A Switch-controller for Improved Measurements in the NIST Magnetic Suspension Mass Comparator

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***Abstract*—We describe a switch-based control strategy implemented on a proof-of-concept version of the Magnetic Suspension Mass Comparator (MSMC) at the National Institute of Standards and Technology. The MSMC apparatus is used to compare mass artifacts held in air to mass artifacts held in vacuum, without having to remove either artifact from its respective environment; thus, eliminating the need to use empirical sorption models. This comparison is achieved by magnetically suspending the mass artifact held in air. The switch-controller utilizes a combination of a magnetic field and displacement measurement to achieve the desired robustness and stability.**

***Index Terms*—laser velocimetry, magnetic levitation, mass metrology, sorption, state feedback, switch controller.**

I. Introduction

After the highly anticipated redefinition of the International System of Units, the unit of mass, namely the kilogram, will be defined using Planck's constant [1]. In the United States, mass will be disseminated from the NIST-4 Kibble balance [2]. The realization of the kilogram will occur in a vacuum environment; however, dissemination from the realization artifact to other artifacts will occur in air. In transferring the realization artifact from vacuum to air, the artifact's mass value will change due to sorption effects [3]. Estimating mass changes from sorption is challenging due to the variability of the composition of air, with the effects of hydrocarbons playing a large role. At the National Institute of Standards and Technology (NIST), we have constructed an instrument, namely the Magnetic Suspension Mass Comparator (MSMC), that allows one artifact to remain in vacuum, while another artifact remains in air [4]. The two artifacts can be compared (i.e., a calibration of the air-artifact by comparisons with the vacuum-artifact) by means of magnetic suspension. A detailed description of the MSMC, including its components and the calibration process, is provided in Refs. [4]–[6].

Here, we focus on the control system used to magnetically suspend the mass that is held in air. There have been two notable improvements in the magnetic suspension control scheme from what has been previously reported in Refs. [5] and [7]. First, a laser interferometer has been implemented to measure the displacement of the suspended mass when making comparisons. Second, a switch-based control scheme has been designed which utilizes both displacement and magnetic field measurements. This control approach has been demonstrated on a proof-of-concept system, shown in Fig. 1. Here, we document advantages and disadvantages of each controller and the integration of both controllers using a switch-based approach to achieve the desired stability and robustness needed to perform automated mass calibrations.

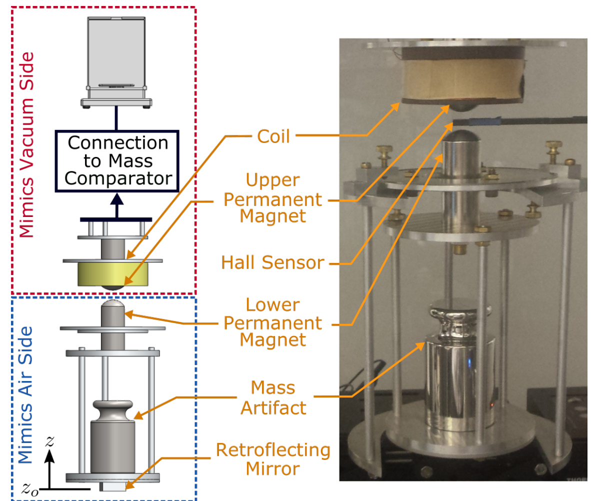

Fig. 1. A photograph of one portion of the proof-of-concept system with annotations. Within the photograph, the lower magnetic assembly (i.e., the assembly contained within the side that mimics air) is fully suspended.

II. Control Strategy

A. Switch-based Controller

A block diagram of the control scheme used to magnetically suspend the mass is shown in Fig. 2. The control scheme is a switch-controller wherein the control is either performed using a proportional-integral-derivative (PID) scheme with the magnetic field (B-field) as the feedback signal, or state-feedback control of the suspended mass displacement, measured optically with a laser interferometer. Each of the two controllers has their advantages and disadvantages. By using the switch-based approach, we can utilize the advantages of each one. The PID with the B-field measurement scheme is more robust to large disturbances which would otherwise cause the optical measurement to lose signal from misalignment of

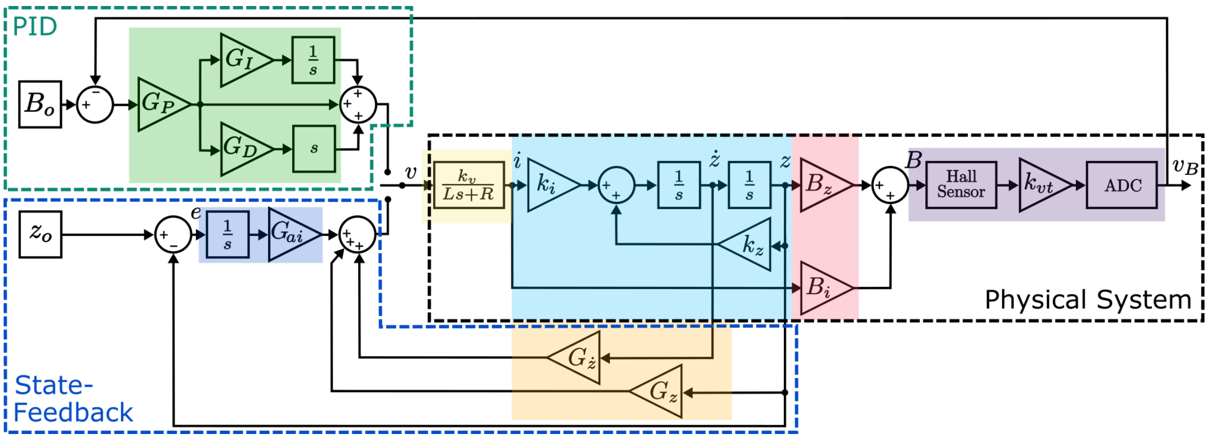

Fig. 2. Block diagram of the control scheme used to suspend the mass held in air. The portion within the dashed black lines represents the physical system, the block diagrams within the dashed blue lines represent the digitally implemented state-feedback controller, the portion within the dashed green lines is the digitally implemented PID controller. **Physical System:** *yellow*: magnetic coil, *light blue*: dynamics of the suspended mass, *red*: generation of the magnetic field, *purple*: sensing of the magnetic field. **State-feedback**: *dark blue*: action integrator, *orange*: feedback control of the position z and velocity $\dot{z}$. **PID:** *green*: PID using the B-field as the control signal.

the two orthogonally polarized optical beams (i.e., a loss of interference signal). Additionally, the absolute position of the mass is uniquely determined from the magnetic field (with the addition of a known control current – specifically zero), whereas the interferometer is a relative measurement that must be re-zeroed when signal is lost. On the other hand, the optical signal has much less noise than the B-field measurement and can be used to stabilize the position of the mass with a significantly less standard deviation about the set-point.

B. Switching Condition

The switching between the two modes is performed as follows. The PID with the B-field measurement is initially used to suspend the mass to a specified B_o which corresponds to an absolute z location. Once the mass is at the desired location z_o, the controller switches to the optics mode which has a lower noise floor and can stabilize the mass in space about the set point z_o. This stabilization is essential, as any oscillations or motions of the mass will have small accelerations, which in-turn will produce erroneous forces that the mass comparator may measure. Additionally, as a precaution, the strength of the interferometer signal is continuously monitored. If the signal falls below a threshold value, the PID and B-field controller then take over; although this case rarely occurs in the MSMC.

III. Performance

The switch-based control scheme has been implemented in the proof-of-concept system shown in Fig. 1. Data gathered from this system indicate that the suspension system is able to stabilize the mass in free-space with a vertical standard deviation of less than 75 nm about the set-point, which is an order of magnitude smaller than the previous PID control scheme. We note that the environmental conditions in the proof-of-concept system are not as tightly controlled as in the MSMC, therefore the 75 nm standard deviation is expected to decrease even further when this displacement measurement is implemented in the MSMC. These small oscillations or deviations from the set-point can potentially lead to variations in the mass balance reading; data indicate that we are able to stabilize the mass reading to within the resolution of the proof-of-concept balance (100 μg).

IV. Conclusion

We presented the control scheme used to magnetically suspend a mass artifact based on a switch controller with a proof-of-concept system used to mimic the NIST MSMC. This control scheme stabilizes the location of the mass in free-space and consequently lowers the standard deviation of the indicated mass reading to less than the previous control efforts which relied solely on the magnetic field measurement and PID control. At the CPEM 2018, we will present data gathered from the MSMC with the control scheme presented here.

Acknowledgment

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