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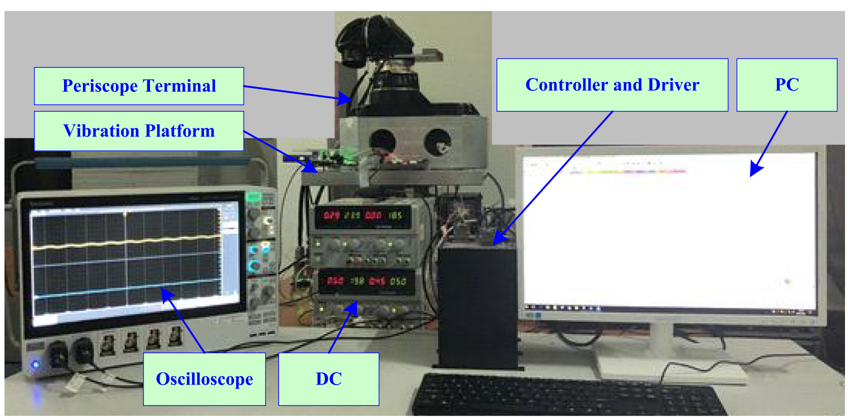

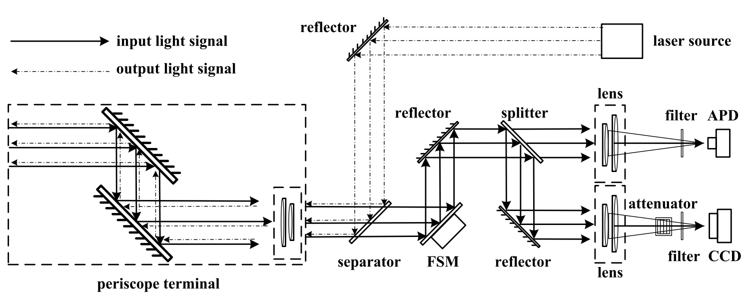

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High Precision Implementation With Design Considerations and Experimental Tracking Results for Single-Sensor Optical Communication Terminal

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Abstract: Vibration interference reduces the precision of control system and leads to the instability of the satellite optical communication link. So how to improve the tracking accuracy of terminal system under vibration conditions is an important work for the laser communication systems. In this paper, an experiment was conducted to investigate the high precision tracking system with single-sensor consideration, which can be accomplished with a servo control system combined with the coarse and fine tracking technologies, the tracking data analysis has been presented to estimate the performance based on reasonably tested which consists of three cases collected including different vibration amplitude and acceleration settings. The high tracking precision implementation are carried out on a servo control experiment, and the obtained test results (less than 2 μrad) demonstrate the effectiveness of the proposed single-sensor and multiple-axis tracking scheme.

Index Terms: Optical communication, coarse tracking assembly, fine tracking assembly, control accuracy, multiple-axis tracking.

1. Introduction

Space communication links can be implemented using optical technology and microwaves. Optical technology offers lots of potential advantages and superior performance over microwave, such as the higher data rate and less power consumption [1]–[3]. A high precision positioning and tracking of laser beam can provide an efficient media for satellite-to-ground and inter-satellite communication. And the communication beam must be pointed to the receiving terminal with sufficient precision to satisfy the link power budget requirement [4]–[7].

Additionally, the design of optical communication system can dominate the performance of tracking precision, which is needed to maintain continuous illumination of the opposite terminal. Thus the investigation of communication system design should be developed for improving the positioning and tracking accuracy of the system [8]–[10]. Optical systems typically need angular stability to a fraction of the beamwidth [11]. Therefore, laser communication system needs a tracking system that

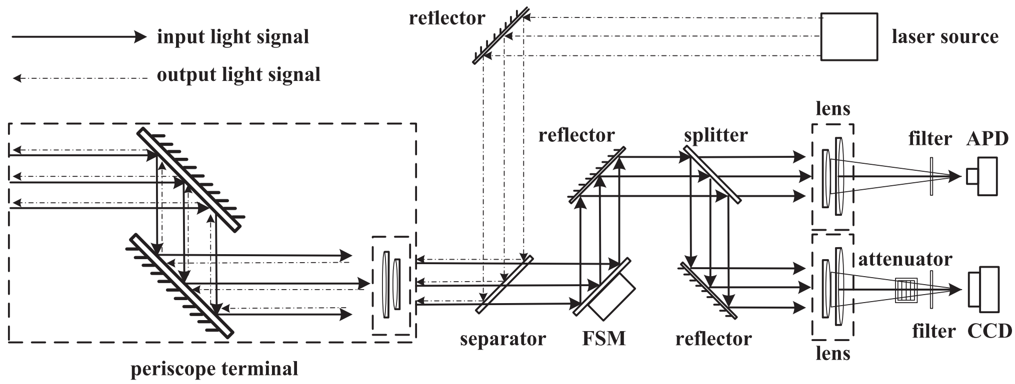

Fig. 1. The configuration of the communication terminal.

will hold the tracking error on the microradian level, making the servo system with high precision, high bandwidth, and large dynamic range is necessary. Pointing, Acquisition and Tracking (PAT) is a major technology in the laser communication system, which allows for the experimental research of various performance characteristics [12]–[13]. To achieve the required tracking precision, the subassemblies of the PAT subsystem should be employed in the optical closed control loop, such as the detecting sensor, which can be used for receiving the laser spot and sensing the tracking error [14]–[16]. A number of papers have described the design of such tracking system. This paper will discuss some additional design consideration and the corresponding experimental results.

In this paper, we focus on the design and implementation issues of coarse and fine tracking loop. We develop a tracking system and a laboratory experimental verification, and the single-sensor technique is mainly used for performing both coarse tracking and fine tracking functions. Compare the performance of two tracking mode based on the different platform vibrations, and then we discuss the quantitative error data in such a high accuracy tracking system, and we also present the data analysis, in order to prove the effectiveness of the proposed scheme in the laser communication system.

2. Experimental setup

2.1 Communication Terminal System

For the PAT system of the communication terminal, Charge coupled devices (CCD) is the primary candidate sensor for performing acquisition and tracking functions. In acquisition mode a large field of view (FOV) and slow readout rate are required for the initial beacon detection, however, in tracking mode a small FOV and fast readout rate are needed. Therefore, to solve these conflicting requirements, these two functions are usually performed using separate sensors. In this paper, a single CCD sensor is employed for performing both coarse tracking and fine tracking functions. And the control electronics of the terminal are easier to implement and will be presented below. The component configuration for the experimental system is given in Fig. 1, and shows how the various structures and optical elements are combined. This is standard practice for this type of system, using a nested pair of mechanisms for performing the coarse tracking and the fine tracking functions.

The former periscope, as shown schematically in Fig. 1, is the coarse tracking assembly which has a large operating angular range but a small bandwidth, while the latter fast steering mirror (FSM), the fine tracking assembly, has a small operating angular range and a large bandwidth. Therefore, compared with the conventional approach, this fine tracking system is designed to cope with the external interference of the full frequency band. These control loop elements in conjunction with the acquisition and tracking sensor which detects the line of sight of the input optical beam. The terminal design which has been produced to meet the communication system requirements

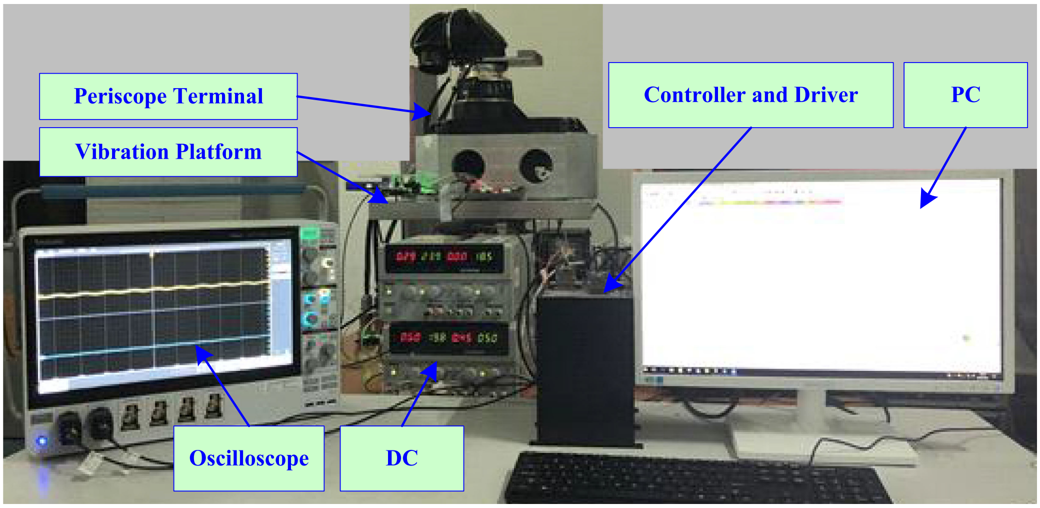

Fig. 2. Photograph of the experimental platform.

includes a periscopic pointing mechanism, fiber coupled laser, an avalanche photodiode (APD), and combined acquisition and tracking sensor (tracking camera). Such a combination enables a unique terminal design, which achieves the communication system small and lightweight. After successful acquisition, the terminals are operating in the tracking mode. The disturbances which introduce pointing oscillation into the communication beam are attenuated by the tracking control loop, in order to enable acceptable communication link to be obtained.

2.2 Multiple-Axis Tracking Technology

Fig. 2 shows the experimental setup in the photograph form. The optical beam must be precisely pointed towards the partner terminal so that sufficient light power can be received to meet the communication rate and link quality requirements. Consequently, it is necessary to conduct closed-loop tracking for the laser beam transmitted by the partner terminal. The closed-loop tracking subsystem includes a tracking sensor which determines the direction of the input light with an angular resolution of 20 microradians and a FSM which compensates laser mispointing effects. The configuration of the control system is the combination of coarse and fine tracking, that is, the multiple-axis tracking, successfully designed coarse tracking and FSM control system are capable of reduction of tracking error. For the dynamic coarse tracking process, in which the image miss-distance on CCD camera is received as the feedback value in the optical close-loop, then the control value is computed, and the periscope terminal implements the coarse tracking by driving the azimuth axis and elevation axis.

The fine tracking loop (FTL) is required to further attenuate the error so that the residual mis-track angle is a small fraction of the beam width. The performance of the FTL is determined by the dynamic properties of the FSM and the achieved readout rate of the sensor in fine tracking mode. To achieve both coarse tracking and fine tracking functions, switching window technology is employed to read-out different parts of the array at different rates. When the communication terminal achieves stable coarse tracking, the master control computer will continuously send three execution commands, the first is the periscope structure to stop the coarse tracking, and then the camera will switch from large window to small window, and finally starts FSM to perform fine tracking. The sensor is a tracking camera with an array of 1024 by 1024 pixels, each pixel being 10.6 μm square. For the coarse tracking, the sensor uses the full field of view, as shown in Fig. 3, and the image processing board controls the tracking camera to record the light spot images at 100 frames/s. For the fine tracking, the tracking camera is used by reducing the image size to a certain region (160

Fig. 3. Image photo of the coarse tracking.

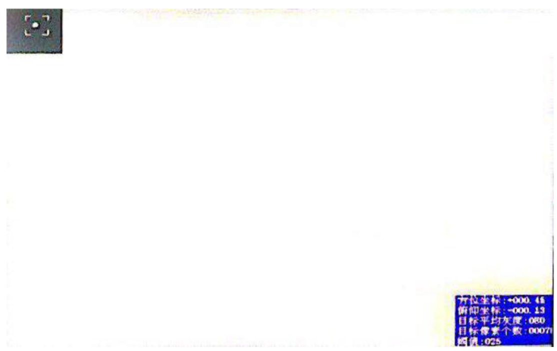

Fig. 4. Image photo of the multiple-axis tracking.

by 160) by switching windows, as shown in Fig. 4, and the image processing board controls the tracking camera to record the light spot images at 2000 frames/s. The FTL uses the feedback of the high frame-rate camera based on the coarse tracking described above, the periscope terminal use the FSM position as the feedback value for the following movement, at the same time, this method can solve the problem of the small scope of FSM actuator in the large range tracking process.

3. Data Analysis

PAT control system consists of two tracking mechanisms (coarse tracking assembly, fine tracking assembly), the combined acquisition and tracking sensor, and the control electronics. The functions implemented in PAT system includes the pointing loop, acquisition loop, coarse tracking loop and fine tracking loop. In the tracking process, the input disturbance is the individual contribution to the oscillation bias of each axis. Fig. 5 shows the design of the servo control system based on permanent magnet synchronous torque motor, including the inner current loop (see Fig. 5(a)–(b)) and velocity loop (see Fig. 5(c)) to provide the control voltages, its function is to guarantee the stability of the system and the ability to resist disturbance. Position loop (see Fig. 5(d)) is to ensure the system tracking precision and further improve the tracking performance of the system.

3.1 Analysis of Coarse Tracking Performance

Various error analysis for this research have been investigated for their effect on system performance. The main intent of the experimental work described here is to verify some research results obtained for multiple-axis tracking using single detector techniques. The experiment used an optical closed-loop to track a light signal at a wavelength of 0.8 μm. A large field of view tracking sensor

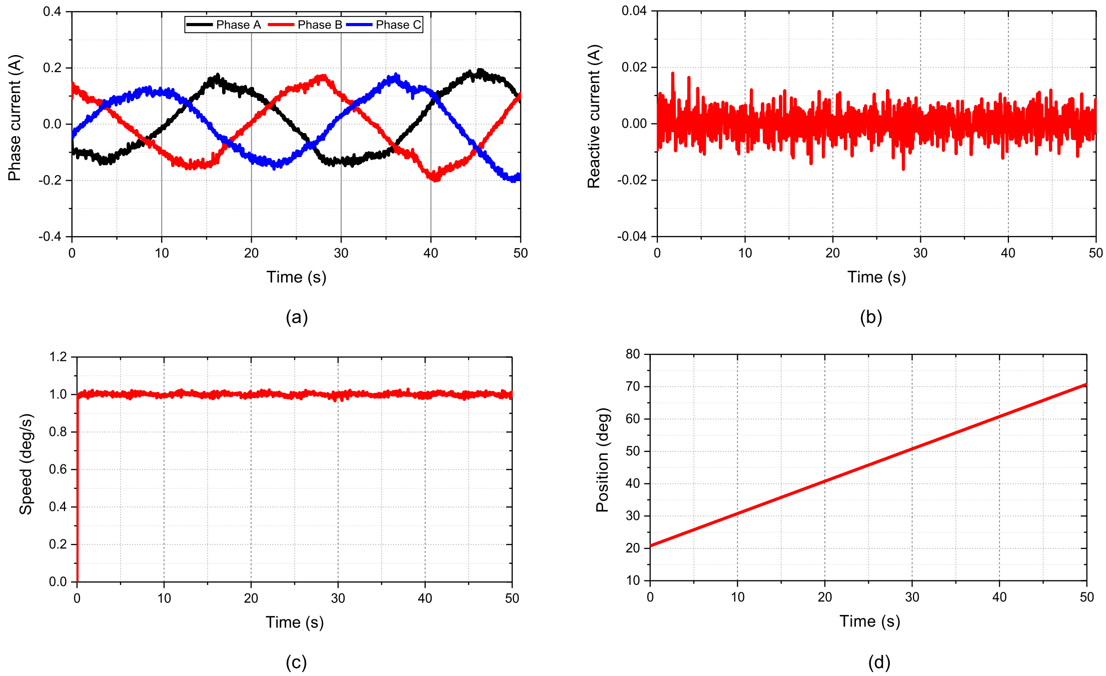

Fig. 5. Experimental response curves of the servo control loop.

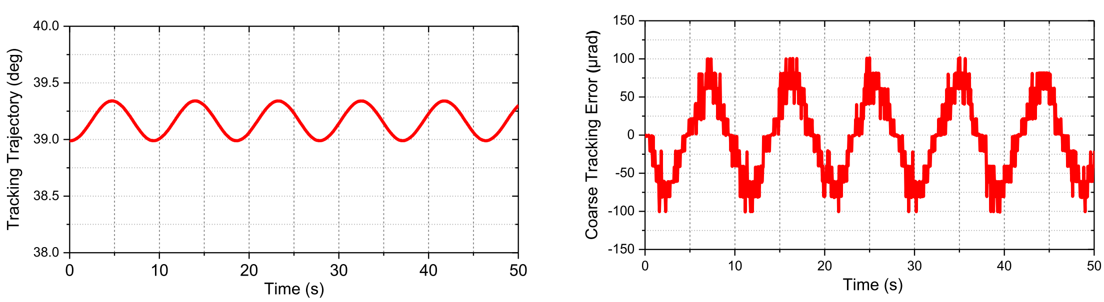

Fig. 6. Experimental result of coarse tracking, in which the period of platform vibration is 9s and the maximum acceleration is 0.085°/s^2.

is used to feedback the position deviation of the light from partner terminal with a resolution of 20 microradians. A specification on imbalance is based on maintaining the tracking precision in the presence of base-motion disturbances. Appropriate closed-loop tracking is previously determined through the servo design, the output error of the track loop is calculated. We describe the significance of single-detector tracking by plotting the dynamic following curves and the tracking errors after calibration. We also have summarized several curves representative values of tracking errors. The cause of this change is that the communication system is directly influenced by different external oscillation excitation, including different vibration amplitudes and accelerations. To demonstrate the terminal performance of tracking with single detector, we illustrate the typical coarse tracking results in Figs. 6–8 for maximum vibration acceleration of 0.085, 0.329 and 0.055, respectively. The curve in the left of each graph is the position trajectory of periscopic pointing mechanism during the process of coarse tracking, on the right is the camera feedback for the light spot, which is called image mis-distance or the coarse tracking error. Hence, operation of the terminal system at the single sensor once multiple-axis tracking applied is necessary to maximize the performance. At first, as shown in Fig. 6, it appears that higher vibration amplitude (0.35°p-p) with the maximum

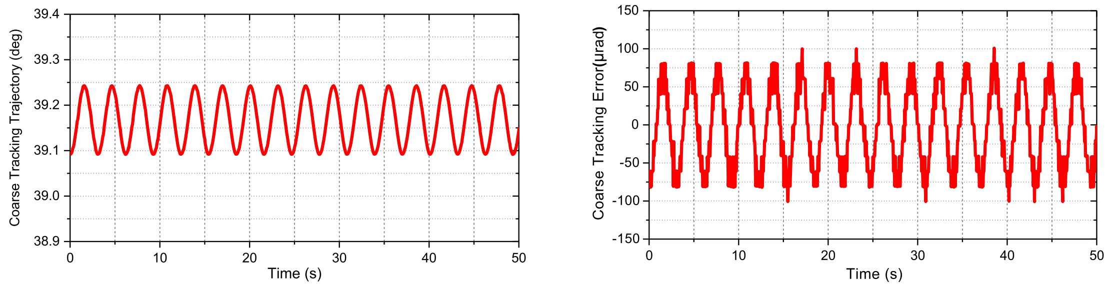

Fig. 7. Experimental result of coarse tracking, in which the period of platform vibration is 3s and the maximum acceleration is 0.329°/s^2.

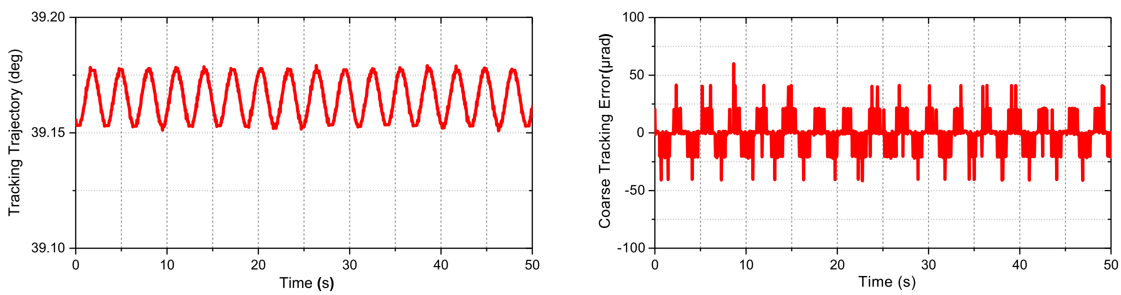

Fig. 8. Experimental result of coarse tracking, in which the period of platform vibration is 3s and the maximum acceleration is 0.055°/s^2.

acceleration (0.085°/s^2) result in the coarse tracking error of less than 100 μrad. Furthermore, when the conditions are that vibration amplitude is 0.15°p-p, the maximum acceleration is 0.329°/s^2. For such cases, the coarse tracking error changes from -60 μrad to 60 μrad (see Fig. 7). In the Fig. 8, the vibration amplitude (0.025°p-p) with the maximum acceleration (0.055°/s^2) result in the coarse tracking error of less than 40 μrad.

3.2 Analysis of Fine Tracking Performance

This paper focuses on laser tracking accuracy via the proposed single sensor and multiple-axis tracking with the platform oscillations on the real communication system. Instead of applying several sensors, the procedure of the PAT tracking subsystem is employed using a single light detector. The image processing circuit controls the operation state which generates an appropriate clock waveform for the CCD according to the work mode demanded. The selections feedback signal and command signal for the actuators and the output frame frequency of the image sensor are all controlled by PAT communication processing board. The detector signal is fed to an image board generating the FSM control signal. The position signal of the FSM mirror is used as the command signal for the coarse tracking assembly system. A microprocessor calculates the control value in accordance with the control law based on this command signal and the current position of the periscope terminal, then commands the corresponding driving electronics to complete the motor drive. The movement of the coarse tracking assembly influences the laser direction after it has passed the periscope with a fixed gain factor. This direction in accordance with the position of the FSM mirror is finally sensed by the detector. A repeatability specification is necessary for servo and mechanical design considerations. The reduction of tracking error by the combination of the coarse and fine tracking is shown in Figs. 9–11, respectively, which indicates that the oscillations can be drastically reduced by the proposed approach. The effectiveness of the selected technique can be explained by the fast tracking response and the extremely high tracking precision. This section

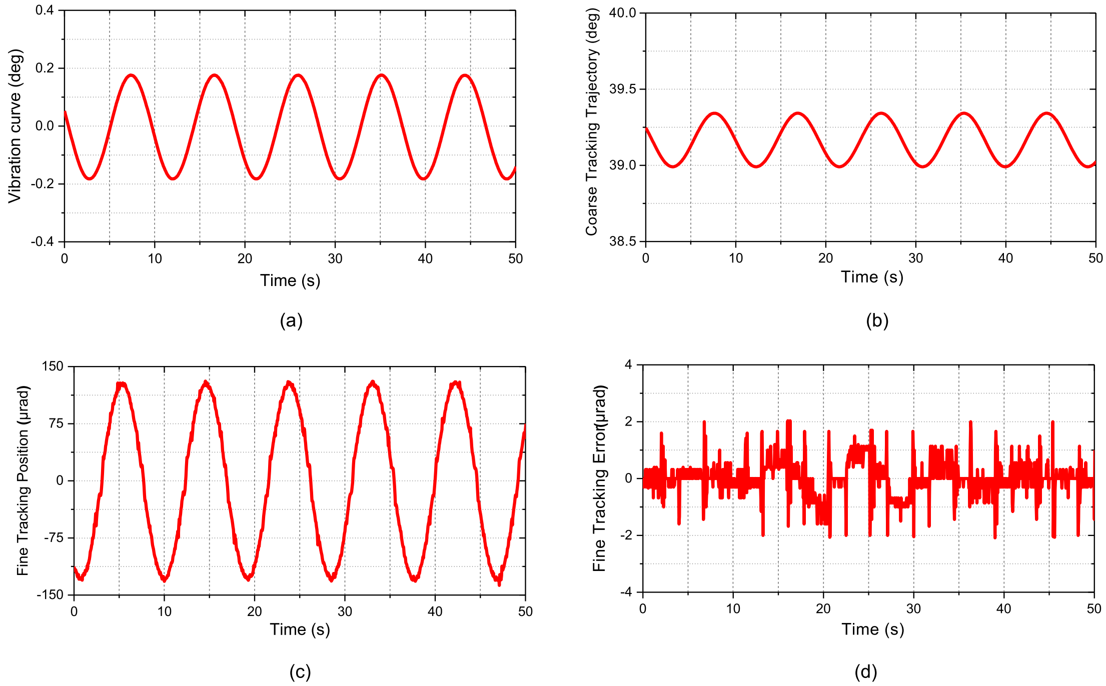

Fig. 9. Experimental result of the combination of coarse and fine tracking, in which the period of platform vibration is 9s and the maximum acceleration is 0.085°/s^2, (a) Platform vibration curve; (b) Tracking trajectory of periscope telescope; (c) Tracking trajectory of FSM; (d) Fine tracking error.

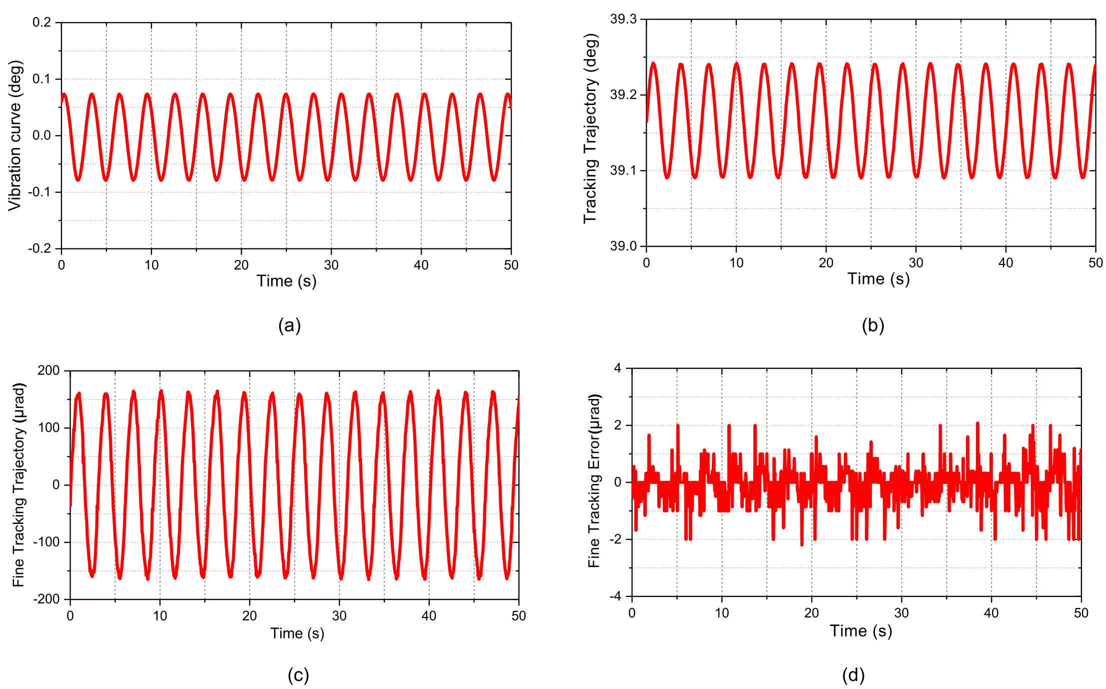

Fig. 10. Experimental result of the combination of coarse and fine tracking, in which the period of platform vibration is 3s and the maximum acceleration is 0.329°/s^2, (a) Platform vibration curve; (b) Tracking trajectory of periscope telescope; (c) Tracking trajectory of FSM; (d) Fine tracking error.

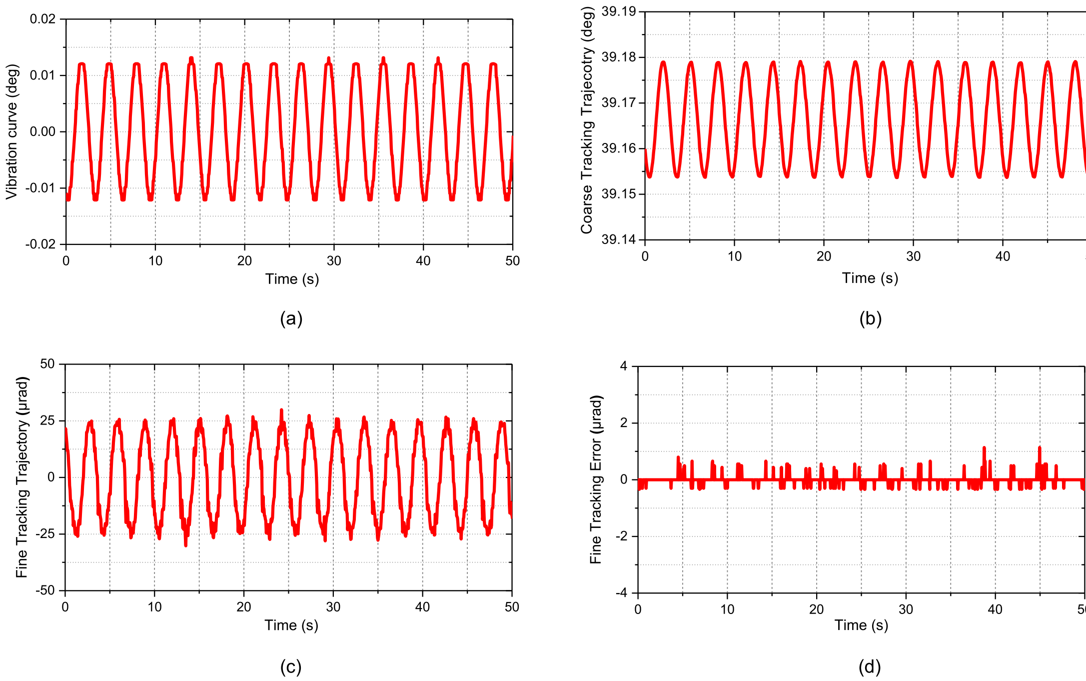

Fig. 11. Experimental result of the combination of coarse and fine tracking, in which the period of platform vibration is 3s and the maximum acceleration is 0.055°/s^2, (a) Platform vibration curve; (b) Tracking trajectory of periscope telescope; (c) Tracking trajectory of FSM; (d) Fine tracking error.

discusses that the critical component in the PAT subsystem is an FSM with sufficient accuracy and control bandwidth for the purpose of achieving several microradians tracking.

Fig. 9 illustrates the disturbance rejection characteristics. The tracking response characteristics are shown in the four subplots. It appears that higher vibration amplitude (0.35°p-p) with the maximum acceleration (0.085°/s^2) result in the fine tracking error from -2 μrad to 2 μrad. Furthermore, when the conditions are that vibration amplitude is 0.15°p-p, the maximum acceleration is 0.329°/s^2. For such cases, it can be observed that the error values are suppressed to 2 μrad in the coarse and fine tracking mode as shown in Fig. 10. Finally, in the Fig. 11, the vibration amplitude (0.025°p-p) with the maximum acceleration (0.055°/s^2) result in the fine tracking error of less than 0.8 μrad. This mispointing angle equates to a small pointing loss for the transmit beam, which also demonstrates that the tracking performance is adequate to provide both control accuracy and bit error rate meeting the design requirements. This high precision tracking system with laser beam that allows for the establishment of a two-way communication links, which may increase the link stability of the optical communication system with the wave propagating in the atmospheric turbulence conditions.

4. Conclusions

An experiment was conducted to investigate the high precision tracking system with single-sensor consideration, which can be accomplished with a servo control system combined with the coarse and fine tracking technologies. The tracking data analysis has been presented to estimate the performance based on reasonably tested which consists of three cases collected including different vibration amplitude and acceleration settings. However, it still clearly shows what distinguishes between coarse tracking and the combination of coarse and fine tracking. It was suggested that although the tracking errors of laser beam for the PAT system are not fixed values under different perturbation conditions, but mostly they are less than 2 μrad. The experimental results of the high tracking accuracy have been presented to demonstrate the effectiveness of the proposed single-sensor and multiple-axis tracking scheme. Results of this study indicate that the PAT system described above can meet tracking system requirement. This work is also benefit for free space laser communication system design.

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