Description of 2009 FUZZ-IEEE Conference Competition Problem

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

Magnetic suspension is contact-free and wear-free and hence has the potential to achieve large travel ultra precision motion control of an object (e.g., 1-μm resolution). Fig. 1 illustrates the simplified magnetic suspension system utilized in this competition. There are four equal–size cubic electromagnetic actuators (only two of them are visible in Fig. 1 due to the cross-section view that just blocks the images of the other two). They are securely attached to the four corners of a rectangle plate stator that is mounted on a stationary metal plate. The DC current in the coil of the *k*-th actuator ($i_k(t)$, *k* = 1,2,3,4) can be adjusted by changing the DC voltage $u_k(t)$ applied to the coil wrapped around an iron core. This will result in varying magnetic force $f_k(t)$ exerting on iron floator *k* along the z axis, that is, vertically. There are four floaters, as shown in Fig. 2, which are equal cubes with equal mass. The mass density of the floators is assumed to be uniform. There are only two forces acting upon each of the floators – the magnetic force and the gravity. Through the balancing of these two vertical forces, the floators float in the air. 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 origin of the z axis is marked in Fig. 1, so is the target horizontal level of the floators, z_{SP}.

2. Dynamics of the Magnetic Suspension System

The magnetic suspension system's input is the DC voltage $u_k(t)$ and its output is $z_k(t)$. Hence, this system is multi-input, multi-output. The dynamic relationship can be established by using the physical principles (e.g., [1,2]). Our magnetic suspension system is supposed to be governed by the following nonlinear differential equations (k = 1, 2, 3, 4):

$$R_k \cdot i_k(t) + \frac{A_k N_k^2 \mu_0}{2 z_k(t)} \cdot \frac{d i_k(t)}{dt} - \frac{A_k N_k^2 \mu_0 i_k(t)}{2 z_k^2(t)} \cdot \frac{d z_k(t)}{dt} = u_k(t) \tag{1}$$

$$f_k(t) = \frac{A_k N_k^2 \mu_0}{4} \left(\frac{i_k(t)}{z_k(t)} \right)^2 \tag{2}$$

The meanings, values (and their limits) and units of all the parameters above (and below) are given in Table 1. There are four pairs of the equations characterizing the four electromagnetic actuators. In this competition, we suppose the four actuators to be in the same size but possess different electromagnetic properties. In other words, the values of the parameters in the equations are different from actuator to actuator (Table 1).

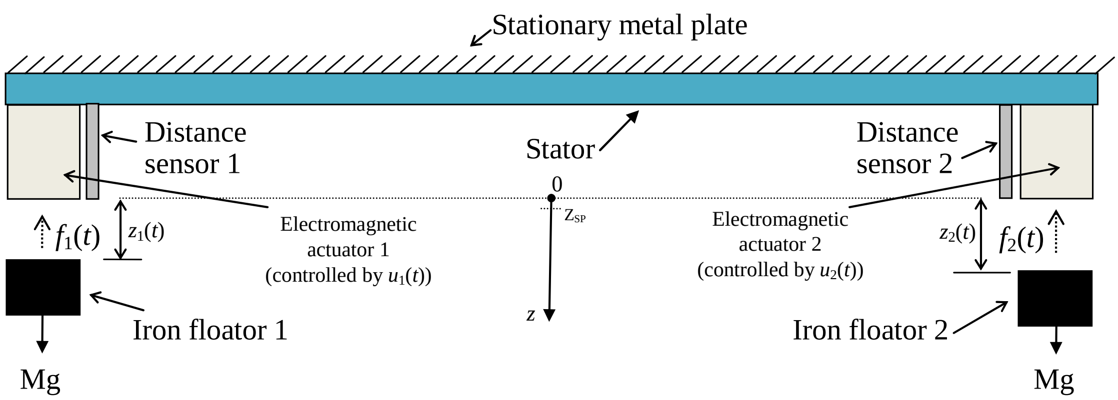

Fig. 1. Cross-section view of the simplified magnetic suspension system.

Fig. 2. Aerial view of the four equal-size iron floaters that are aligned horizontally and vertically. An electromagnetic actuator is placed above each floator (not shown here; see Fig. 1 for actuators 1 and 2)

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

Symbol	Meaning	Value, Limit, and Unit
$f_k(t)$	magnetic force acting up electromagnetic actuator k	≥ 0, N
	($f_k(0) = 0$ for all k)	
$z_k(t)$	distance between actuator k and iron floator k	> 0, m
z_{k0}	initial distance between actuator k and iron floator k	m, see Table 2
$\dot{z}_{k0}$	initial speed of iron floator k	0 m/s
z_{SP}	distance set-point for all the four floators	0.002 m
μ_0	magnetic conductivity in the air	$4\pi \times 10^{-7}$H/m
M	mass of each iron floator	3 kg
g	acceleration due to gravity	9.8m/s^2
$u_k(t)$	DC control voltage applied to actuator k	0 - 100V for k = 1,2
	($u_k(0) = 0$ for all k)	0 - 150V for k = 3
		0 - 140V for k = 4
R_k	coil resistance of actuator k	5Ω for k = 1,2 10Ω for k = 3 8.5Ω for k = 4
$i_k(t)$	DC control current in actuator k	0 - 20A for k = 1,2
	($i_k(0) = 0$ for all k)	0 - 15A for k = 3,4
A_k	sectional area of actuator k	0.0002m^2 for k = 1 0.000237m^2 for k = 2 0.0005m^2 for k = 3 0.0004m^2 for k = 4
N_k	coil loop circle number of actuator k	300 for k = 1,2 600 for k = 3 500 for k = 4

Because all the magnetic forces act vertically, when floating in the air, the floaters can move up and down along the z axis only. Owing to Newton's second law,

$$M \frac{d^2 z_k(t)}{dt^2} = f_k(t) - Mg \tag{3}$$

The initial conditions for this equation, $\dot{z}_{k0}$ and z_{k0}, are given in Tables 1 and 2.

3. Fuzzy Control System Performance Requirements

The control objectives for this competition are

1. to drive the four floators to a pre-specified z_{SP} from their initial positions as quickly as possible with minimum distance overshoot by adjusting $u_k(t)$,
2. $z_k(t)$ should try to stay in the same plane all the times, which means they should satisfy the constraint $z_1(t) + z_3(t) = z_2(t) + z_4(t)$ as much as possible.

You need to evaluate your control system using the three different sets of initial positions of the four floators specified in Table 2 (Not all these tasks are necessarily practically realizable by the current technologies. They are to make the competition challenging and interesting). The same fuzzy control algorithm that you will design should be used for all these settings. You may set different values of the controller's parameters for different settings. Using significantly different fuzzy control algorithms to deal with the different settings is undesirable for the sake of this competition.

Table 2. Three different sets of initial positions of the four floaters.

	Initial Position Setting 1	**Initial Position Setting 2**	**Initial Position Setting 3**
z_{10}	0.001m	0.005m	0.006m
z_{20}	0.003m	0.003m	0.008m
z_{30}	0.009m	0.011m	0.014m
z_{40}	0.007m	0.013m	0.012m

Fuzzy control system performance under each of the three settings will be evaluated. Under the condition that the second control objective stated above is met, the control performances should be assessed according to the following measures (k = 1,2,3,4):

1. minimum rise time of $z_k(t)$ (the time elapse when $z_k(t)$ rises from z_{k0} to reach z_{SP} for the first time),

2. smallest maximum overshoot of $z_k(t)$,
3. shortest settling time of $z_k(t)$ (the time when $z_k(t)$ enters and stays in the band of $\pm 2\% \times (z_{k0} - z_{SP})$),
4. smallest 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 ($k = 1, 2, 3, 4$):

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. $i_k(t)$ and $u_k(t)$ are subjected to the limits given in Table 1.

3. Reporting Requirements

For all the 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 web site (*k* = 1, 2, 3, 4):

1. Plots showing $z_k(t)$ (and the lines of $z = z_{SP}$ and $z = 0$), $z_1(t) + z_3(t) - z_2(t) - z_4(t)$, $i_k(t)$, $u_k(t)$ and $f_k(t)$. The constraints on $i_k(t)$ and $u_k(t)$ given in Table 1 should be displayed in the plots of $i_k(t)$ 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*. When appropriate, please insert legends for the curves in the plots. There should be a total of 15 (5x3) plots.
2. Please make a Microsoft Word file with the name *readme.doc* to list the names of all these plot files with a brief description of what each file contains.
3. For each set of the initial positions, please make a table to show: (1) the rise time of each $z_k(t)$ and their average, (2) the maximum overshoot of each $z_k(t)$ and their average, (3) the settling time of each $z_k(t)$ and their average, (4) the largest absolute

value of the steady-state error of each $z_k(t)$ and their average, and (5) the largest absolute value of $z_1(t)+z_3(t)-z_2(t)-z_4(t)$ and its mean and standard deviation. There should be a total of 3 tables

4. Please provide a Microsoft Excel file that contains the time stamps and all the $z_k(t)$. Each of $z_k(t)$ as well as $z_1(t)+z_3(t)-z_2(t)-z_4(t)$ should occupy a column in the file. The first row should provide clear labels for the columns. There should be a total of 16 (1+5x3) data column, including the first column being the time stamps.
5. In a document file (handwriting is not acceptable), list all the equations/formulas used in your control algorithm. Show numerically how they are utilized to compute the next positions of the four floaters from their initial positions of the first setting given in Table 2 (i.e., calculations involved in just one time step). All the intermediate calculation steps involving the other variables should also be provided. The demonstration should be in such detail that it will enable a Task Force member to compute the positions of the floaters using your control algorithm for any instance of system time.
6. All the computer programs related to your fuzzy control solution. A reasonable amount of documentation is required to enable the Task Force to understand not only the functionality of each of the programs but also the 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 on the computers of the Task Force members to produce the exactly same results that you submit.
7. All the files mentioned in items 1-6 should be zipped into one file, with the file extension of either ZIP or RAR, before uploaded to the conference submission web site with your paper manuscript.

Please read this section carefully and prepare all the files item by item to make sure no file will be missing. Please make your files as self-explanatory as possible. Failure to understand your results can substantially damp Task Force’s enthusiasm on your work.

References

1. Shiakolas, P.S.; Van Schenck, S.R.; Piyabongkarn, D.; Frangeskou, I., "Magnetic levitation hardware-in-the-loop and MATLAB-based experiments for reinforcement of neural network control concepts," *IEEE Transactions on Education*, 47:33 – 41, Feb. 2004.
2. Kwang Suk Jung; Yoon Su Baek, "Precision stage using a non-contact planar actuator based on magnetic suspension technology," *Mechatronics*, 13:981 – 999, 2003.