2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

Prototype Development of the Hardware-in-the-Loop Testbed for Spacecraft Interferometry Formation Flight Control

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***Abstract*— We present a prototype of the Hardware-In-the-Loop (HIL) testbed for precise spacecraft formation flight control. The testbed serves as a platform to verify and validate the multifaceted aspects of interferometry formation flight control systems. The prototype demonstrates the three essential features of the HIL testbed: laser link acquisition, laser locking, and interferometry relative position control, by integrating the Michelson laser interferometer onto the 6-axis motion stage. We conduct an experiment of two-spacecraft formation control to ascertain the efficacy of the prototype in demonstrating these features.**

I. Introduction

High-precision spacecraft interferometry formation flying is of growing interest in astronomical and space science. The coordinated action among spacecrafts using interferometry enables unprecedented resolution in observation, surpassing inherent limitations of grand-based or single spacecraft telescopes. Inspired by the successful on-orbit demonstrations of formation flying in [1], [2], various international missions such as LISA [3], DECIGO [4], and LIFE [5] are currently under development. Both DECIGO and LISA are required to maintain relative positions among three spacecrafts with nano-meter precision to detect low-frequency gravitational waves. LIFE mandates a micro-meter level of precision in the relative positions among five spacecrafts to detect the thermal emissions of exoplanets through a mid-infrared nulling interferometer. While those missions leverage interferometry to measure and maintain the highly precise relative position, the requirements of the control systems vary depending on the specific phenomena to be detected and the configuration of interferometry employed.

Hardware-in-the-Loop (HIL) testing is a verification and validation methodology for autonomous embedded control systems in the aerospace and automobile industries. It provides a safe, low-cost, and effective means of conducting system-level verification and validation for the control systems encompassing on-board components and software. Developing a HIL testing platform for interferometry formation flight control is essential due to its complex scenarios induced by the coordinated action among multiple spacecrafts.

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In this abstract, we develop a prototype of the HIL testbed designed for two-spacecraft formation flight control. The prototype incorporates the Michelson laser interferometer onto a 6-axis motion stage. We demonstrate the three fundamental functions essential for an interferometer formation flight controller: laser link acquisition, laser locking, and interferometry relative position control. Specifically, one spacecraft locates its counterpart by sweeping laser irradiation angle (laser link acquisition), maintaining the laser link once established (laser locking), and subsequently utilizing the Michelson interferometer to measure and regulate the relative position (interferometry relative position control). An experimental validation is conducted to ascertain the capability of the proposed prototype to realize these features.

II. Testbed prototype configuration

The configuration of the prototype testbed is illustrated in Fig. 1. The left-hand 6-axis motion stage generates the relative dynamic motion between two spacecrafts, denoted as SC1 and SC2. Optical equipment corresponding to SC1 is mounted on the left-hand motion stage, while SC2 on the right-hand table, thereby configuring the Michelson interferometer.

The laser beam is irradiated from SC1, which is split into two paths via the beam splitter. One of the split beams proceeds towards SC2 and is divided into two paths again. In one direction, the beam reaches the quadratic photodetector (QPD) located at SC2, while in the other direction, it is reflected to SC1. The QPD outputs a two-dimensional point (x, y) indicating the position of the laser pointing and its intensity. The reflected beam interferes with the returning beam from the mirror at SC1, whose intensity is measured by the photodetector (PD). The intensity is determined by the path difference between the two interfered beams, representing the relative distance between SC1 and SC2, Consequently, the distance can be measured by the PD. By maintaining the intensity, the relative distance can be regulated with an accuracy of the laser beam wavelength, set at $1.5\,[\mathrm{\mu m}]$.

The controller for SC1 and SC2 are implemented in the real-time target machine, equipped with several I/O ports for receiving measurement signals from the QPD and PD, and transmitting target position and attitude to the motion stage via the motion stage controller, representing the relative motion of the spacecrafts. EtherCAT communication protocol is used for the information exchange between the real-time target machine and motion stage controller.

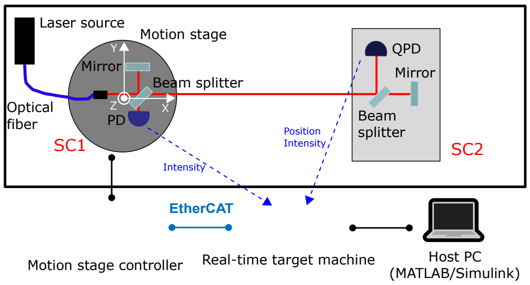

Fig. 1. Prototype testbed configuration

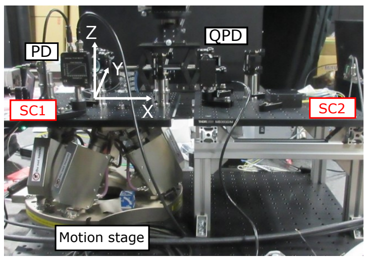

Fig. 2. Appearance of the testbed

III. Experimental Validation

We conduct experimental validation to verify the three essential features of interferometry formation flight control: laser link acquisition, laser locking, and interferometry relative position control.

Firstly, SC1 searches for the QPD on SC2 to establish a laser link. By changing the laser irradiation angle, the QPD is located. Thresholds are set for the QPD intensity, enabling to detect the laser link acquisition when the intensity exceeds these thresholds. The searching phase consists of three substeps to locate the center of the QPD: a coarse Lissajous search (pitch, yaw), followed by a fine spiral search. In the first substep, the laser scans by drawing a wide Lissajous curve, and in the second a narrow spiral curve on the (x, y)-plane of the QPD to effectively identify the center.

Subsequently, proportional control is employed to ensure that the laser pointing position remains centered. By the closed-loop control, the laser link is maintained even in the presence of disturbances.

Finally, another proportional control based on the PD intensity is implemented. By regulating the PD intensity, the relative distance between SCs is maintained with an accuracy of the laser light wavelength.

In Fig. 3, we show the result of the experiment. At first, laser angle is swept to locate the QPD. When the light intensity exceeds each threshold of the substeps, the fine tracking is initiated, where the closed-loop control adjusts the laser pointing position to the center of the QPD, thereby achieving laser link locking. The detailed result of fine tracking is depicted in Fig. 4. We see that the QPD pointing position converges to zero with a small steady-state error of $0.08[\mathrm{V}]$, equivalent to $20\,[\mu\mathrm{m}]$.

Finally, relative distance control is initiated as illustrated in Fig. 5. The light intensity of the PD remains constant at the target intensity of $4.5[\mathrm{V}]$, indicating that the relative distance is maintained with a micro-meter level of accuracy corresponding to the wavelength of the laser.

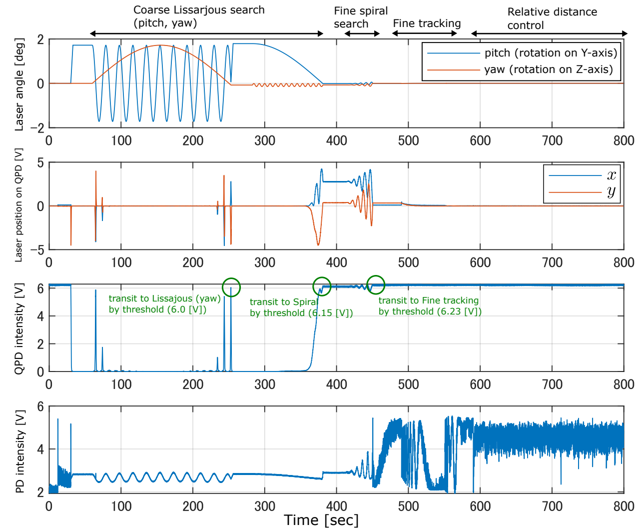

Fig. 3. Results of the experiment from laser link acquisition to precise relative distance control

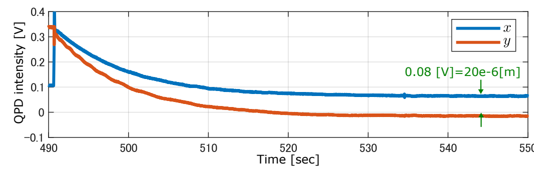

Fig. 4. Detailed results of laser link locking

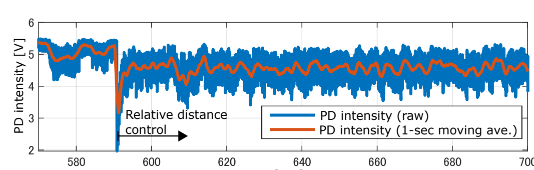

Fig. 5. Detailed result of interferometry relative distance control

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