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Engineering Notes

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Laser Pointing and Tracking Using a Completely Electromagnetically Suspended Precision Actuator

Zhaohui Ren*
Mohawk Innovative Technology, Inc., Albany, New York 12189
and
Lyndon S. Stephens†
University of Kentucky, Lexington, Kentucky 40506

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I. Introduction

STABLE and precise laser beam positioning is required for reliable laser communications among satellites. A very small angular movement of the source laser corresponds to a significant beam position error when amplified by the large distance between the transmitting and receiving stations and can thus throw a laser beam far off target. The desired pointing and tracking accuracy is typically on the order of 1 μrad rms [1,2]. Many efforts have been taken to improve performances of the pointing and tracking systems for intersatellite optical links. A Stewart platform demonstrated a 1 μrad rms pointing error in the ambient laboratory disturbance environment [3]. Passive vibration isolation techniques are usually adopted to reduce adverse effects of vibrations on the precision pointing performance objectives [4].

Magnetic levitation technology has been used in high performance motion control systems, owing to its noncontact nature, active control ability, and feasible multiple degree-of-freedom (DOF) actuation. A 6-DOF hybrid magnetic/fluidic positioning stage achieved a 0.3 nm resolution within a 100 μm cube [5]. A 6-DOF magnetically levitated device covered a 300 μm travel range in translation and 3.5 mrad in rotation with a 2 nm accuracy in translation and 300 nrad in rotation, and a 5 nm resolution [6]. But these systems require many actuators that add difficulties in controls. Very limited stroke is another major barrier [7]. Magnetic bearings are advantageous in special environments with vacuum or extreme temperature, where lubrication problems associated with mechanical bearings cannot be ignored. Self-bearing motors (SBMs) combine magnetic bearing and electric motoring functions into a single electromagnetic actuator to perform both force and torque production, and are attractive to space applications where room and weight are also of great concerns. One particular permanent magnet (PM) SBM design featuring a slotless stator allows for a smoother torque generation and is considered to be a good candidate to solve space-borne precision pointing and tracking problems [8].

To investigate its potential of improving pointing accuracy within a large range, two such slotless PM SBMs were incorporated into a 6-DOF magnetic actuator. Reference [9] showed that six decoupled proportional-integral-derivative (PID) controllers achieved stable levitation and smooth angular slewing of the 6-axis active actuator as a positioning stage, using a tape encoder system as the pointing sensor. In this work, the actuator is integrated into a laser pointing and tracking system setup to demonstrate its capability in tracking an external optical pointing sensor through a laser crosslink. The laser acquisition and reacquisition as well as precision pointing and tracking of the system in azimuth are implemented by a switching control strategy between the large-angle encoders and a small-angle laser position sensing detector (PSD) in rotation control, whereas the other five axes remain closed-loop controlled for magnetic bearing stabilization and precision noncontact pointing. Experimental results show that the system achieves high accuracy laser pointing and tracking over a large azimuth range using the single actuator.

II. System Description

Figure 1 is an overview of the laser pointing and tracking system, consisting of a laser source (S1FC635 from THORLABS) fixed on the test table as the transmit system, a PSD with filter (PSM2-10/F25-635 from ON-TRAK Photonics) mounted on a stage that travels along an arc track of 22 deg angle and 1 m radius as the receive system, and a mirror attached to the top of the shaft of the 6-DOF magnetic actuator. Both the center of the track and the reflecting surface of the mirror align with the rotational axis of the actuator.

The two-dimensional PSD is an optical position sensor with high linearity and resolution. Its associated amplifier (OT-301 from ON-TRAK Photonics) provides analog output voltages, PSD_X and PSD_Y, directly proportional to X and Y positions of an incident light spot on its detector active area of 10 mm × 10 mm and independent of light intensity fluctuations, and total amplified detector output, PSD_{SUM}, allowing simultaneous monitoring of position and light intensity. Whenever the PSD detects the laser, PSD_{SUM} jumps above certain value dependent on laser intensity, which thus indicates whether the laser beam from the laser source is bounced onto the PSD by the mirror.

Figure 2 is a schematic of the 6-DOF magnetic actuator (developed at Airex Corp.), with two slotless PM SBMs to produce motoring torque in θ direction and radial bearing forces in x/y directions, one conventional thrust active magnetic bearing (AMB) in between to provide axial support in z direction, and one cylindrical sensor plate attached to each end of the shaft with a reflective metal tape wrapped around its outer diameter and targeted by four optical encoder read heads 90 deg apart. In addition, two eddy current probes 90 deg apart are installed next to each sensor plate to measure radial displacements at each end of the shaft, and one eddy current probe is positioned close to the center of the bottom sensor plate to measure shaft axial displacement. The shaft is completely magnetically levitated and 6-DOF capable, with a range of ± 45 deg azimuth in θ direction, ± 0.135 deg elevation in α/β direction, and ± 508 nm radial/thrust motion in $x/y/z$ direction.

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*Research Engineer, 1037 Watervliet-Shaker Road.

†Associate Professor, Department of Mechanical Engineering, 277 Ralph G. Anderson Building.

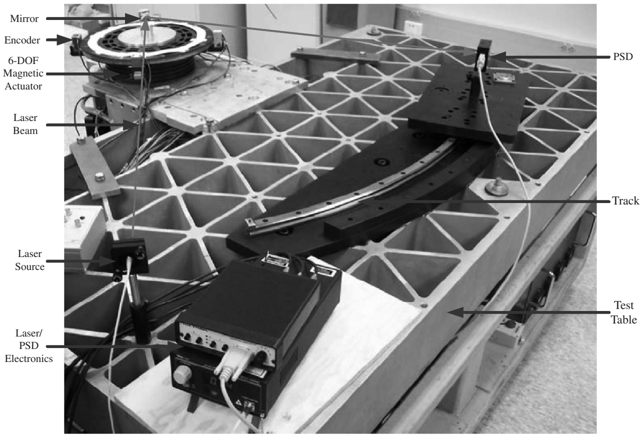


Fig. 1 System overview.

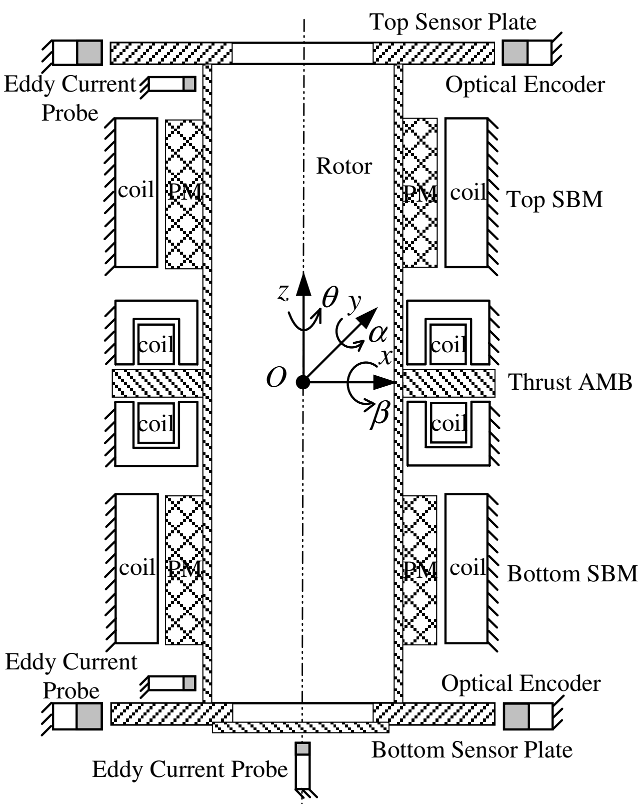


Fig. 2 6-DOF magnetic actuator schematic.

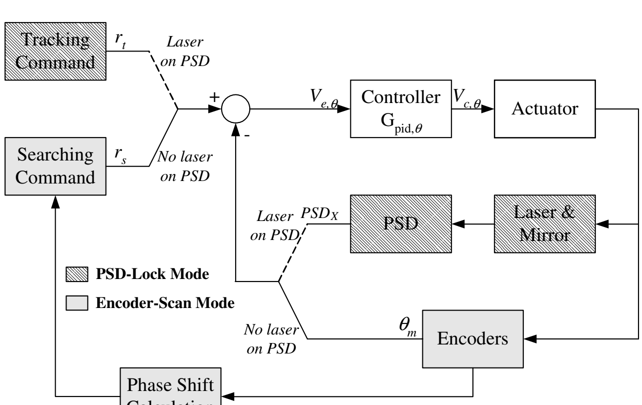
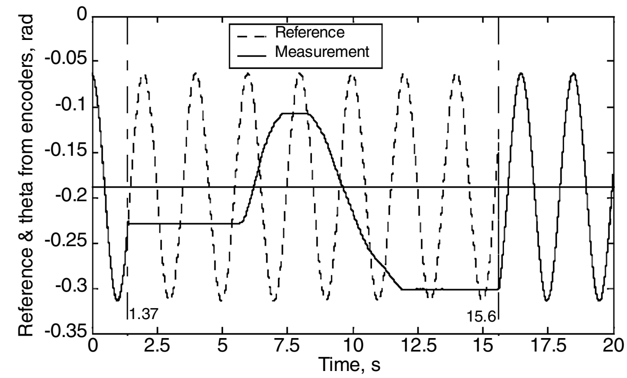
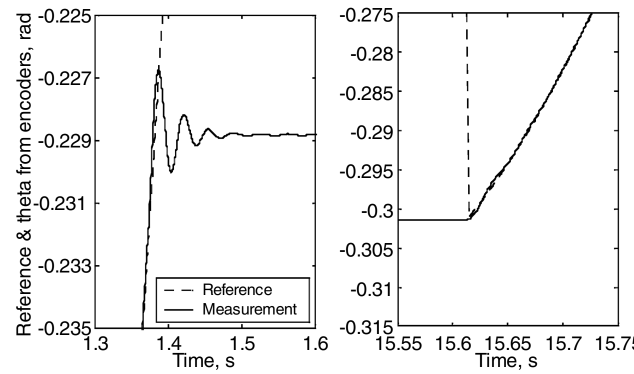


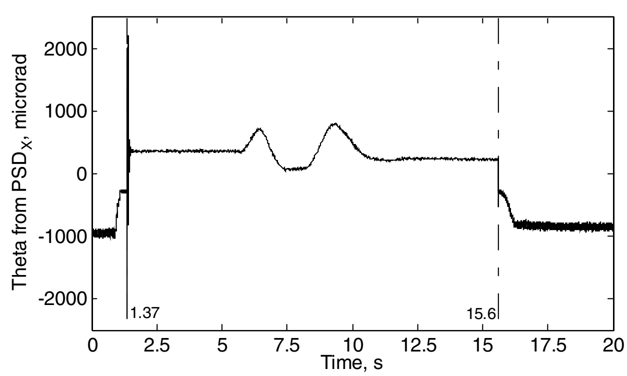
Fig. 3 Rotation control with switching between encoder and PSD feedbacks.



a) Scanning reference and encoder signal



b) Enlargement of 4a during switching



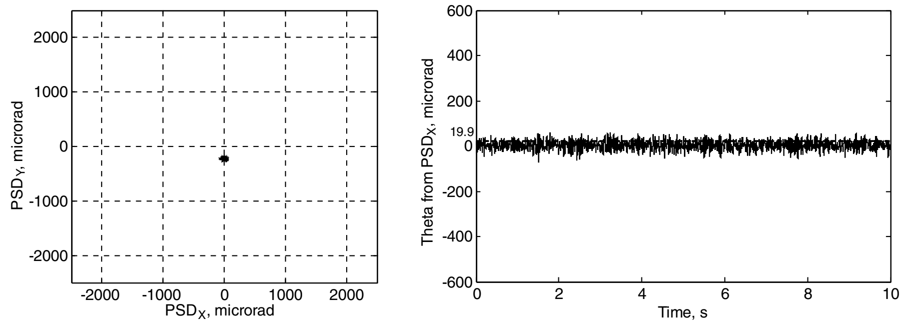
c) PSD_X signal

Fig. 4 Switching demonstration.

III. Control Strategy for Laser Acquisition, Reacquisition, Pointing, and Tracking

Because the 6-DOF magnetic actuator is open-loop unstable, six decoupled PID controllers perform the 6-axis active controls. The four radial and one axial gap sensors are used in the five bearing closed-loop controls to levitate the shaft within clearance air gap [9]. As shown in Fig. 1, the eight encoders can measure a large shaft angle, whereas the PSD works as an angular position sensor within a small range. For a given beam from the laser source, a turn in the mirror from shaft rotation produces an angular movement of the projected beam, corresponding to a linear laser dot movement on the PSD in X direction. The PSD_X signal is scaled compatible with the encoder signal representing actual shaft angle, whereas PSD_Y indicates the level of the laser source, mirror, and PSD, or tilting of the shaft, which is not of main concern here.

Therefore, optical acquisition, pointing, and tracking performance of the system is demonstrated by switching the angular feedback



a) Laser orbit on PSD

b) PSD_X signal (dashed line indicates rms error)

Fig. 5 Laser locking on stationary PSD.

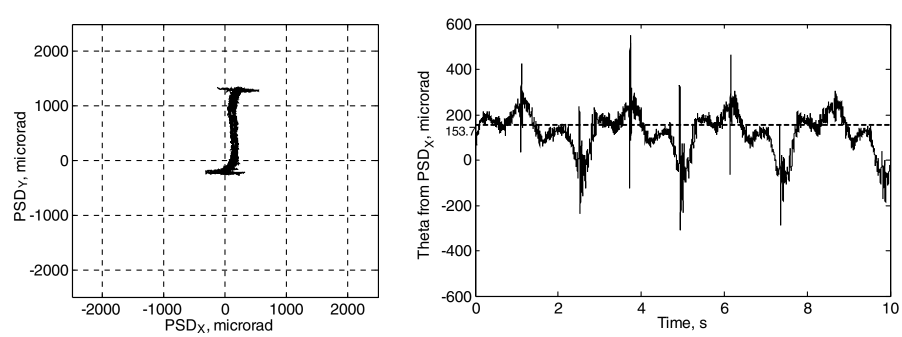
device between the encoders and PSD and their corresponding reference in rotation control of the actuator. As illustrated in Fig. 3, after complete levitation using six PID controllers, the shaft begins a sinusoidal scan covering the entire track using encoder feedback; whenever the PSD detects the laser projected by the mirror, PSD_X then takes over and the shaft rotates to track the PSD traveling along the track. If the PSD loses the laser, the control is switched back to encoders to ensure system stability. But it is always the encoder signal that provides the rotor angle in commutation logic of both SBMs. Encoder-scan is switched to PSD-lock immediately because of the small PSD dimension. Because the shaft can rotate up to 11 deg to track the PSD, the instantaneous error between the reference and sensor signals on the encoder side could be very large when the PSD loses the laser, a direct switch from PSD-lock to encoder-scan may cause bad transients, even instability. When the PSD signal is lost, the feedback measurement switches to the encoders, and the reference command switches to a shifted sine wave with an initial phase corresponding to the instantaneous encoder reading at PSD signal loss.

IV. Experimental Results

In this section, switching between encoder and PSD feedback loops, laser locking on stationary and moving PSD within maximal travel range, and laser tracking to a small reference on stationary PSD are evaluated experimentally.

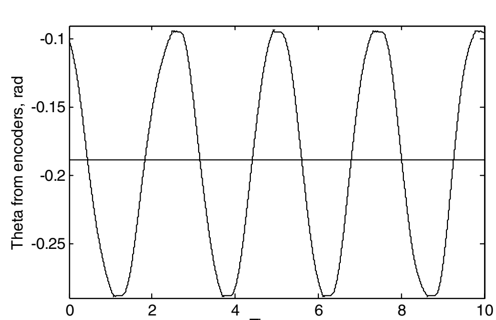
A. Switching

The switching strategy between searching and tracking in θ direction PID control loop is incorporated into the overall real-time control system implementation. A complete demonstration is tested as follows: the laser is first blocked and the levitated shaft initiates a sinusoidal scanning; after the PSD detects the laser, random PSD motions are introduced manually and the shaft tracks the PSD; the laser is blocked again and the shaft searches to reacquire the PSD. Figure 4a shows the sinusoidal reference and θ measurement on encoder side, the first vertical line indicates when switching to PSD-lock occurs and is detailed in the left plot in Fig. 4b, whereas the second corresponds to switching back to encoder-scan with an enlargement in the right plot in Fig. 4b. The PSD_X signal in Fig. 4c is only valid between the two vertical lines, with the first for PSD taking over and the second for PSD losing the laser. During initial encoder-scan, the shaft follows the sine wave. Once the PSD detects the laser, switching to PSD-lock occurs immediately, a sudden increase of the error on the PSD side causes slight oscillations. The PSD first stays where it is and is moved randomly and then stopped, the shaft keeps up with the PSD so the laser stays locked on the PSD. Once the laser



a) Laser orbit on PSD

b) PSD_X signal (dashed line indicates rms error)



c) Encoder signal showing manual PSD motion

Fig. 6 Laser locking on PSD traveling along track.

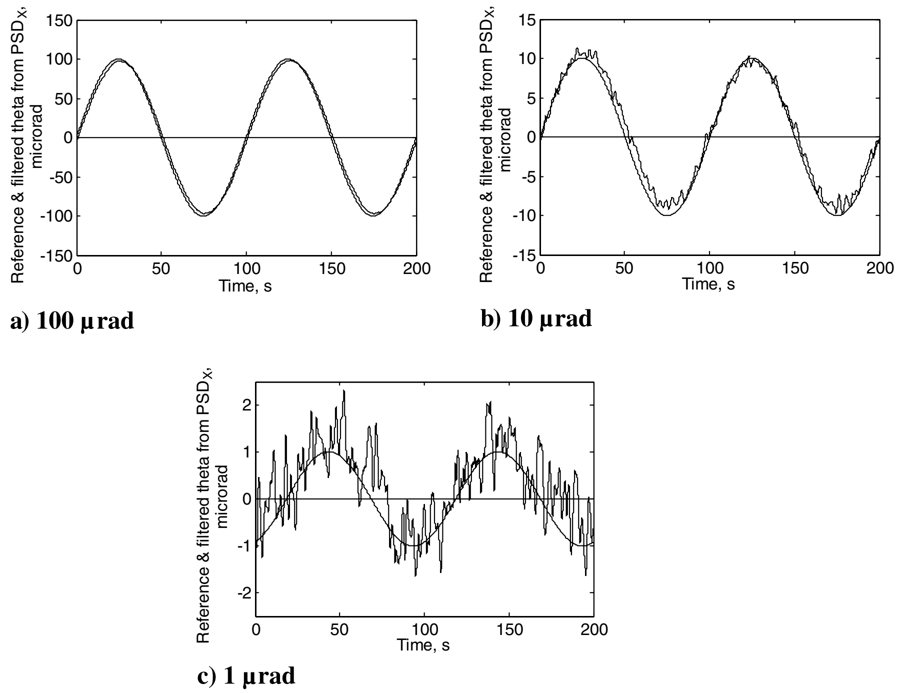


Fig. 7 Laser tracking to 0.01 Hz sinusoidal references of decreasing amplitudes.

is blocked, the encoder reference is immediately adjusted based on current shaft position and the shaft is back to sinusoidal scanning shifted from the original sine wave in phase angle but of the same amplitude.

B. Laser Locking on PSD

The performance of laser locking on PSD is further investigated. Figure 5 illustrates laser locking on a stationary PSD, equivalent to laser pointing using the PSD, where Fig. 5a displays laser orbit on the PSD, and Fig. 5b depicts the trace of PSD_X signal with the rms error of 19.9 μrad corresponding to the dashed line.

Figure 6 shows the results of laser locking when the PSD is moved back and forth manually within the maximal range along the track, or laser tracking the PSD. The shaft rotates about 0.19 rad (11 deg) peak-to-peak to follow the PSD motion of up to about 22 deg on the track, as shown by the encoder signal in Fig. 6c. As shown in Fig. 6a, the laser stays locked on the PSD during such a large travel. The variation of PSD_Y implies changes in the level of the track or tilting of the shaft due to low bearing stiffness currently applied. PSD_X varies little except for at the ends, where direction of the motion is changed suddenly corresponding to the spikes in Fig. 6b. Compared with the stationary PSD case, rms error is increased to 153.7 μrad as indicated by the dashed line in Fig. 6b, which is the error of laser tracking within a large range.

C. Small-Angle Laser Tracking

In the current experimental setup, there is no mechanism to move the PSD precisely on the track. To investigate small-angle laser tracking, the laser on the PSD is desired to follow a trace defined by a small dynamic reference input in the PSD feedback loop, whereas PSD itself is stationary, equivalent to moving the PSD within a small range while keeping the laser locked at the PSD horizontal center by setting the PSD reference to zero.

Sinusoidal references of decreasing amplitudes are used in the PSD feedback loop, and a PID controller with a nonzero integral gain replaces the one without integral gain used in the previous experiments. For each reference, the PSD_X signal filtered by a low-pass filter with a cutoff frequency of 2 rad/s is captured together with the input. The results for 0.01 Hz sine waves with amplitudes of 100, 10, and 1 μrad are shown in Fig. 7, with an rms tracking error of 5.27, 1.11, and 0.603 μrad, respectively. The tracking error decreases with the decreasing input and, most importantly, laser tracking to a 1 μrad sine wave using the PSD achieves an rms tracking error of 603 nrad.

V. Conclusion

Compared with the state-of-the-art systems in precision motion controls and intersatellite laser communications, the laser pointing and tracking system, featuring a 6-DOF capable magnetic actuator with two SBMs and one AMB for a complete electromagnetic suspension and precision noncontact pointing, achieves an accuracy below 1 μrad over a large azimuth range in an ambient laboratory environment using a PSD as the laser detector. However, to meet the 1 μrad specification, the target has to be approached through a large step followed by a series of smaller steps. The discussion is focused on the rotational axis only because of the limited sensor resolution in the five bearing control loops.

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