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Dynamic isotropy design and analysis of a six-DOF active micro-vibration isolation manipulator on satellites

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ABSTRACT

The payload and strut mass plays significant roles in the dynamic analysis of Stewart platforms. However, until now there is little literature considering these effects on optimization and vibration isolation. In this paper, a new decoupling condition of stiffness matrix is proposed base on elegant algebraic approach, with which the dynamic isotropy index can be expressed in terms of natural frequencies. When the height of the mass center of the payload is zero, dynamic decoupling as well as translational and combined dynamic isotropy can be satisfied at the same time. Since the dynamic mass matrix is coupled when the height is not zero, an objective function that concerns the dynamic isotropy index and strut masses is formulated. The effects of the strut masses and payload on the natural frequencies and dynamic isotropy index are discussed. The genetic algorithm and differential evolution algorithm are implemented to obtain the suitable parameters for optimization design and vibration isolation purpose. That the optimization results of the two algorithms are nearly the same indicates that the optimized configurations are convincible. On the basis of the optimization process, we take into account a real link and fabricate a real optimized configuration in our laboratory. The dynamic model is also verified by both horizontal and vertical experimental results. It can be concluded that after optimization, a combined dynamic isotropy configuration is achieved, and the frequency range of vibration isolation can be extended.

1. Introduction

Optical satellites have to deal with various disturbances on orbit. For sensitive payloads, not being able to reduce the disturbances to a sufficiently low level can either degrade the performance or causes malfunction. To satisfy the increasingly strict requirements of optical payload in satellite, many manipulators that can be used for six Degree-of-Freedom (DOF) active vibration control have been carried out based on the Stewart platform [1–3], which is of high load carrying capacity, good dynamic performance and precise positioning [4,5]. However, how to select parameters of the platform appropriately remains an active problem. In recent decades, numerous researchers have been focused on optimization of the platform.

In general, optimization objectives can be subdivided into maximized workspace or dexterity [6–10], decoupling or orthogonal manipulators' design [11,12], and isotropic optimization [13–21]. Decoupling configurations enable us to transform multiple-input-multiple- output (MIMO) system to single-input-single-output (SISO) one, which is beneficial for high-precision motion control for telescopes, precision pointing, and micro-vibration isolation. Since the operation is over a very small workspace, these applications can enjoy decoupling and resulting higher performance throughout their workspace [11]. The isotropy is one of the common measures of performance of a manipulator. Typically, it is composed of three types: static isotropy [13,14], kinematic isotropy [15,16] and dynamic isotropy [17–21]. Fattah and Ghasemi [13] pointed out a fully isotropic configuration of Stewart platform cannot be achieved, whereas a partial isotropy can be designed. The so-called isotropy implies that Jacobi matrix multiplies its transpose equals a diagonal matrix in which all the elements are of the same value. The definitions of stiffness isotropy, velocity isotropy and force isotropy were systematically summarized by Fassi et al. [14]. The stiffness and velocity isotropies are equivalent to static and kinematic isotropies, respectively. Bandyopadhyay and Ghosal [15,16] classified the Jacobi matrix as translational and rotational parts (force and moment part), and converted the condition number problem into an eigenvalue one. They obtained the conditions of static isotropy, including translational, rotational and combined isotropy. Physically, the isotropy indicates that the platform end-effector can rotate and/or translate with equal ease in all spatial directions.

Jiang and coworkers [19–23] argued that it is essential to take into account the dynamics property of Stewart platform for some applications such as high-speed precision machining and vibration isolation. At the design stage, natural frequencies can serve as stability index [23] of

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the platform. Ma and Angeles [17] first proposed the concept of dynamic isotropy, and investigated applications in trajectory planning and the optimal design of a platform mechanism under dynamic isotropy conditions [17]. Jiang and coworkers proposed [19–22] another type of 'dynamic isotropy' to analyze the mass-geometric characteristics of the platform. They pointed out that fully dynamic isotropy, which means that all the natural frequencies of the configuration are the same, cannot be achieved. Whereas other forms of isotropy, such as combined isotropy and translational isotropy can be developed. However, the assumption used in the existing literature that the system mass matrix is diagonal seems difficult to realize once the payload is installed on the upper platform. They also proved that the symmetric generalized Stewart platform at a neutral position could be fully decoupled by adjusting the payload's center of mass to coincide with its compliance center. Actually, the compliance center is, to some extent, equivalent to the case when the height of the mass center of the payload equals zero under the decoupling condition.

Except for the analytical approaches, some optimization algorithms are utilized to obtain the optimal parameters of the Stewart Platform [24–28]. Lopes' group [25,26] applied Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) to search for the ideal structural parameters. Lou et al. [28] explored the convergence of five optimization algorithms based on the Delta robot and the Gough–Stewart platform in-depth. The results showed Differential Evolution Algorithm (DE) and Particle Swarm Optimization (PSO) perform effectively and steadily for the two examples.

Besides dynamic isotropy optimization on Stewart platform, very recently, Afzali-Far and coworkers [29–32] did some excellent works on analytical and algebraic analysis of Stewart platform. They established a parametric and closed-form model for the damped vibrations of Stewart platforms. Particularly, the model can be applied to design, optimize and control the platforms in high-precision/bandwidth applications. They also analytically investigated the conditions for the decoupled vibrations and the effect of strut inertia on these conditions, which are all of high values.

However, in practice, the system matrices of the Stewart platform are coupled due to its intrinsically structural couplings and nonlinearities among the six links. Recently, we proposed a novel dynamic model of Stewart platform with the base excitation via Kane's method [33,34]. It can be observed that the strut mass and the payload, which is mounted on the upper platform, explicitly appear in the mass matrices. Therefore, the dynamic properties of the whole system closely rely on the two parameters. Consequently, different from merely geometrical optimization in previous studies, in this paper we add the strut masses and the height of mass center of the payload for optimization besides the other three geometrical parameters—the radius of the base platform and two half angles of the upper and lower platform. This is especially significant for the platform that will be employed to isolate the micro-vibration on satellites due to the high-precision demand. The expressions for the natural frequencies can be obtained accordingly through the elegant algebraic approach by utilizing these variables which are of obvious physical meaning. On the basis of the decoupling condition of the stiffness matrix, we extend the design possibilities of dynamic isotropy [20] to obtain an optimized Stewart platform by concerning the effects of the payload and the strut masses. One important purpose of dynamic isotropy optimization in our view is vibration isolation whose fundamental idea is to shift the natural frequencies of the open loop system to be lower enough so that low-frequency vibrations can be suppressed. To guarantee the frequency range of vibration isolation of the upper platform to be exactly or nearly the same, we should make the whole system to be dynamic isotropic as much as possible in the design stage. Furthermore, we also discuss some considerations of dynamic isotropy design based on the real link in our laboratory and present an optimized configuration. Furthermore, that an excellent agreement between horizontal and vertical experiments and the theory demonstrates the validity of the dynamic model. All the results in this paper may serve as a design guidance of

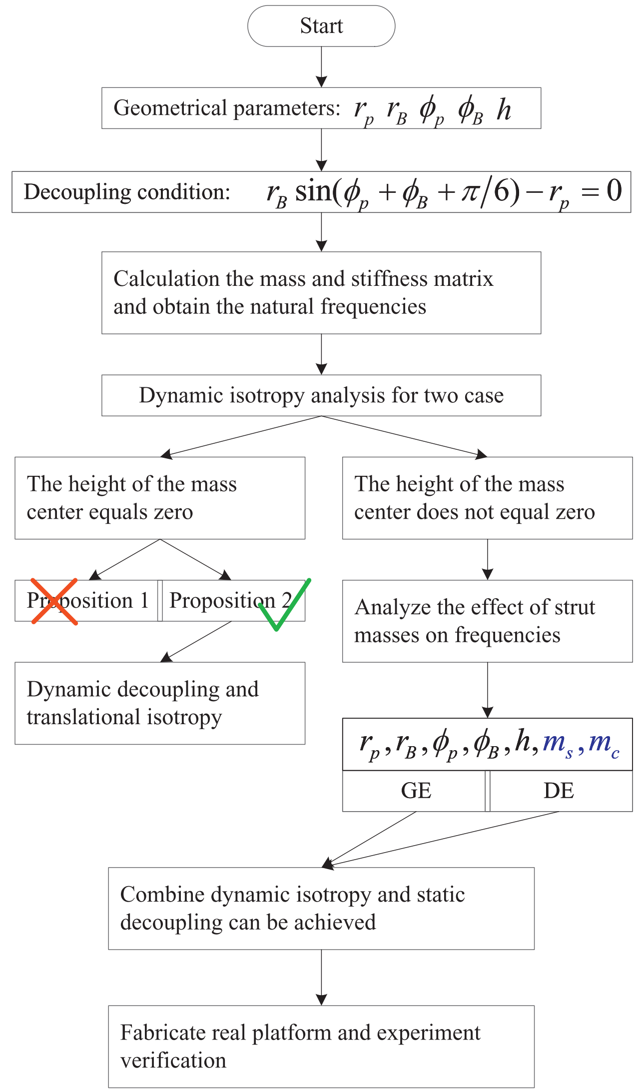

Fig. 1. Optimization and analysis procedure.

the Stewart platform for dynamic isotropy and vibration isolation purposes. The analyzed procedure of the manuscript is illustrated in Fig. 1.

2. Decoupling configurations

The basic configuration is showed in Fig. 2. In this section, we will analyze the stiffness decoupling condition through the algebraic approach based on the same configuration. All the equations are expressed in the inertial coordinate whose origin is fixed at the center of the base platform. The parameters of the platform are illustrated in Table 1 in which five parameters r_p, r_B, ϕ_p, ϕ_B, h are selected to obtain the stiffness decoupling of the Stewart platform.

The Jacobi matrix of the platform [34]

$$\mathbf{J}_p = \begin{bmatrix} \mathbf{u}_1 & \cdots & \mathbf{u}_6 \\ \tilde{\mathbf{p}}_1\mathbf{u}_1 & \cdots & \tilde{\mathbf{p}}_6\mathbf{u}_6 \end{bmatrix} \tag{1}$$

where $\mathbf{u}_i$ $(i = 1, 2, \cdots, 6)$ denotes the unit vector of each link, $\mathbf{p}_i$ $(i = 1, 2, \cdots, 6)$ represents the vector of spherical joint on the upper platform that can be expressed as

$$\mathbf{p}_1 = \begin{bmatrix} r_p \cos\phi_p & r_p \sin\phi_p & 0 \end{bmatrix}^{\mathrm{T}}$$
$$\mathbf{p}_2 = \begin{bmatrix} r_p \cos\phi_p & -r_p \sin\phi_p & 0 \end{bmatrix}^{\mathrm{T}}$$
$$\mathbf{p}_3 = \begin{bmatrix} -r_p \cos(\phi_p + \pi/3) & -r_p \sin(\phi_p + \pi/3) & 0 \end{bmatrix}^{\mathrm{T}}$$