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Modeling and designing levitation, roll and pitch controller for high accuracy maglev tray system

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ABSTRACT

Maglev (magnetic levitation) system has been introduced as one of innovative technologies that transportation is able to move without contacting on the ground so that it has immensely beneficial in eliminating friction and generating high speed. Having some advantages of generating less friction and dusts in maglev technology, we design a high accuracy maglev tray system to carry organic light-emitting diode (OLED) display. To carry OLED display in a stable condition, it is necessary to control precisely the levitation state. In our paper, a multi-degree of freedom model for a high precision maglev tray system analyzed to consider the stability and robustness of levitation performance. This model is then used to design a cascade control strategy and a combined optimal state-feedback controller–observer compensator for the heave, roll and pitch motion of maglev tray system. The proposed controllers demonstrate the excellent levitation performance under comparative simulations such as a large load disturbance and sensor installation error.

1. Introduction

Maglev is an innovative transportation technology that is finding wide acceptance in many varied applications including, although not limited to, maglev trains, magnetic bearings, and magnetic suspensions, etc. [1–4]. Maglev systems are capable of rapid motion and the elimination or reduction of vibration owing the virtual elimination of friction. Recently, this emerging technology has found application in the precision transport of displays during the manufacturing processes.

One of technical challenges in transport of displays is to carry it under stable levitation performance. Therefore, controller design is paramount in the successful implementation of a stable levitation system. Many control strategies have been tried including the following with varying degrees of success. Li et al. [5] used the Taguchi method of control strategies to obtain the optimal parameters in the controller with noise factors for a maglev tray system. While Park et al. [6] used a Linear Quadratic Regulator (LQR) approach to design a controller for a maglev tray system. Kim et al. [7] designed a maglev conveyor system for carrying LCD glass. Lee et al. [8] designed a Proportional Differential Acceleration (PDA) controller to accommodate the pitch motion.

Recently, high accuracy maglev tray transportation systems have been introduced in the process of manufacturing organic light-emitting diode displays (OLED) [9]. OLED displays have certain advantages over other display technologies including: lightweight, flexible, thin, and brighter light output. But OLED is an organic thin film so that it must be guarded from heat, vibration, dust, and exposure to air during the manufacturing process. Thus, a high precision maglev tray system is proposed for the transportation of OLED displays during the manufacturing process. This system is capable of moving the displays without any electrical components in the vacuum chamber. This approach represents a new paradigm for these sensitive material-based displays.

In our previous research [9,10], the maglev system was analyzed as a single-mass system in which only the vertical (heave) motion of the tray was considered in the design of the levitation controller. Because of external load disturbance, different levitation forces exerted by the levitation electromagnets and sensor installation errors, rotational movements of the tray can occur and affect the levitation control performance of the maglev system.

In this paper, the 3-dimensional dynamics of heave, roll and pitch motion are established based on the airgap relationship and to design the levitation, roll and pitch controller. Especially, owing to the unique spatial influence areas of the levitation electromagnets utilized to levitate the tray, a novel approach is to establish for the dynamics of the roll and pitch motions required to design the controller. Therefore, we develop the mathematical approximation of the airgap relationship with the roll and pitch angles and combine this with the dynamic models to form a linear time-invariant state space system. Furthermore, we determine the efficacy of the controller using external load

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disturbance and sensor installation errors to evaluate control variables and overall the levitation control performance.

The paper is organized as follows. The high accuracy maglev system is described in Section 2. Section 3 presents a model of the maglev system including terms for the dynamics of heave, roll and pitch motion using Newtons method. This section also presents the equations describing the levitation forces and voltage approximations linearized about the nominal equilibrium point. In Section 4, the levitation controller is described; it utilizes a cascade control strategy which consists of current and airgap controllers. In Section 5, the roll and pitch controller using an optimal control strategy is introduced. This section also introduces an observer design to estimate state variables. A compensator is developed using an optimal control/observer approach. In Section 6, the simulation results for the combined levitation, roll, and pitch control design under various conditions are presented. Finally, the paper concludes with a summary of our work and recommendations for future improvements.

2. Maglev tray system design

The high accuracy maglev tray system for OLED display manufacture is shown in Fig. 1. In our system, the tray is designed to carry 5th generation glass-boards of size and weight 1400 mm × 1300 mm and 400 kg, respectively. The longitudinal length of frame is approximately 4.0 m and a tray moving length is 2.6 m. The overall length of system can be extended with additional modules. When active, the tray is levitated by 1 mm under feedback control.

Major components of maglev tray system are levitation electromagnets, guidance electromagnets, gap sensors, propulsion linear motor and linear encoder as shown in Fig. 2. All major components are installed outside of tray (on the upper frame) to eliminate heating. Moreover, the tray does not supply any power to the system, so there is no internal heat added in the process of carrying the OLED display. Levitation electromagnets are installed on the upper frame discontinuously to levitate tray and it causes a fluctuating movement periodic with the translation of the trays. In order to minimize the fluctuating movement of maglev tray, 7 levitation electromagnets at right and left side are activated to support tray at any position. The guidance electromagnets are used to control the translational movement in the lateral axis and its rotational movement (yaw). Gap sensors are used to measure the vertical displacement between maglev tray and levitation electromagnets and propulsion linear motor generates a force along its length to move maglev tray. Linear encoder is used to determine the position of maglev tray.

Fig. 1. High accuracy maglev tray system.

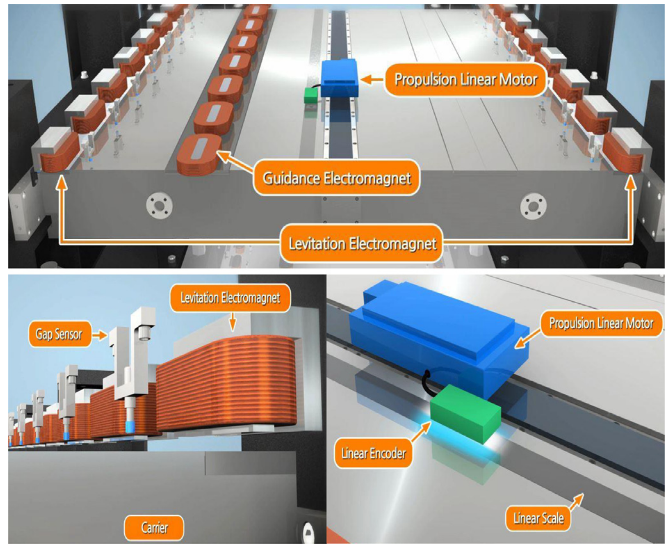

Fig. 2. Major components of high accuracy maglev tray system.

3. Dynamic models of maglev tray system

In our research, we have focused on the design of levitation, roll and pitch motion of the maglev tray system. The maglev tray is a six-degree of freedom system (DOF). However, the lateral movement and yaw motion of the tray are constrained by the guidance electromagnets. Additionally, the translation movement in the propulsion axis is not considered in our current research. The 3-dimensional axis of maglev tray system is shown in Fig. 3. The x, y and z-axis are the propulsion, the lateral and the heave (vertical) axis, respectively. Other variables in Fig. 3 are explained in each dynamic model section. The heave, roll and pitch motion are analyzed based on the translational and rotational direction of Fig. 3. The tray models are established based on the following assumptions; the shape of tray is rectangular, it is flat, mass of tray is equally distributed, lateral movement and yaw motion are constrained to the guidance electromagnets, angles of roll and pitch are relatively small, the effect of eddy current damping is relatively small and magnetic field of coils on each levitation electromagnet may be negligible.

3.1. Levitation force and voltage equation

To control the vertical dynamics of maglev tray system, we firstly analyze the levitation force and the voltage equation exerted by each electromagnet which are described by Sinha et al. [11]

$$f(i_k, c_k)_k = f_k = \frac{\mu_0 N^2 A}{4}\left(\frac{i_k}{c_k}\right)^2, \ k = 1, 2, 3 \ldots n \tag{1}$$

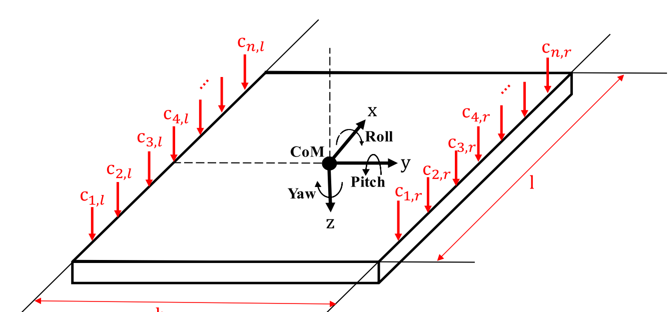

Fig. 3. 3-dimensional maglev tray system.