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MODULAR CONTROL SYSTEM FOR A MAGNETIC LEVITATED STAGE

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Abstract: *We developed a magnetic levitated stage system, which allows precise positioning in six DoFs, with only one mover. It requires control of force in many points. Besides, the number of controlled points can vary with the travel range. For these reasons, a modular concept for the control and driving system is required. The paper presents the way in which the modularity is obtained in terms of control algorithm, embedded computing and driving.*

Keywords*: advanced magnetic levitation systems, control systems*

1. INTRODUCTION

Magnetic levitation appears to be a promising technology for achieving the extreme precision required by today's fabrication processes, especially those used in IC production. Unlike the conventional systems that use stacked movers to obtain the desired DoFs, in case of a magnetic levitated stage, motion on three linear axes along with three rotational ones is obtained with a single moving part, floating over an active surface.

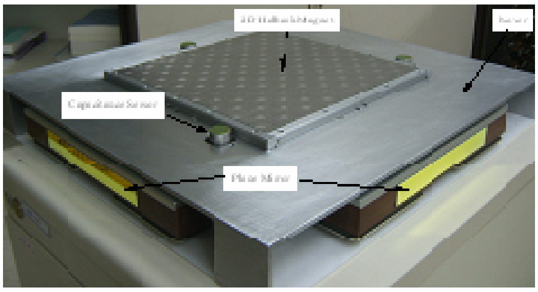
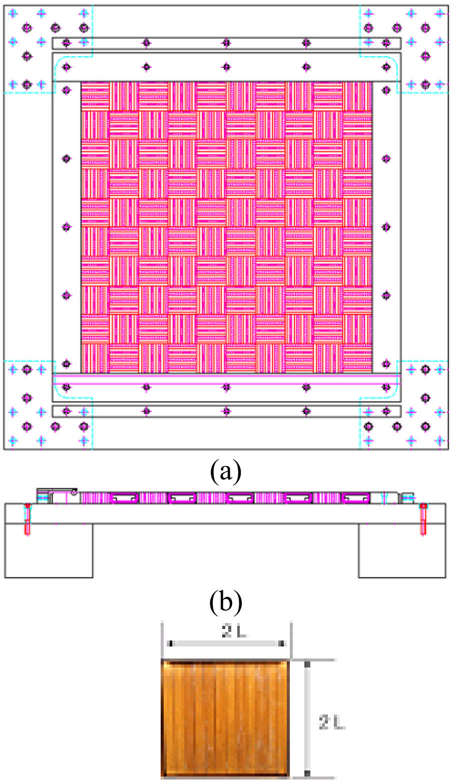


Fig. 1. Bottom view of the mover

From the point of view of motion generation, the mover can be passive, with no need for energy to be brought on it. This is obtained by attaching a permanent magnet (PM) array on its bottom (Figure 1).

The pseudo-sinusoidal magnetic field yielded by the PM array interacts with that of the coils, which are mounted in a chessboard array in the fixed part of the machine (Figure 2). All the coils contribute to levitation and motion in the three vertical modes (Z, Θ_x, Θ_y). Half of the coils provide motion in X direction, the other half in Y direction and together, allow the control of yaw (Θ_z).


(a)

(b)

(c)

Fig. 2. Coil assembly (a) Schematic, top view.(b) Schematic, side view. (c) Coil module (L ismotor pitch)

The experimental setup is shown in Figure 3. It is easy to notice that, in this system, the travel range of the mover is restricted only by the size of the coil array, which, based on the modularization and power management methods presented in this paper, is theoretically unlimited. This is another major advantage of magnetic levitation approach over the conventional systems and opens the way for a new concept for process clusters (Figure 4). The coil bed is used for conveying the specimen and for its fine positioning during processing as well. More specimen holding movers can float simultaneously, on the coil bed.

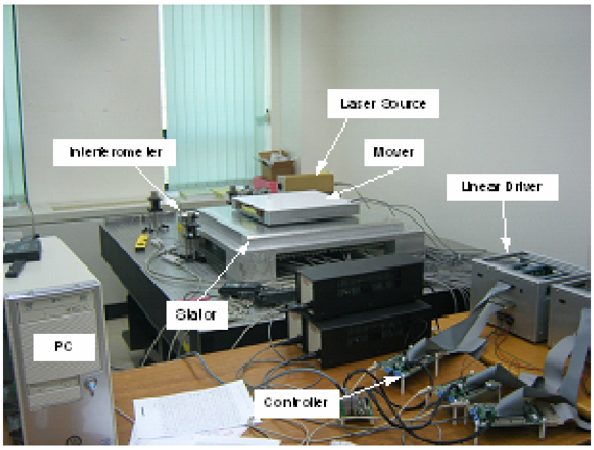


Fig. 3. Experimental setup of magnetic levitated stage

No wear and very low contamination are other advantages of magnetic levitation, stemming from its contactless nature. These advantages are provided by air bearings as well, with restrictions related to operation in vacuum environment, which is not the case with magnetic levitation. When vacuum operation is not a condition, in order to reduce current in coils, it's worth considering adding air bearing levitation to magnetic levitation.

With the appropriate metrology, positioning accuracy of few nanometers can be achieved. In the current embodiment, laser interferometers are used for the horizontal modes and capacitive gap sensors for the vertical ones. Since the plate which cover the coils is not a reliable target for the gap sensors mounted on the bottom of the mover (see Figure 1), we plan to find another solution for sensing the vertical modes.

The great and variable number of coils leads to the necessity of a modular control and driving system. This is more obvious when a structure like that shown in Fig. 4 is considered.

Those presented in the following sections refer to the embodiment shown in Fig. 3, but some ideas can be easily ported to the structure shown in Fig. 4. The control strategy is presented in Section II. The modular control and driving structure is presented in Section III.

2. CONTROL STRATEGY

The mover is levitated by the repelling forces between PM array and powered coils. Since levitation by repulsion is not laterally stable, the basic task of the control system is to stabilize the mover, which cannot stay in the normal, levitated position without control. In this case, the guide of the mover is a system of forces (Figure 5), created and continuously maintained by the control system. The guide provides both stiffness and flexibility, allowing precise motions of the mover in six DoFs.

The forces shown in Figure 5 are of Lorentz type, resulted from the effect of the magnetic field of PM array on the powered phases of the coils. The current distribution in the coils is pseudo-sinusoidal. The controller can apply the needed forces by controlling the amplitude and spatial phase of the current wave. As shown in Figure 5, all the coils contribute to levitation (forces in Z direction) and, according to their orientation (see Figure 2), generate thrust forces is X or Y directions, respectively.

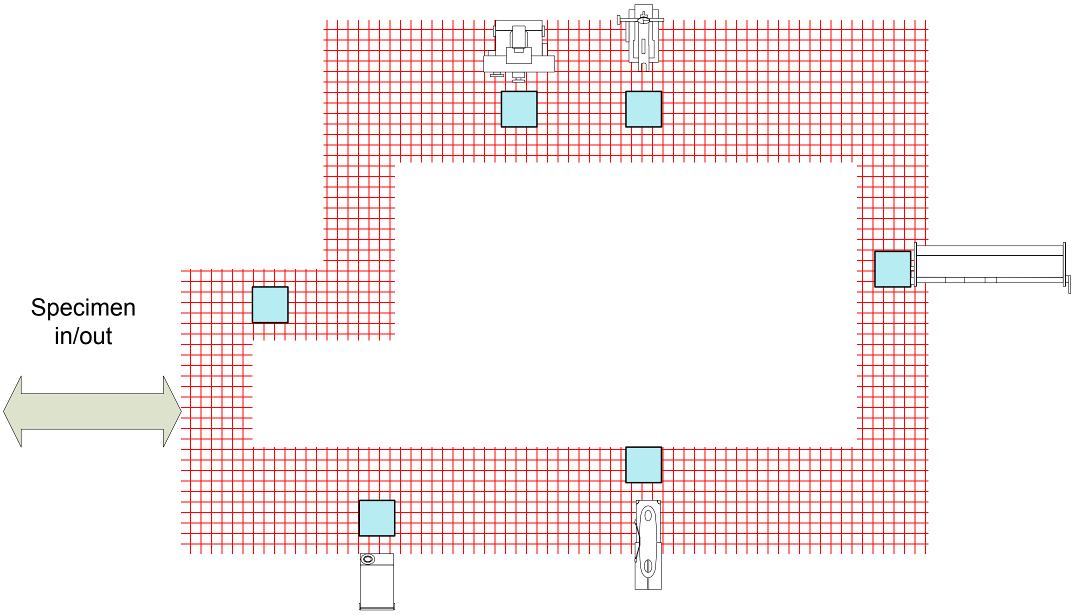


Fig. 4. Processing cluster with five nodes; the coil bed provides both specimen's conveying and its attitude in the processing node; six movers float on the coil bed

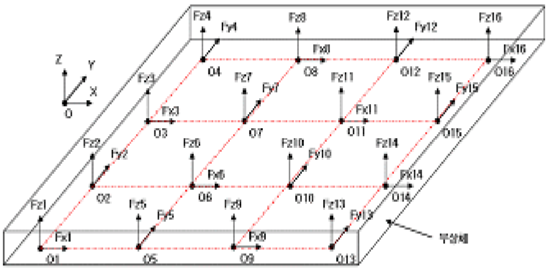


Fig. 5. Forces for a 4 by 4 coil array

The conventional control method (Figure 6) compensates the errors in the six modal axes by generating control efforts as follows: three forces for the linear DoFs (X, Y and Z) and three torques for the rotational DoFs (Θ_x, Θ_y, Θ_z). These forces and torques has to be decomposed to the forces that can be physically generated. Force decomposition requires a non-square matrix to be inverted, operation that has not a unique solution.

We developed an alternative method (Figure 7), with which, the position of the force application points is directly controlled and the outputs of the compensator are physical forces, those presented in Figure 5.

The equations for translation and rotation are:

$$C_r = R_r C_0 + P_{rlin}$$
$$C = RC_0 + P_{lin} \tag{1}$$

where $\mathbf{P}_{\mathbf{rlin}}$ and $\mathbf{P}_{\mathbf{lin}}$ are vectors with linear components (X, Y and Z) of $\mathbf{p}_\mathbf{r}$ and $\mathbf{p}$, respectively, and $\mathbf{R}_\mathbf{r}$ and $\mathbf{R}$ are rotation matrixes made from the angular components, approximated from Euler angles for very small values:

$$R = \begin{bmatrix} 0 & -\theta_z & \theta_y \\ \theta_z & 0 & -\theta_x \\ -\theta_y & \theta_x & 0 \end{bmatrix} \tag{2}$$

Error vector **e** has two components for each force application point, one for each direction for which the corresponding coil can generate force.

In both methods, decoupled control, with Lead-PI compensators, has been used.

The main advantage of the alternative method over the conventional one comes from the fact that the compensators generate directly physical forces, eliminating the necessity of finding an optimum solution for the decomposition of modal forces. Thus, the process of conceiving the control algorithm is simplified. Moreover, the alternative method seems to address more efficiently the parasitic coupling between axes generated by the imperfections of the physical system; during experiments made at the beginning of our project with both methods, using a simpler structure of the stage, the position noise with the alternative method was 30% smaller than that with the conventional method.

A disadvantage of the alternative method comes from the great number of compensators, two for each coil, compared with a total number of six, in case of conventional method. But with the computing power of today's DSPs, this disadvantage can be easily overcome.

The great number of controlled points is another issue in the control strategy. In fact, there is a minimum number (N) of coils that must be active for a given position of the mover; these are the coils facing, totally or partially, the PM array. One solution was to build a control and driving unit with N outputs along with a switching circuit used to commute coils in relation with the changes in the horizontal position of the mover. But, being concerned of the transients that could generate position glitches and foreseeing future evolutions, we preferred to create a structure in which, the control loops for all the coils are executed continuously, as if the PM array is virtually stretched over the whole area of coils. For the coils outside the active area, the current is set to zero, whatever the value yielded by the compensator.

With the latter approach, it is worth distributing the control tasks, i.e. coils, to a number of identical modules. All the modules run the same program but, based on their ID, they extract from a configuration file, the specifications of allocated coils.

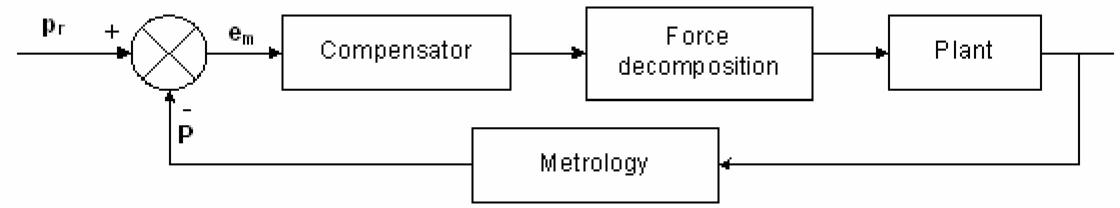


Fig. 6. The conventional control method; p and p_r are the process and reference position vectors with 6 components, one for each DoF; e_m is the modal error

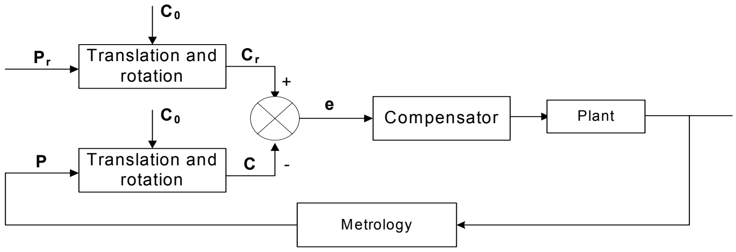


Fig. 7. The alternative control method; c0 is a vector containing the coordinates of the force application points with mover in the rest position

3. CONTROL AND DRIVING SYSTEM

The schematic of the control and driving system is presented in Figure 8. Up to 16 coils are allocated to one module. The DSP included in the module runs the control loops for the allocated coils, based on process and reference position data, received periodically from a central controller, over a high speed RS485 bus. The command signals are sent to the driver boards that use linear power amplifiers to generate the desired currents in the phases of the coils.

The main tasks of the central controller, DSP board on PCI bus, is reading and processing data from displacement sensors, in order to obtain the current position of the mover on the six axes and generating the desired trajectory. The results are periodically broadcasted to the modules.

The DSPs in the modules perform, for all the allocated control points, the following tasks:

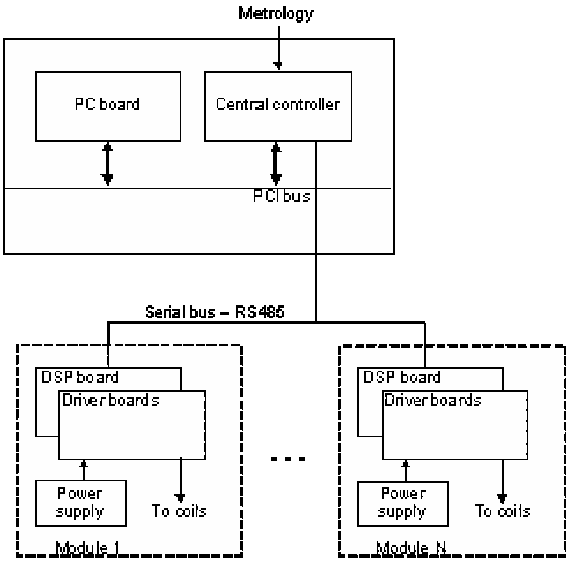


Fig. 8. Modular control and driving system

- Communication with central controller;
- Rotation and translation of the original force application point with the actual and reference position of the mover in 6 Dofs;
- Lead Pi;
- DQ to three phases transform.

The control loop period is 100μs. A data packet of 56 bytes is sent every period from central controllers to modules with a bit rate of 12.5 MHz. A DMA channel is used for transferring data from memory buffer to the serial port. Each module sends back, when selected, status information and DQ current values for all allocated coils.

The PC board runs the HMI, data logging and other auxiliary tasks.

The maximum power required by a module can be drastically reduced by optimizing the coil allocation. The optimization is enabled by the fact that, for any position of the mover, only the coils facing the PM array have to be powered. Consequently, if a group of neighbor coils are allocated to one module, the total power needed by a module can vary, depending of the position of the mover, from a maximum, all coils powered, to zero. In order to avoid this inefficiency, a scattered allocation of coils is required.

A program has been written for this purpose. It allocates the coils so that maximum six coils to be powered by a module, in any position of the mover. In order to reduce heat dissipated by the driver boards, optimization continues with allocation of coils to driver boards within a module.

This program makes also the graphical simulation of the power commutation procedure (Figure.9). After being tested on the simulator, this procedure can be easily ported to the control program.

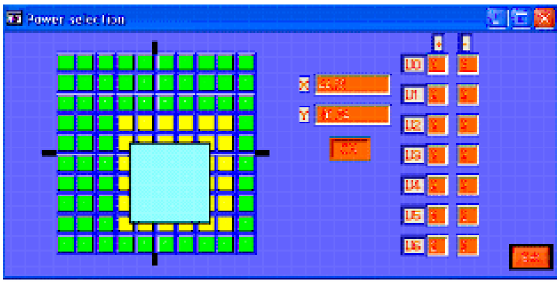


Fig. 9. Control panel of the power commutation demonstrator

3. CONCLUSIONS

The modular control and driving system presented in the paper allows for easy building of magnetic levitated stages with different maximum horizontal linear strokes. An alternative control method eliminates the necessity for force decomposition and contributes to the reduction of position noise. The allocation of coils to modules is optimized in order to reduce power requirements and dissipated heat.

In the future, modularity can be brought at coil level. An “intelligent” coil module will contain driver and DSP controller with wireless connection to the central unit. They will be used like bricks for building large conveying and processing areas.

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