Modern Control Solutions for Mechatronic Servosystems. Comparative Case Studies

Claudia-Adina Dragoş, Stefan Preitl, Radu-Emil Precup, Marian Crețiu

"Politehnica" University of Timisoara, Department of Automation and Applied Informatics, Bd. V. Parvan 2, 300223 Timisoara, Romania
{claudia.dragos, stefan.preitl, radu.precup}@aut.upt.ro, cretiu_marian@yahoo.com

János Fodor

Budapest Tech Polytechnical Institution, Institute of Intelligent Engineering Systems, Bécsi út 96/B, H-1034 Budapest, Hungary
fodor@bmf.hu

Abstract: The paper presents a comparison between several modern control solutions for mechatronic systems. A synthesis of the structures included in the modern based-design solutions is presented. They deal with model predictive control, fuzzy control, adaptive control and combination between different strategies and control structures. Digital simulation results are based on step and rectangular modifications of the reference input.

Keywords: mechatronic systems, modern control solutions, model predictive control, fuzzy control, adaptive control, magnetic levitation system

1 Introduction

Mechatronic systems include mechanical systems, electronic systems, control and information technology. The involvement of microcomputers into the mechatronic systems is useful due to the achieved advantages: speed control in all conditions, control of the plant with nonmeasurable or estimated parameters. Electromagnetic actuators are used in mechatronic systems to convert the energy created by electricity to linear motion [1].

Three modern control solutions are developed and used to obtain better performances, model predictive control [2], fuzzy control [3], adaptive control [4].

It is shown in [5] that these methods must include the model of the nonlinear plant, and the possibility to estimate the parameters and the state variables. In [6], Ho presents optimal controller design using systems based on Takagi-Sugeno fuzzy models, and the state variables are expressed as orthogonal functions.

The paper presents a synthesis on the development and verification of performances ensured by the control structures of mechatronic applications in automotive systems. The presented structures are used for a class of specific applications – electromagnetic actuated clutch – which can provide better performances and can be implemented easily [7]. Comparative conclusions related to the development of the control solutions are presented in the final of the paper.

2 Position Control Solutions

The control solutions developed in this paper were applied for (1) an electromagnetic actuator as part of the vehicular power train system and (2) a magnetic levitation system (laboratory set): (a) control solution with PI controller; (b) control solution with PID controller; (c) control solution with Takagi-Sugeno fuzzy controller and (d) control solution with predictive controller.

2.1 PI and PID Control Solutions

In automatic control, the PI controller is the most used controller [8]. The tuning parameters of the PI controller are adjustable; the parameter modifications by adapting, k_R and T_i, lead to favourable modifications of the system behaviour. The integral component of the PI controller ensures the zero control error. Also, T_i can compensate for the large time constant of the plant T_1, so the plant becomes faster.

The PID controller presents a pole at the origin and two zeros, which can compensate for two large time constants of the plant. Other advantages of using the PID controller are the same as in the case of using the PI controller. Both control solutions, PI and a PID with a first-order lag filter controller, have been designed based on modulus optimum method using pole-zeros cancellation. The transfer function (t.f.) of the PI controller is discretized using Tustin's method. Both solutions offer good performances.

Due to the plant nonlinearities, the commutation from one controller to another depending on the operating points is used to ensure better performances, Fig. 1. The condition to commute without bumps from one controller to another one needs re-computations and modifications of the controller parameters and reconsidering the past values [9]. The schematic structure of such crossing is presented in Fig. 2.

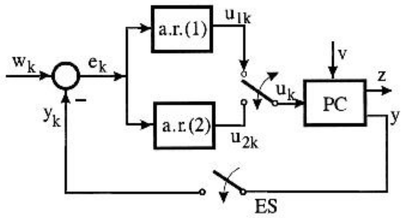


Figure 1
The commutation from one controller to another one [9]

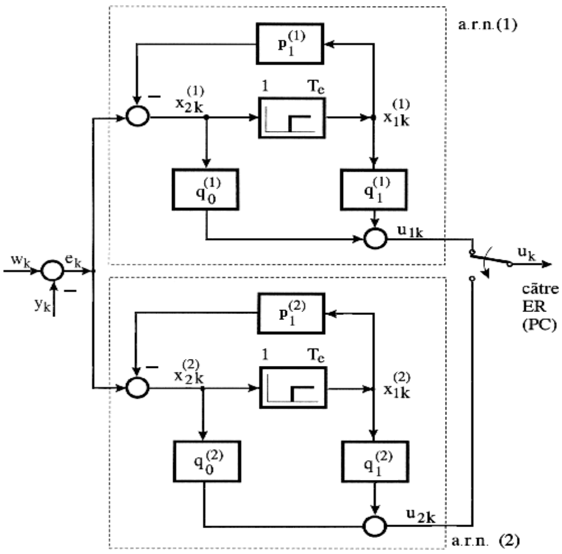


Figure 2
Detailed block diagram relative to the controller commutation [9]

2.2 Takagi-Sugeno Fuzzy Controllers Solutions

Takagi-Sugeno fuzzy controller (TS-FC) is flexible to operating point changes and it can be developed based on PI or PID control solutions. Theoretically it can ensure better performances in the cases of plants with nonlinearities. The linearized model used for the TS-FC design can be treated as a linear system with variable parameters. To describe the nonlinear dynamic system, the TS-FC uses *if–then* fuzzy rules [10]:

R_i: If $\{z_1$ is a_{1i} and z_2 is a_{2i} and … and z_n is a_{ni} $\}$ Then $\{u_k = f(z_1, z_2, ..., z_n)\}$. (1)

Two control structures with TS-FC have been developed in this paper. The designed structures are basically the same as shown in Fig. 3, where TS–FC – Takagi-Sugeno fuzzy controllers with output integration, FC – fuzzy block processing, P – controlled plant, w_k – reference input, $e_k = w_k - y_k$ – control error, u_k – control signal, y_k – measured output, x – controlled output (position of the mechanical system) [3]. The structures differ by the combination of the control rules in the decision table and by the value of the parameter γ. The parameter γ is used to introduce additional nonlinearities to improve the performances of the control system. The TS-FC structure (with pseudo-PI behaviour) is homogeneous, with four inputs: e_k, Δe_k – the first order increment of the control error, I – the current and x – the position, and one output: V – the control signal.

The input variables, i and x, were introduced to stabilize better the selective action of the decision table. Three linguistic terms with triangular membership functions (N, ZE, P) are used for each input variable, and nine linear linguistic terms are used for the output variable, for both TS-FC controllers. The consequents in the control rules of the TS-FC are detailed in Table 1. The decision table of each controller contains 81 rules (*3x3x3x3*). The controllers use *MIN–MAX* operators in the inference engine and the weighted average method for defuzification.

An extension of the TS-FC solutions, based on Takagi-Sugeno fuzzy models, uses the optimal linear quadratic controllers design techniques [11].

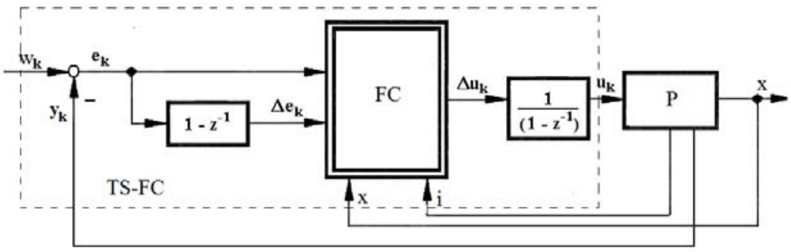


Figure 3
Block diagram for the control system with Takagi-Sugeno fuzzy controller

Table 1
Transfer functions of plant and consequent in rule base of TS-FC

Number of Operating Point	$H_{PC}(s)$	u_k
$(3): x_0 = 0.00025, i_0 = 24, V_0 = 12$	$\frac{0.52}{(1+0.0036s)(1+0.0017s)(1+0.0011s)}$	$\gamma*(9.55*e_k + 338.6*\Delta e_k)$
$(5).x_0 = 0.001, i_0 = 48, V_0 = 24$	$\frac{1.08}{(1+0.0036s)(1+0.0019s)(1+0.0011s)}$	$\gamma*(4.3*e_k + 152*\Delta e_k)$
$(9).x_0 = 0.0039, i_0 = 95, V_0 = 47.5$	$\frac{2.05}{(1+0.0036s)(1+0.0021s)(1+0.0011s)}$	$\gamma*(2.12*e_k + 75*\Delta e_k)$

2.3 Model Predictive Control Solutions

Model predictive control solutions were used to mechatronic system control due to better performances obtained: robustness, presence of a single tuning parameter, obtaining a transfer function (t.f.) with reduced order, and modelling the response to both modifications of the inputs (step and rectangular types).

A class of predictive control systems is based on the linear (linearized) model of the plant (model based predictive control, MPC) and provides good results. The control algorithm can be adapted on-line to the current operating points.

Two MPC solutions have been approached: (1) using one-step ahead quadratic objective function, and (2) using multi-step ahead quadratic objective function [2]. To obtain the next control signal, the specific objective function is minimized. In both cases, if the plant does not contain integrators the nonzero control error can appear. The ARX model of the plant and a first order predictor were used in the MPC design.

In the first case, the controller is obtained by minimizing the one-step ahead quadratic objective function based on the control error:

$$J = \frac{1}{2}[\hat{y}(k+1) - r(k+1)]^2, \tag{2}$$

with the resulted two-degree-or-freedom control algorithm:

$$u(k) = \frac{AT^*}{AR + q^{-1}BS} r(k+1) - \frac{\frac{CS}{D}}{AR + q^{-1}BS} e(k). \tag{3}$$

Multi-step ahead quadratic objective functions with the weighted control are used to solve the problems related to the non-minimum phase zeros:

$$J = \sum_{i=1}^{p} [\hat{y}(k+i) - r(k+i)]^2 + \lambda u^2(k+i-1). \tag{4}$$

To obtain the minimum variance, the conditions (minimum prediction horizon, control horizon and the weight coefficient) differ depending on the plant.

2.4 Adaptive Control Solutions

To control dynamic systems with unknown parameters which are variable in a sied range it is required to do the on-line estimation of these parameters. Two design methods can be adopted [ref]: model reference adaptive control and self-tuning control.

The chosen model for adaptive control should be achievable and must to reflect the desired performances. The unknown parameters of the plant and the controller parameters lead to nonzero control error (the system output is not the same as the reference model output). The control error cancellation is done by an adaptive control law.

3 Applications and Plant Models

The applications used in the paper are related to the electromagnetic actuator systems: (1) a mechatronic system for electromagnetic actuator clutch and (2) a magnetic levitation system with two electromagnets (laboratory set). If in the case (2) the bottom electromagnet is neglected and the spring is introduced, then a magnetically actuated mass-spring-damper (MaMSD) system is obtained. The modelling of an electromagnetic actuator systems is based on the MaMSD system.

3.1 Mathematical Model of Electromagnetic Actuator

The schematic structure of an electromagnetically actuated MaMSD system is used to model the system, Fig. 4. Based on it, the primary equations of the system are detailed in [12]. The characteristic variables (position, speed, acceleration, force and the currents) are partly measurable, and the others can be estimated. The obtained nonlinear model is detailed in (5):

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{k}{m}x_1 - \frac{c}{m}x_2 + \frac{k_a}{m(k_b + d - x_1)}x_3^2 \\ \dot{x}_3 = \frac{R}{2k_a}x_1x_3 - \frac{R(k_b+d)}{2k_a}x_3 - \frac{1}{2k_a}x_1V + \frac{(k_b+d)}{2k_a}V + \frac{1}{(k_b+d-x_1)}x_2x_3 \\ y = x_1 \end{cases} . \quad (5)$$

To avoid the detailed manipulation of the nonlinearities in (5) and to design the control systems, the nonlinear model (5) was linearized around nine operating points from static input-output map, Fig. 5.

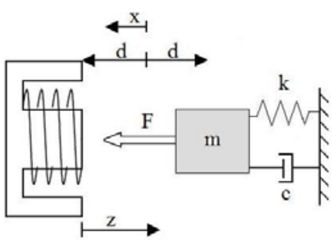


Figure 4
Schematic structure of magnetically actuated mass-spring-damper system

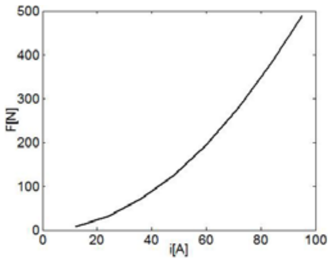


Figure 5
Static input-output map

Based on this, nine t.f.s were obtained, synthesized in [12]. Three operating points were selected, and for these three control structures were designed, Table 1.

3.2 Mathematical Model of Magnetic Levitation System

The schematic structure for magnetic levitation system with two electromagnets (MLS2EM) is detailed in Fig. 6, [13].

The nonlinear model of the plant was obtained starting with the primary equations, detailed in (6), where: x_1 – sphere position, $x_1 \in [0, 0.016]$; x_2 – sphere speed; x_3, x_4 – currents in the top and bottom electromagnets, $x_3, x_4 \in [0.03884, 2.38]$; u_1, u_2 – the control signals for the top and bottom electromagnets, $u_1, u_2 \in [0.00498, 1]$.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\dfrac{F_{em1}}{m} + g + \dfrac{F_{em2}}{m} \\ \dot{x}_3 = \dfrac{1}{f_i(x_1)}(k_i u_1 + c_i - x_3) \\ \dot{x}_4 = \dfrac{1}{f_i(x_d - x_1)}(k_i u_2 + c_i - x_4) \end{cases} \qquad \begin{aligned} F_{em1} &= x_3^2 \frac{F_{emP1}}{F_{emP2}} \exp(-\frac{x_1}{F_{emP2}}) \\ F_{em2} &= x_4^2 \frac{F_{emP1}}{F_{emP2}} \exp(-\frac{x_d - x_1}{F_{emP2}}) \\ f_i(x_1) &= \frac{f_{iP1}}{f_{iP2}} \exp(-\frac{x_1}{f_{iP2}}) \end{aligned} . \tag{6}$$

The nonlinear model was linearized around the following operating points were used: $x_{10} = 0.007, x_{20} = 0, x_{30} = 0.754, x_{40} = 0.37$ resulting:

$$\begin{cases} \Delta \underline{\dot{x}} = \underline{A} \Delta \underline{x} + \underline{b} \Delta V \\ \Delta y = \underline{c}^T \Delta \underline{x} \end{cases} \text{ with } \underline{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & 0 & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & 0 \\ a_{41} & 0 & 0 & a_{44} \end{bmatrix}, \underline{B} = \begin{bmatrix} 0 \\ 0 \\ b_3 \\ b_4 \end{bmatrix}, \underline{c}^T = [1 \quad 0 \quad 0 \quad 0] . \tag{7}$$

with the expression of the parameters in (8):

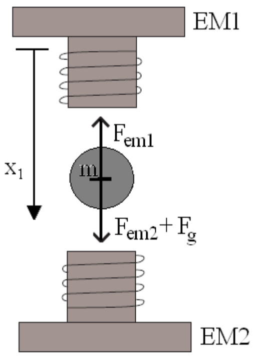


Figure 6
Schematic structure of magnetic levitation system [13]

$$\begin{aligned}
&a_{2,1} = \frac{x_{30}^2}{m}\frac{F_{emP1}}{F_{emP2}^2} e^{-\frac{x_{10}}{F_{emP2}}} + \frac{x_{40}^2}{m}\frac{F_{emP1}}{F_{emP2}^2} e^{-\frac{x_d - x_{10}}{F_{emP2}}}, \quad a_{2,3} = -\frac{2x_{30}}{m}\frac{F_{emP1}}{F_{emP2}} e^{-\frac{x_{10}}{F_{emP2}}}, \\
&a_{2,4} = \frac{2x_{40}}{m}\frac{F_{emP1}}{F_{emP2}} e^{-\frac{x_d - x_{10}}{F_{emP2}}}, \quad a_{3,1} = -(k_i u + c_i - x_{30})(x_{10} / f_{iP2}) f_i^{-1}(x_{10}), \quad a_{3,3} = -f_i^{-1}(x_{10}), \\
&a_{4,1} = -(k_i u + c_i - x_{40})(x_{10} / f_{iP2}) f_i^{-1}(x_d - x_{10}), \quad a_{4,4} = -f_i^{-1}(x_d - x_{10}), \\
&b_3 = k_i f_i^{-1}(x_{10}), \quad b_4 = k_i f_i^{-1}(x_d - x_{10}).
\end{aligned} \qquad (8)$$

4 Control Structures Developed

4.1 Control Structures Dedicated to Electromagnetic Actuator

4.1.1 PI(PID) Control Structures

The control structure (CS) with PI and PID controllers is a classical one. It has been designed using the Modulus Optimum method and pole-zero cancellation [astrom]. The resulting PI and PID controller parameters are detailed in Table 2 for three representative operating points.

Table 2
PI and PID controller parameters

Number of Operating Point	PID controller parameters			PI controller parameters	
	k_r	T_{r1}	T_{r2}	k_r	T_r
(3)	874.13	0.0036	0.0017	343.4	0.0036
(5)	437	0.0036	0.0018	166	0.0036
(9)	221	0.0036	0.0021	76	0.0036

4.1.2 Takagi-Sugeno Fuzzy Control Structures

Based on PI controller parameters, two fuzzy control structure of Takagi-Sugeno type, were designed, with the control law (9) and parameters detailed in Table 1.

$$\Delta u_k^i = \gamma (k_k \Delta e_k + k_i e_k) = \gamma k_k (\Delta e_k + \alpha e_k) \cdot \tag{9}$$

In the first case $\gamma = 0.00065$, and in the second case $\gamma = 0.001$.

4.1.2 Model Predictive Control Structures

MPC structures were designed based on the linearized plant model around the nine operating points. In this paper, the simulation results are presented for the controller designed around the average operating point.

The controller designed using the one-step ahead quadratic objective function is detailed in (10):

$$u(k) = \frac{0.0243}{0.0243(0.0243 - 0.0032q^{-1}) + 0.001} r(k+1) \frac{0.0243(1.72 - 0.74q^{-1})}{0.0243(0.0243 - 0.0032q^{-1}) + 0.001} y(k), \tag{10}$$

and for the multi-step ahead quadratic objective function the controller is:

$$\begin{bmatrix} u(k) \\ u(k+1) \\ u(k+2) \end{bmatrix} = \begin{bmatrix} 0.00032 & 0.00053 & 0.00023 \\ 0.0098 & 0.00149 & 0.00053 \\ 0.00059 & 0.00093 & 0.00032 \end{bmatrix} \begin{bmatrix} r(k+1) \\ r(k+2) \\ r(k+3) \end{bmatrix} - \begin{bmatrix} -26.8596 & 17.1013 & 0.0702 \\ -39.9832 & 24.876 & 0.1197 \\ -45.479 & 28.798 & 0.1183 \end{bmatrix} \begin{bmatrix} y(k) \\ y(k+1) \\ u(k-1) \end{bmatrix}. \tag{11}$$

4.2 Control Structures Dedicated to Magnetic Levitation System

To stabilize the magnetic levitation system (MLS2EM), a state feedback control structure was designed. In the paper, the following poles were used: $p_1^* = -0.25, p_2^* = -240$, and the parameters $\underline{k}_c^T = [40 \quad 5]$ were obtained.

To ensure the zero control error, the model was reduced to a third order with the following state variables: the position; the speed and the current in the top electromagnet (neglecting the current in the bottom electromagnet). The obtained transfer function is detailed in (12):

$$H(s) = \underline{c}^T (sI - \underline{A}_x)\underline{b}_u = \frac{-0.11}{(1 + 0.2s)(0.000023s^2 + 0.0034s + 1)}. \tag{12}$$

Taking into account the t.f. (12) and the performance requirements (zero steady-state control error, the phase margin of 60^0, small settling time), a PID controller was developed using the pole-zeros cancellation [8].

4.3 Simulation and Experimental Results

The performances of the designed control structures have been tested by simulation in Matlab&Simulink and by real-time experiments.

4.3.1 Simulation Results for Electromagnetic Actuator

The control structures behaviour was verified for all nine operating points, but in the paper, the simulation results are presented only for the control structures designed around an average operating point. For each structure two simulation scenarios have been used: (1) system response with respect to the step modifications of the reference input, and (2) system response with respect to the rectangular modifications of the input. In this paper, only the simulation results with respect to the rectangular reference input of the CS designed for MaMSD-s are presented . The simulation results are detailed in Table 3: the obtained results by using the fisrt TS-FC with γ=0.00065, are presented in fig. a, and by using the second TS-FC with γ=0.001 in fig. b, the CS with model predictive controller using multi-step ahead quadratic objective function in fig. c, and using one-step ahead quadratic objective function in fig. d, the CS with PI controller in fig. e, and the CS with PID controller in fig. f.

In the simulation results, the output of the predictive control system presents a small overshoot (σ_1=2%), in comparison with the second case, where the output of the system presents a higher overshoot σ_1=4.8%, Fig. 8. It is noticed that the settling time is reduced, t_r=0.004, and in the second case the settling time is slightly improved.

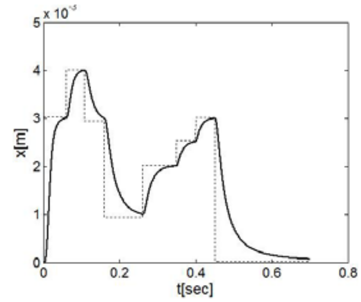
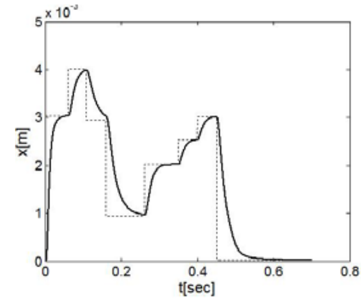
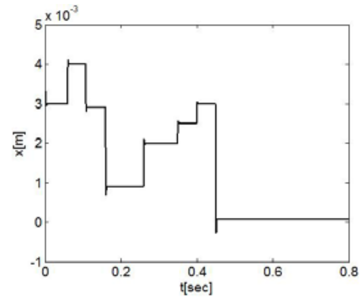
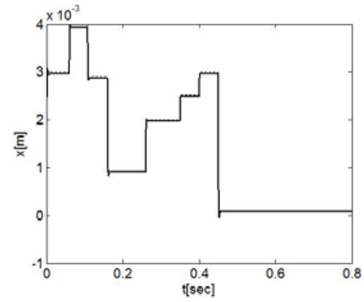
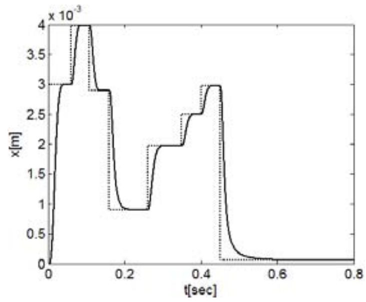
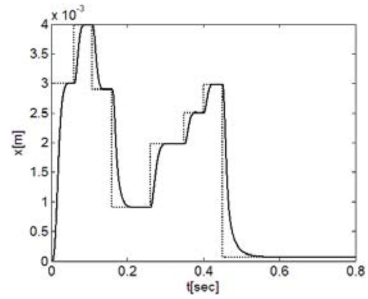
4.3.2 Simulation Results for the Magnetic Levitation System

The block diagram illustrated in Fig. 7 was used to verify the state feedback control structure (used for stabilization) and the PID controller (used to ensure the zero steady-state control error) for the magnetic levitation system in real-time experiments.

The simulation results related to the control structure behaviour are detailed in Table 4: sphere position behaviour (a), sphere speed (b), current in top and bottom electromagnets (c), and control signal for both electromagnets (d).

The experimental results, synthesized in Table 4, show the real-time behaviour of the control structure designed for the MLS2EM. The oscillations at the beginning of transience response (around the value of the reference input) are due to the complex conjugated poles and the nonlinearities of the plant; they stabilize well to the reference value. The results for the current in both electromagnets present oscillations at the beginning. All these results do not modify the speed, which remains zero.

Table 3
Simulation results

TS-FC	 (a)	 (b)
MPC	 (c)	 (d)
PI(D)-C	 (e)	 (f)

Conclusions

The paper presents control systems for two applications: an electromagnetic actuator clutch and a magnetic levitation system [14], [15]. For the first application, four control solutions were designed and for the second a state feedback control structure and a conventional PID control loop were designed.

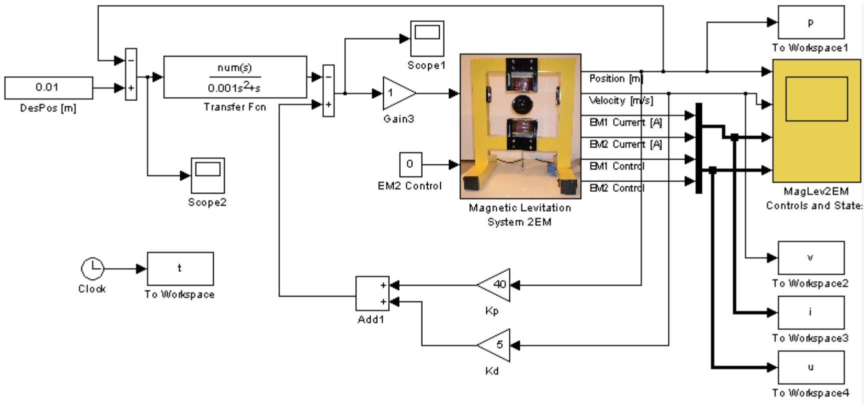
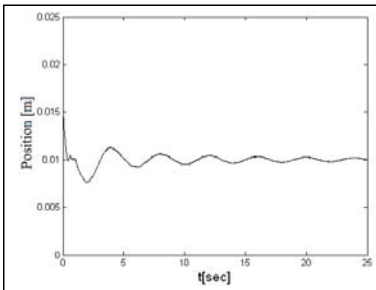
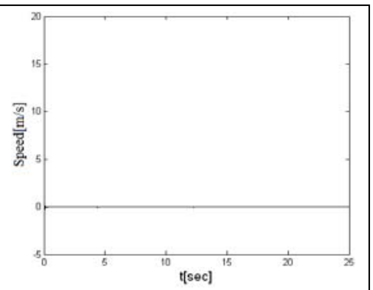
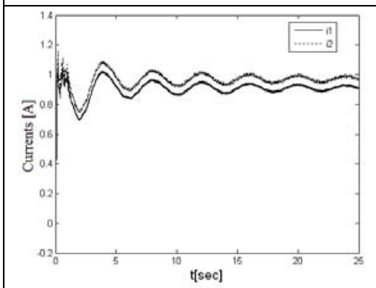
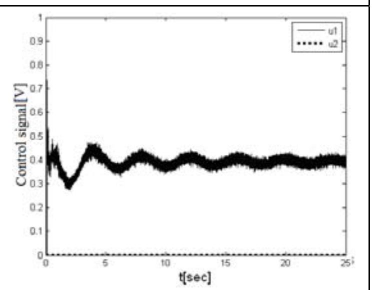


Figure 7
Block diagram of control structure for SLM2EM

Table 4
Experimental results

 (a)	 (b)
 (c)	 (d)

In the case of MaMSD modelling, the nonlinear model has been linearized around a several operating points (nine operating points) and then the linearized models have been obtained. These models have been used to design the control structure with PI(D) controller, the Takagi-Sugeno fuzzy control structure, the model predictive control systems.

The simulation and experimental results have proved that all solutions are viable. Similar results were obtained also for the second category of test signals.

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