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Vibration isolation and dual-stage actuation pointing system for space precision payloads

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ABSTRACT

Pointing and stability requirements for future space missions are becoming more and more stringent. This work follows the pointing control method which consists of a traditional spacecraft attitude control system and a payload active pointing loop, further proposing a vibration isolation and dual-stage actuation pointing system for space precision payloads based on a soft Stewart platform. Central to the concept is using the dual-stage actuator instead of the traditional voice coil motor single-stage actuator to improve the payload active pointing capability. Based on a specified payload, the corresponding platform was designed to be installed between the spacecraft bus and the payload. The performance of the proposed system is demonstrated by preliminary closed-loop control investigations in simulations. With the ordinary spacecraft bus, the line-of-sight pointing accuracy can be controlled to below a few milliarcseconds in tip and tilt. Meanwhile, utilizing the voice coil motor with the softening spring in parallel, which is a portion of the dual-stage actuator, the system effectively achieves low-frequency motion transmission and high-frequency vibration isolation along the other four degree-of-freedom directions.

1. Introduction

Pointing and stability requirements for future space missions are becoming more and more stringent. However, spacecraft suffer from various inevitable disturbances during on-orbit operation. The vibration sources may include reaction wheels, solar array drive assembly, cryocoolers, solar pressure, and thermal gradient. These vibrations will degrade the performance of space-borne precision devices. Furthermore, the philosophy of faster, cheaper brings more challenges to meet unprecedented pointing and stability requirements [1].

For most spacecraft, the major sources of vibration exist in the bus. Thus, in the past, the desired precision is usually achieved by developing a low noise bus, but considerably increasing the system cost [2]. Active compensation with fast steering mirrors (FSM) to reduce pointing jitter is generally effective, and it has been applied in many precision pointing systems, such as Micro-Precision Interferometer (MPI) testbed [3] and James Webb Space Telescope (JWST) [4]. However, this method is not sufficient for several systems with even higher performance requirements [5], nor suited for the precision payloads which need directly pointing the line-of-sight (LOS). The most promising vibration migration approach is to provide a very high level of isolation to prevent spacecraft-induced vibrations from propagating into the precision payloads [6].

In recent decades, a variety of vibration isolation methods have been designed to protect high precision payloads from the impact of micro-vibration in onboard spacecraft [7]. Passive vibration isolators for the reaction wheels have been successfully applied to prior space telescopes, including the Hubble Space Telescope (HST) and the Chandra X-ray Observatory [6]. But passive approach is not suited for low frequency vibration isolation since the resulting mechanism is too soft to withstand the launch environment [8] and introduce low local modes affecting high frequency vibration isolation effect [9]. Hence, active vibration isolation techniques are usually proposed to deal with the low frequency vibration which is common in spacecraft.

For the multi-degree-of-freedom (DOF) vibration problems, the parallel mechanism provides a good solution. For example, a Stewart platform, which uses six linear motion elements to achieve space six-DOF motion control, was introduced to serve as a six-DOF vibration isolator for a wide range of space-based as well as earth-based precision systems [10]. Since 1990s, several types of Stewart platforms have been implemented by researchers for six-axis active vibration isolation in space [11–15]. These platforms can be divided into two different categories: hard active mount (HAM) and soft active mount (SAM). HAM uses a stiff

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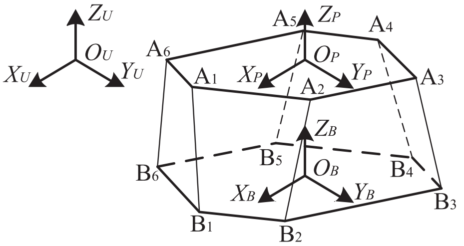

Fig. 1. Schematic of Stewart platform.

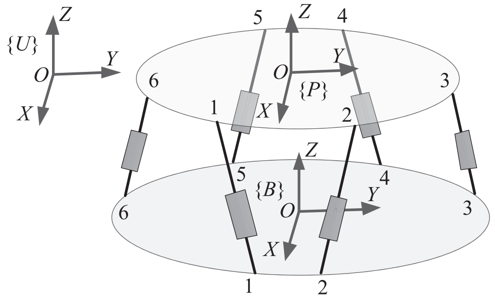

Fig. 2. Coordinate frames of the proposed system.

actuator, such as a piezoelectric actuator [11]. While SAM utilizes a soft actuator, typically a voice coil motor (VCM) in parallel with a softening spring [12–14]. Compared with the hard Stewarts, the soft ones have far more actuation stroke allowing for pointing control [12]. And previous studies have shown several orders of magnitude reduction in vibration can be achieved by combining an isolator with payload active steering [16].

Recently, the disturbance-free payload (DFP) non-contact isolation technology, proposed by Pedreiro [5], has attracted the attention of many researchers. It would be prioritized in the Advanced Large Aperture Space Telescope (ATLAST) to meet the stringent stability requirements [17]. Xu et al. [18] investigated the modeling and robust H-infinite control of a non-contact Stewart spacecraft. Wu et al. [19] analyzed the coupling characteristics of the DFP spacecraft. However, demonstrating this technology is quite difficult but necessary to avoid risk. It is also important to investigate other potential isolation and pointing techniques to reduce system cost and risk [17]. A novel vibration isolation system containing a Stewart platform and multiple tuned-mass dampers for reaction wheel was studied [20]. A low-cost, low micro-vibration control moment gyroscope was developed [21]. From the perspective of pointing control, adding payload active pointing control system on the basis of the spacecraft three-axis stabilized attitude control system is also beneficial to the pointing performance. As shown in Ref. [22], the addition of a Stewart telescope pointing system driven by VCMs enabled pointing the telescope with stability 10× better than Hubble but with a spacecraft bus ten times less capable than Hubble. To meet various space payloads ultra-high pointing and stability requirements, this work follows the above pointing control method, retaining the payload mechanical isolator to guarantee the system robust in the event of a power failure, focusing on the payload active pointing improvement.

In the precision positioning systems, many research groups have proposed dual-stage actuation concept to obtain high speed, high resolution and long motion stroke control. Commonly, the idea of dual-stage actuation is to combine a long stroke coarse stage and a high resolution fine stage in series [23]. Now, this concept has applications in hard disk drive (HDD) [24,25], robotics [26,27] and precision manufacturing [28–30].

This research proposes a novel soft Stewart platform that is capable of six-DOF active/passive vibration isolation as well as improved payload active pointing provided by replacing VCMs with the dual-stage actuators. Introducing such a platform can also reduce the spacecraft attitude control requirements, and then only an ordinary spacecraft base is needed, saving the cost. Based on a specified payload, the corresponding platform was designed to be installed between the base and the payload for enhancing the payload LOS pointing performance. Here, passive isolation is achieved via a simple form installing a softening spring in each strut, constituting a conventional two-parameter isolator. The resonances caused by the vibration isolator modes are limited through active isolation using VCMs. Payload active pointing control utilizes the dual-stage actuation concept. The dual-stage actuator is created by connecting a higher resolution fine actuator serially onto the original VCM in each strut. The piezoelectric (PZT) actuator is selected as the fine actuator because it owns the extremely fine resolution [31]. The associated simulations preliminarily verify the effectiveness of this system.

The rest of the article is organized as follows: Section 2 presents the design of the proposed soft Stewart platform. In Section 3, the system dynamic model is established and the controllers are designed. Section 4 provides the simulation results. Finally, the conclusions are drawn in Section 5.

2. Vibration isolation and dual-stage actuation pointing platform design

2.1. Configuration and layout design

A typical Stewart platform is shown in Fig. 1, consisting of six variable-length struts connecting an upper plate to a base plate. A_i, B_i ($i = 1, \ldots, 6$) denote the attachment points of strut i to the upper and lower plates, respectively. $\{U\}$ is the inertial reference frame; $\{P\}$, $\{B\}$ are frames fixed at the upper and lower plates, with origins O_P and O_B at their center of mass, respectively, and their Z axis perpendicular to the plate.

The decentralized control strategy was selected, which means the entire system is controlled using six independent single-input single-output (SISO) strut control loops. Compared with the multi-input multi-output (MIMO) control, the SISO method obtains lower order controllers, achieving smaller calculation amount and easier engineering application. If the coupling among the six struts is small, the decentralized control will gain quite good results. Hence, the "cubic configuration" [32], where the adjacent struts are orthogonal to each other making the coupling between the struts negligible, was chosen in this study. Moreover, the six struts are designed identical to minimize the mechanical design effort and simplify control system design and implementation.

In the practical payload vibration isolation and pointing system, the upper and lower plates are unnecessary. The six struts can be connected directly to the payload and the spacecraft bus through certain mechanical interface mounts. Therefore, the upper plate represents the payload, while the lower plate represents the spacecraft bus. The coordinate frames of the proposed system are shown in Fig. 2.

The definitions of these frames are the same as those in Fig. 1. $\{P\}$ and $\{B\}$ were named as the payload frame and the base frame, respectively. For the purpose of simple kinematics and dynamics analysis, $\{P\}$ and $\{B\}$ were established to have their XZ-plane located at the symmetry plane of the platform and their axes aligned.

Here, the given payload mass is 600 kg. Its principal moments of inertia are $I_1 = 270$ kg m^2, $I_2 = I_3 = 500$ kg m^2. The payload LOS is nominally in parallel with the XY-plane of the platform. Generally speaking, payload requires precise pointing for the tip and tilt of the LOS, whereas the motion control along the other four directions is less important. Thus, the vibration isolation and pointing platform only need to provide fine pointing control about these two axes. In the layout design, the platform Y axis was aligned with the payload LOS. Then, the platform X and Z axes were aligned with the tip and tilt of the LOS, respectively. The payload active pointing control could be regarded as the rotation control around the platform X and Z axes, fully utilizing the symmetry of the platform. Furthermore, $\{P\}$ could nearly coincide with