Tilt Control of Magnetically Suspended Platform Using Zeropower Control [⋆]

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Abstract: This paper proposes a new type of tilt control mechanism for zeropower controlled noncontact magnetic suspension system. A suspended platform using zeropower control keeps horizontal level using the proposed mechanism, even if an arbitrary load is added to the platform. The proposed mechanism uses hybrid magnets whose locations are controlled as the platform level is horizontal. Positioning control of additional permanent magnets also achieves inclination control of the platform. First, conceptual proposal of proposed mechanism is explained and a prototype system is introduced. Hardware and system limitations are discussed and simulation results are provided which confirm the feasibility of the proposed control strategy.

Keywords: Magnetic suspension, electromagnetic device, zeropower control, tilt control, hybrid magnet.

1. INTRODUCTION

Magnetic suspension is a technology for supporting or manipulating objects without mechanical contact by means of magnetic forces. As no mechanical contacts, magnetic suspension systems have many advantages of no friction, no dirt, lubrication free, and maintenance free. Using these advantages, many magnetic suspension mechanisms have been proposed[Jayawant [1981]]. In these suspension mechanisms, electromagnetic suspension systems are widely used that control the coil currents of the electromagnets for suspension forces. Recently, aiming save energy during suspension, zeropower control has been developed for conveyors in clean environments [M. Morishita [1988], D. L. Trumper [2002], Hoque et al. [2006], van West et al. [2007]]

Zeropower magnetic suspension system uses HEM (hybrid electromagnet) composed of electromagnet and permanent magnet. It aims to suspend an object by levitating it in its equilibrium position of the force of the permanent magnet and to be converged to real zeropower state. Take for example a simple single degree of freedom case, where a magnetically ferromagnetic sphere is suspended under a permanent magnet. When the air gap between the sphere and the magnet is at its equilibrium value, the magnetic attraction between the sphere. And the magnet is equivalent to the gravitational force acting upon the sphere and no additional force is required to keep the system at rest. However, naturally, this is an unstable equilibrium position: if the air gap is increased, the sphere will fall to the ground, and if the air gap is decreased, the sphere will be attracted towards the magnet. Here then, it is the aim of zeropower magnetic levitation to employ active control, by means of, for example, an electromagnetic coil, to keep the system suspended in its equilibrium position. In practice, of course, energy is still required to power a computer and sensors, and to account for the imperfection in hardware and measurements.

When systems in more than one dimension suspended in this manner are considered, for example in the suspension of a platform rather than a sphere, the zeropower orientation is defined by the equilibrium orientation of the system and cannot be freely selected. That is, to achieve a specific attractive magnetic force, a specific air gap is required, which then determines the equilibrium orientation of the system.[Annasiwaththa and Oka [2016], Morishita et al. [1989]]

The goal of this research to provide a method achieve zeropower levitation of a platform under arbitrary loading while also being able to keep the platform in its preferred level orientation.

2. CONCEPT OF TILT CONTROL

2.1 Zeropower control mechanism

The conceptual illustration of zeropower control mechanism is shown in Fig. 1. A HEM which combine an electromagnet and a permanent magnet is used for a zeropower control suspension system. Force of a permanent magnet is indicated as "Passive Magnet" and force of electromagnet is as "Active Coil" which is controlled actively. The downward arrow indicates the gravitational force. When the force of passive magnet and the gravitational force is same, the suspended object is levitated without coil current. However, the system is unstable and for stabilization electromagnet force is used by feedback control. When the suspended mass was changed, zeropower system adjusts

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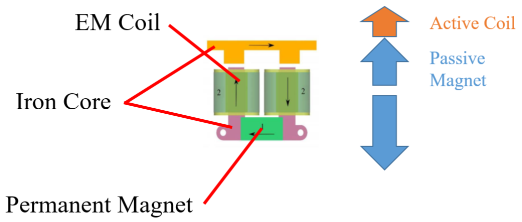
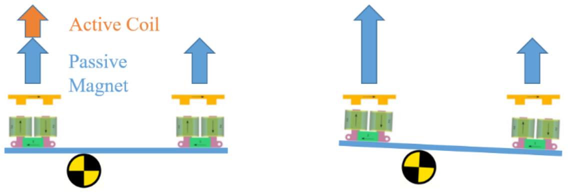


Fig. 1. Zeropower control mechanism of 1 d.o.f. system



(a) Tip-Tilt Control
Not Zero-Power

(b) No Tip-Tilt Control
Zero-Power

Fig. 2. When eccentricity load is added during multi d.o.f. zeropower control suspension system

the air gap as the passive force and the gravitational force are same.

A typical suspended zeropower platform cannot remain level under uneven loading. To exemplify, consider a uniform iron bar which is suspended horizontally by zeropower controlled magnets on either end. The suspension force in each magnet is same and the air gaps between the magnets and the bar would have to be the same and the bar is represented horizontally

Now, if a mass was suspended eccentrically from the bar as shown in Fig. 2, the magnet forces would no longer be equal in Fig. (a), and the necessary equivalent air gaps between the HEMs and the bar would also not be equal, causing the bar to be tilted in Fig. (b).

2.2 Proposed mechanism

To prevent this problem, two mechanisms are proposed as shown in Fig. 3. First, it is proposed that the location of the HEMs, be moved such that the center of mass of the system lie symmetrically between the HEMs as shown in the system 1. Under this condition, the forces at each location would be equivalent, again allowing the system to be level. This solution also works in three dimensions, where the center of mass would be placed at the centroid of three (or more) HEMs.

Second, it is proposed that the location of an additional permanent magnet, be moved such that the HEM generating forces are equal as shown in the system 2.

These mechanisms allow the suspension system to be both zeropower and tilt controlled simultaneously. In this paper, the mechanism of System 1 will be discussed.

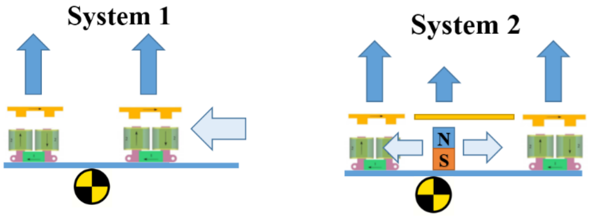


Fig. 3. Conceptual illustration of the proposed tilt control of multi d.o.f. zeropower control mechanisms

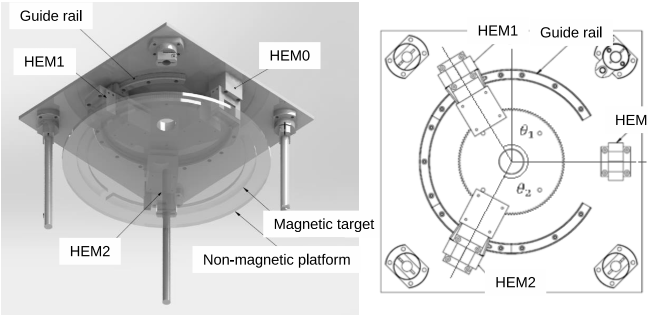


Fig. 4. Photographic view of proposed hardware implementation and schematic view of HEM arrangements

3. PROPOSED SUSPENSION SYSTEM

3.1 Prototype

A hardware configuration is proposed as an example implementation of the proposed zeropower levitation concept, though any number of other configurations are feasible. This configuration consists of an active upper portion which suspends a passive lower platform as shown in Fig. 4. The example implementation was chosen for design simplicity in hardware and software, which makes it more suitable for industrial application.

The active portion of the system consists of three HEMs (the minimum requirement), which are constrained circularly on a level plane as shown in the left in the figure. A single HEM is fixed, while the position of the other two HEMs are actively controlled (the minimum requirement) by a gear-servo system about a circular guide rail. The arrangement of the HEMs is as shown in the right in the figure. The north and south poles of the HEM are aligned tangentially, as opposed to radially to reduce the radial width of the magnetic target.

A passive platform is suspended below the active portion of the system, which consists of magnetically permeable targets affixed to a non-magnetically permeable plate. The transparent circle in the left figure is the platform. The corresponding target for the fixed HEM is rectangular and of the same outline as the HEM poles. The corresponding targets for the rotating HEMs are arcs of equal radial width to the HEMs, and which are cut and separated symmetrically as to minimize flux leakage to and from neighboring HEMs as shown. Such geometries were selected as to facilitate passive stability against rotation around the z-axis and lateral motions in the xy-plane.

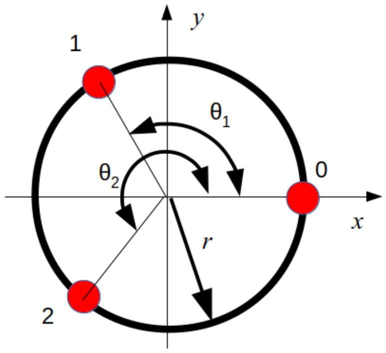


Fig. 5. Analysis model of proposed suspension mechanism

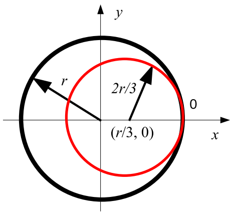


Fig. 6. Controllable range of the platform centroid eccentricity

3.2 Controllable range

The location of the HEM is modeled as Fig. 5. It is same view of the right figure in Fig. 4. The red circles and numbers indicate three HEMs. The location of HEM0 is fixed, other HEM1 and HEM2 are driven actually. The angles of the HEMs are represented as θ_1 and θ_2, and radius of the rail is represented as r.

When the centroid of the platform is assumed as x_g and y_g, it is necessary that the centroid of the platform is corresponding to the center of the three HEMs for simultaneous achievement of zeropower and tilt control. The center of the three HEMs is calculated as

$$\begin{aligned} x_g &= r/3(1+\cos\theta_1+\cos\theta_2) \\ y_g &= r/3(\sin\theta_1+\sin\theta_2). \end{aligned} \tag{1}$$

The following condition of x_g and y_g is given by the (1).

$$\begin{aligned} (x_g-r/3)^2+y_g^2 &= (2r/3)^2(1+cos((\theta_1-\theta_2)/2) \\ &\leq (2r/3)^2 \end{aligned} \tag{2}$$

The condition shows the limit of compensation range of the platform eccentricity as shown in Fig. 6. The simultaneous control can be achieved if the centroid of the platform is inside the red circle.

3.3 Transformation of HEM motion and centroid

When the center of three HEMs and the centroid of the platform are different location, control system makes some effort for agreement. For compensation, two HEMs are driven on the circular rail. It is necessary to know the relationship between the angle of HEMs and the geometric center in xy-plane. The function of these deviations is represented by using a Jacobian matrix which is derived by partial derivatives of (1).

$$\begin{pmatrix} dx_g \\ dy_g \end{pmatrix} = \begin{pmatrix} -\sin\theta_1 & -\sin\theta_2 \\ \cos\theta_1 & \cos\theta_2 \end{pmatrix} \begin{pmatrix} d\theta_1 \\ d\theta_2 \end{pmatrix} \tag{3}$$

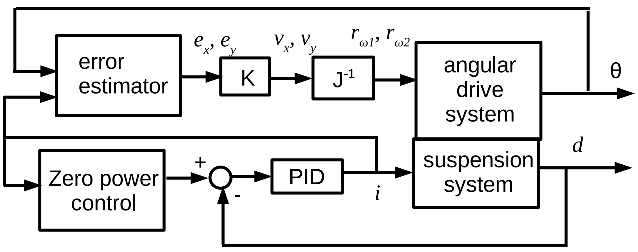


Fig. 7. Control system of simultaneous zeropower and tilt control

This equation is also used for the relationship of the velocity transformation. When the reference velocity is given according to the error of the centroid of the platform, the velocity is easily can be converted to the velocity of the HEMs using inverse matrix. However, if the determinant of the matrix of (3) is zero, the solution cannot calculate. As the case is $\theta_1 = \theta_2$ and the two HEMs is in the same position, calculation may be carried out at normal condition of the platform control.

4. CONTROL SYSTEM

It is convenient to view the control strategy for the proposed system as an integration of two constituent parts: a zeropower z-height controller and a zeropower HEM-angle controller as shown in Fig. 7. In the figure, the upper loop indicates the controller for angle controller, and lower loops is for z-height controller. This is a valid representation as the geometric centroid of the HEMs is independent of the z-height of the system. The responsibility of each controller, respectively, is to tend the system towards the zeropower z-height and zeropower HEM angle pair, together called the zeropower operating point. When the system is at the zeropower operating point, for which when the system is level only one exists for a given load, the center of mass of the system will be at the centroid of the HEMs and the z-height of the system will be such that the total permanent magnetic force is equivalent to the gravitational force, allowing for zeropower levitation.

The control strategy for the zeropower z-height controller can be commonly found in normal magnetic suspension system, where here, principally, the average of the three HEM currents is used in a zeropower feedback loop to change the z-target height of levitation until equilibrium is converged upon. For maintain the level of the platform three PID compensators are used.

For the zeropower angle pair controller, differentials of the three HEM currents are used as feedback to tend the centroid of the HEMs towards the unknown center of mass of the system. The differential values of currents and the position of the HEMs are used for the calculation of the estimation of the centroid of the platform. The difference between the geometric centroid and the estimated centroid is the reference values e_x and e_y of the angle controller. The values are transformed to the reference angle velocity $r_{\omega 1}$ and $r_{\omega 2}$ by multiplying the feedback gain K and inverse Jacobian Matrix J^{-1} as shown in Fig. 7. Consequently, indicating the center of mass becomes at the system center.

It should be noted that the attractive magnetic force between an HEM and a magnetically permeable target is dependent on both the current through the HEM as well as the air gap between the HEM and the target. Therefore, equal current readings do not indicate that the center of mass is at the centroid of the system unless the system is at the same time level. To ensure that the system remains level and reports the proper differential current feedback for this control strategy, it is only required that the response time of the HEM angle pair controller be tuned to be sufficiently slower than the z-height controller. In other words, if the HEMs were to move sufficiently slowly, a robust levitation controller could the correct current differential feedback can be attained by mainlining level levitation.

5. SIMULATION

Some numerical simulations are carried out for the feasibility of the proposed zeropower suspended platform system. In simulation, the characteristic of the force between the HEM and platform is linearized as it has negative stiffness. Controller gains are fixed by try and error.

One of the results is shown in Fig. 8. Three figures indicate the HEM angles, HEM currents, and platform motion from upper one to lower. Condition of the simulation is as follows: at the initial state, the centroid of the platform is located at the center and three HEMs are positioned in equal interval, so the zeropower and level control are achieved, at the next moment 10 % mass of the platform is added at the 20 % length of radius from the center on the x axis.

As seen in the figure of currents, three currents once increased and they all converge to zero. We can recognize that zeropower control is achieved. Current of HEM1 is same as HEM2, so the line cannot be seen. As the load is added on the x axis, current of HEM0 is larger than others.

The orientation of the platform is shown in the bottom figure. It shows that the rotation of the y axis is observed. However, it returns to zero in few seconds. The tilt controller keeps the platform horizontally. The height of the platform changes to upward, because of the added load. The angles of HEM are changed to align the center of HEMs to the centroid of the platform. The simulation result verifies the proposed mechanism and control strategy.

6. CONCLUSION

A concept was proposed which allows for zeropower control to be achieved for systems under arbitrary loading while allowing the system to remain level. A hardware configuration was proposed and simulations are performed to verify the validity of the proposed control strategy, hardware configuration and controller. The control paradigm was confirmed to converge to the zeropower solution in both z and angle under different loading conditions, and it was shown that the z and angle controllers can be run simultaneously without significant negative interference between the two controllers

As the future work, experimental examinations should be necessary for the verification of the proposed system. The results will be presented in the Conference.

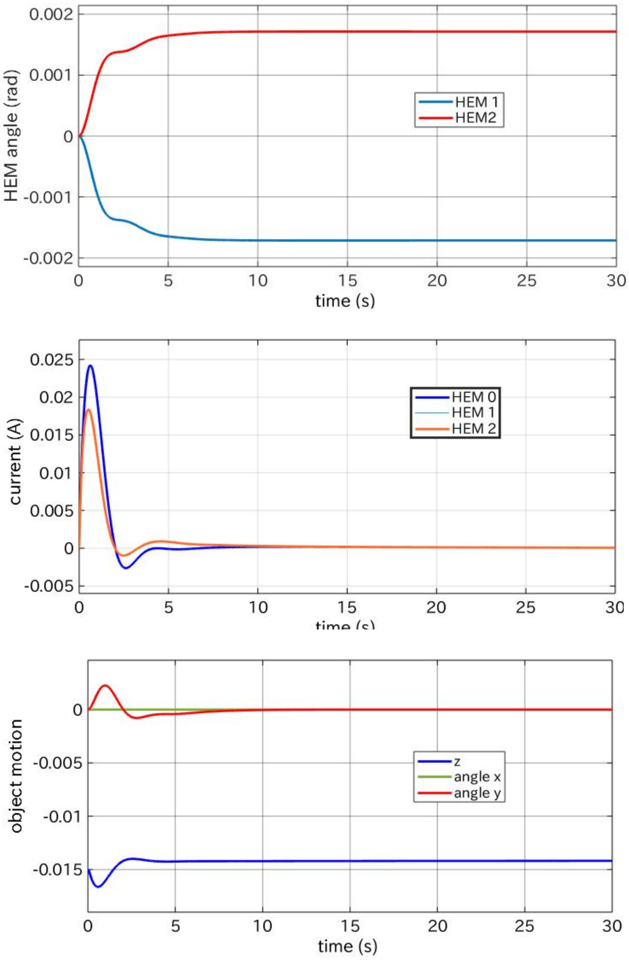


Fig. 8. Controllable range of the platform centroid eccentricity

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