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Competition Problem 1 – A Fuzzy Control Problem

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1. An Introduction to the Competition Problem – Simplified Magnetic Suspension System

Magnetic suspension is contact and wear-free, thus it has the potential to achieve ultra precision motion control of an object (e.g., 1-μm resolution). Figs. 1 and 2 illustrate the magnetic suspension system utilized in this fuzzy control competition. There are four equal–size electromagnetic actuators (only two of them are visible in Fig. 1 due to the sectional view) securely attached to the four corners of a rectangle plane stator that is mounted on a stationary metal plate. DC current in the coil of the *k*-th actuator ($i_k(t)$, k = 1,2,3,4) can be adjusted by changing the input voltage signal $u_k(t)$ applied to the coils wrapped around an iron core. This will result in a change in the magnetic force, designated $f_k(t)$, that vertically pulls up or lowers iron floator *k*. The four floators are securely embedded in the four corners of a non-metal stiff floator carrier and the surfaces of the four floators facing the actuators are manufactured to be perfectly aligned horizontally one other (as illustrated in Fig. 1). The carrier along with the floators forms a rigid plate body that does not bend in any direction. When floating in the air, this rigid plate may move rotationally, as represented by $\alpha(t)$ and $\beta(t)$ in Fig. 2, in addition to the z direction. For this control competition, we limit ourselves to this three-degree-of-freedom motion only even though in reality the motion should be six degrees of freedom. The distance between the *k*-th floator and the *k*-th actuator, $z_k(t)$, is measured in real-time by distance sensor k. The distance origin $z_k(t)=0$ is marked in Fig. 1, as is the target horizontal level of the floators, z_{SP}.

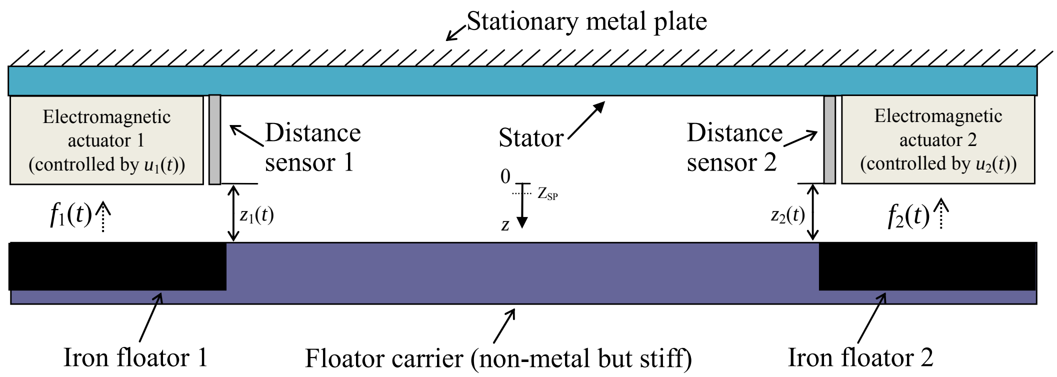

Fig. 1. Sectional view of the magnetic suspension system.

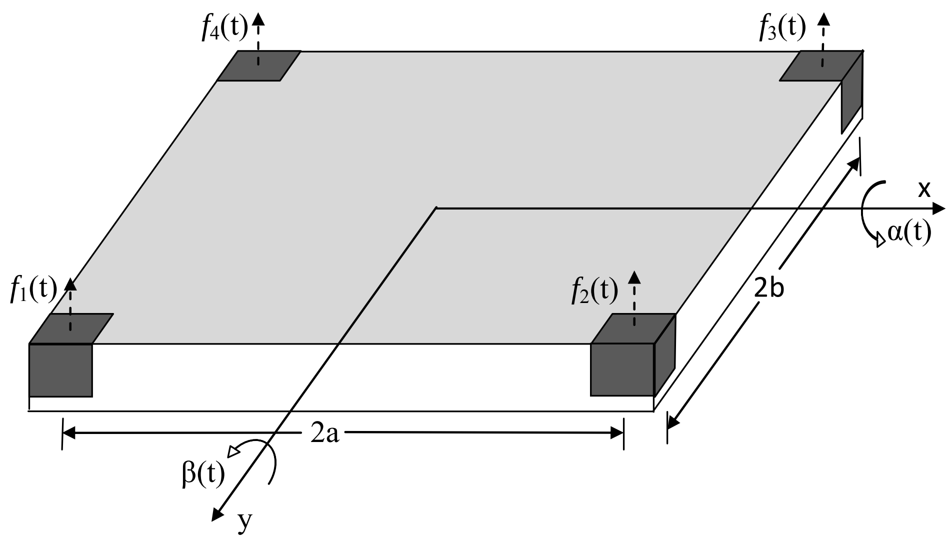

Fig. 2. More detailed description of the four iron floators and the floator carrier.

2. Dynamics of the Magnetic Suspension System

The magnetic suspension system is a nonlinear multi-input, multi-output (MIMO) coupled system. The system input variable is control signal $u_k(t)$ in electromagnetic actuators and its output variable is $z_k(t)$. The control objective for this competition is to keep all the four floators at a user-specified z_{SP} by adjusting the magnetic forces $f_k(t)$ via $u_k(t)$ to counteract the weight of the carrier and the floators. The meanings, values (and their limits) and units of some of the notations are given in Table 1.

Table 1. Symbols and their meanings and values or limits (k = 1,2,3,4).

Symbol	Meaning	Value or Limits and Unit
$z_k(t)$	distance between actuator k and iron floator k	(0, 0.0015], m
z_{k0}	initial distance between actuator k and iron floator k	m, see Table 2
z_{SP}	distance set-point for all the four floators	0.0005, m
$u_k(t)$	control input applied to actuator k	[-6, 6], V

The discrete-time dynamic relationship between the input variables and output variables is approximately described by the following MIMO model at the equilibrium point of interest:

$$\begin{aligned}\triangle\mathbf{z}(n) = \mathbf{A}\cdot\triangle\mathbf{z}(n-1) + \mathbf{B}\cdot\triangle\mathbf{z}(n-2) + \mathbf{C}\cdot\triangle\mathbf{z}(n-3) + \mathbf{D}\cdot\triangle\mathbf{z}(n-4) \\ + \mathbf{E}\cdot\mathbf{u}(n-3) + \mathbf{F}\cdot\mathbf{u}(n-4) + \mathbf{G}\end{aligned} \tag{1}$$

where

$$\triangle\mathbf{z}(n) = \begin{bmatrix}\triangle z_1(n)\\ \triangle z_2(n)\\ \triangle z_3(n)\\ \triangle z_4(n)\end{bmatrix}, \qquad \triangle z_k(n) = z_k(n) - z_{sp}, \qquad \mathbf{u}(n) = \begin{bmatrix}u_1(n)\\ u_2(n)\\ u_3(n)\\ u_4(n)\end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix}0.6598 & 0.1651 & 0.1766 & -0.2301\\ 0.0914 & 0.5618 & -0.0994 & 0.0963\\ 0.2547 & -0.2619 & 0.5633 & 0.2804\\ -0.4270 & 0.3440 & 0.3606 & 0.4378\end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix}0.5107 & 0.0737 & 0.0714 & -0.1301\\ -0.1028 & 0.7682 & -0.0266 & -0.0639\\ 0.0825 & -0.1664 & 0.4332 & 0.0829\\ -0.2172 & 0.1464 & 0.1602 & 0.3984\end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix}0.0221 & 0.0128 & 0.0460 & 0.1468\\ 0.1888 & -0.0351 & 0.0521 & 0.0234\\ -0.0116 & 0.1401 & 0.2531 & -0.0408\\ 0.2623 & -0.0807 & -0.0189 & 0.1158\end{bmatrix}, \qquad \mathbf{D} = \begin{bmatrix}-0.3231 & -0.0852 & -0.1400 & 0.0673\\ -0.1220 & -0.3314 & 0.0355 & -0.0097\\ -0.1501 & 0.1234 & -0.3942 & -0.1233\\ 0.1168 & -0.1442 & -0.2149 & -0.1903\end{bmatrix},$$

$$\mathbf{E} = \begin{bmatrix}-2.418 & -0.584 & -0.954 & -0.496\\ -1.311 & -2.394 & 0.009 & -0.738\\ -0.484 & -0.225 & -3.946 & -0.585\\ -0.795 & -0.274 & -0.681 & -2.520\end{bmatrix}\times 10^{-6}, \qquad \mathbf{F} = \begin{bmatrix}3.906 & 2.106 & 0.642 & 4.344\\ 6.340 & 8.720 & 3.262 & -3.140\\ 1.437 & -0.194 & 6.117 & -1.542\\ 4.451 & 3.147 & 1.638 & -5.622\end{bmatrix}\times 10^{-7}$$

$$\mathbf{G} = \begin{bmatrix} -3.660 \\ -1.117 \\ 2.079 \\ -3.963 \end{bmatrix} \times 10^{-6}.$$

3. Fuzzy Control System Performance Requirements

The fuzzy controller that you will develop should be **innovative** and make the closed-loop system perform as well as possible in terms of $z_k(t)$. You need to evaluate your control system using three different initial positions of the carrier specified in Table 2. Each initial position is characterized by defining the initial locations of the carrier's four corners where the floators are located (Not all these settings are necessarily practically realizable by the current technologies. They are included to make the competition challenging and interesting). The same fuzzy control algorithm that you will design should be used for all the three different settings. You may use different values of the controller's parameters for the different settings. Using a significantly different fuzzy control algorithm to deal with the different settings is undesirable for the sake of this competition.

Table 2. Three different initial positions of the carrier as defined by the initial positions of its four corners (i.e., the four iron floators).

	Initial Position Setting 1	**Initial Position Setting 2**	**Initial Position Setting 3**
z_{10}	0.0001m	0.0005m	0.0006m
z_{20}	0.0003m	0.0003m	0.0008m
z_{30}	0.0009m	0.0011m	0.0014m
z_{40}	0.0007m	0.0013m	0.0012m

Fuzzy control system performance under each of the three settings should be evaluated. The performances should be assessed according to the following measure ($k = 1,2,3,4$):

1. rise time of $z_k(t)$ (the time elapse when $z_k(t)$ rises from 10% to 90% of $z_{k0} - z_{SP}$),
2. maximum overshoot of $z_k(t)$,
3. settling time of $z_k(t)$ (the time when $z_k(t)$ enters and stays in the interval $\left[98\%\left(z_{k0} - z_{SP}\right),\ 102\%\left(z_{k0} - z_{SP}\right)\right]$),

4. steady-state error of $z_k(t)$ with respect to z_{SP}.

Your fuzzy control system must meet the following constraints all the times during the operation:

1. To avoid physical damage, $z_k(t) = 0$ is not allowed, which means that the actuators cannot be touched by the floators. Obviously, $z_k(t) < 0$ is physically impossible.
2. $z_k(t)$ and $u_k(t)$ are subjected to the limits given in Table 1.

4. Reporting Requirements

For all three settings given in Table 2, please submit the following control results to the Task Force along with your paper through the conference paper submission website (k = 1, 2, 3, 4):

1. Plots showing $z_k(t)$ (and the lines of $z = z_{SP}$ and $z = 0$) and $u_k(t)$. The constraints on $z_k(t)$ and $u_k(t)$ given in Table 1 should be displayed in the plots of $z_k(t)$ and $u_k(t)$, respectively. Please use different colors for different curves and use the colors consistently from plot to plot in terms of k. Please insert legends for the curves in the plots. There should be a total of 12 plots.
2. Please make a Microsoft Word file with the name *readme.doc*. Use it to list the names of all the plot files with brief descriptions of their contents.
3. Please provide a Microsoft Excel file that contains the time instances and all $z_k(t)$ for the first 50 time steps. Each $z_k(t)$ should occupy a column in the file. The first row should provide clear labels for each column. There should be a total of 13 data column, including the first column being the time stamps.
4. All the computer programs related to your fuzzy control solution presented in the paper should be submitted to the Task Force. A reasonable amount of documentation is expected to enable the Task Force to understand not only the functionality of each of the programs but also the line-by-line code in each program. The more detailed the documentation is, the better. Furthermore, the author should provide the operation instruction detailing how to set up the programs and their operating environment so that the programs will run correctly and produce the exactly same results given in the paper and the plots mentioned above. Enough information should be available so that the Task Force will be able to replicate the results if it wants to.
5. All the files mentioned above should be zipped into one file, with the file extension of either ZIP or RAR, before uploaded with the paper manuscript.

Please read this section carefully and prepare all the files item by item to make sure no file will be missing. Once the submission deadline passes, the Task Force will not accept any change to its files. Please make your files as self-explanatory as possible. Failure to understand your results can dampen Task Force's enthusiasm on your work.

Thank you for your interest. We look forward to receiving your paper!