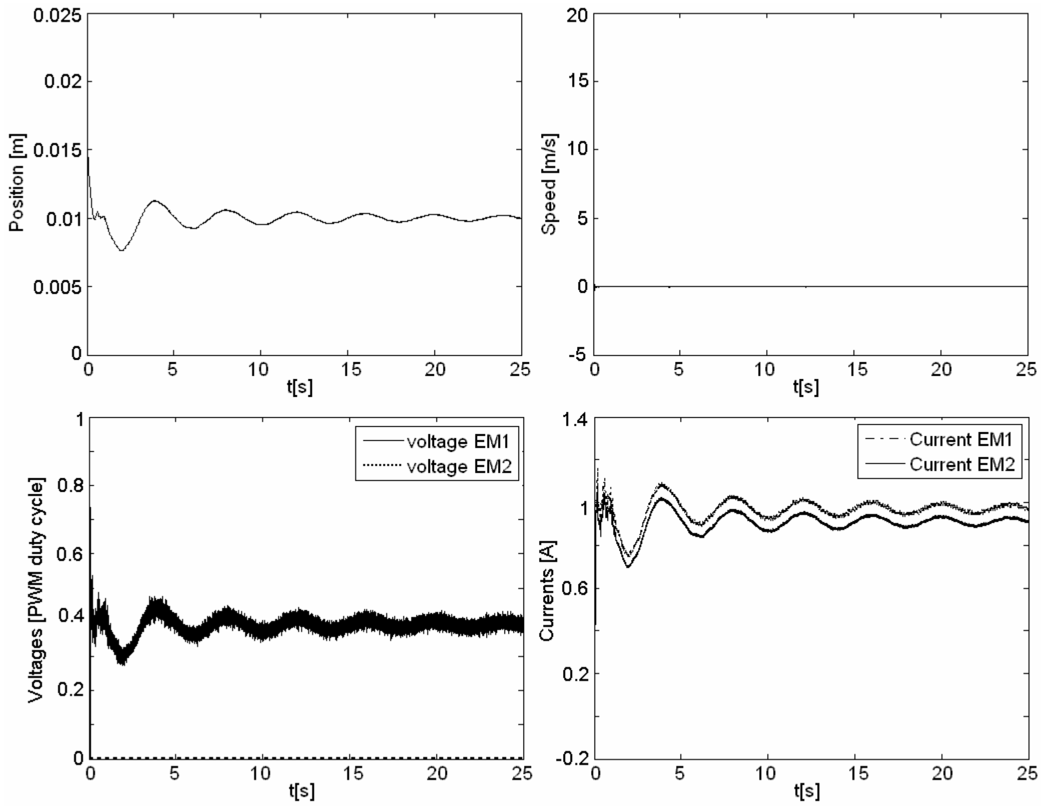

Fig. 8 Real-time experimental results for the combined PID and state feedback control system

The results presented in Figs. 5 to 8 are quite different, because in the case of the experimental scenario the sphere was introduced manually into an initial position. Furthermore, the nonlinear static maps of the actuator and sensors were not taken into considerations in detail as they were approximated by linear models to simplify the controller designs.

The comparative analysis of the behaviors of the two control solutions favors of the state feedback control solution.

The control system responses with respect to the modifications of the disturbance inputs show that better results are obtained for the combined PID and state feedback control solution because of the integral component in the controller.

The sphere does not reach the desired steady-state position set by the reference input for the first control solution. The I component in the controller solves this problem for the second control solution. The steady-state value of the speed is zero in all situations. The presence of some disturbances in all real-time experimental results is observed.

5 Conclusions

Simulation and real-time experimental results has shown that both the state feedback CS and the cascade CS discussed in this paper proved to be simple to design and easy to implement.

A thorough stability analysis is necessary to be conducted for all the considered applications.

Future research will allow extending these solutions to more complex models and controller structures.

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