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Research on the dynamic coupling of the rigid-flexible manipulator

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ABSTRACT

Because of its large dimension, a rigid-flexible manipulator was designed to serve as the feed support system in a Five-hundred-meter Aperture Spherical radio Telescope (FAST). The rigid-flexible manipulator is composed of a flexible cable-driven parallel manipulator and a rigid Stewart platform. Motion of the Stewart platform may induce vibration of the cable-driven parallel manipulator due to reaction forces. The goal of this study is to investigate the dynamic coupling of the rigid-flexible manipulator. The "Virtual Stewart platform" was introduced to obtain a homogenous matrix to describe how much base motion is produced by a given Stewart platform motion. On this basis, an index was proposed to characterize the dynamic coupling of the rigid-flexible manipulator. Based on the proposed index, the factors influencing the dynamic coupling are investigated. The proposed index can be considered as a performance index in design and control of the system. Influence of the dynamic coupling on the feedback control of the rigid-flexible manipulator was also discussed. The simulation results showed that the dynamic performance of the rigid-flexible manipulator is strongly determined by the proposed index.

1. Introduction

In 1994, Chinese astronomers carried out the conceptual design of the Five-hundred-meter Aperture Spherical radio Telescope (FAST) [1]. Because of the large dimension of the telescope, a rigid-flexible manipulator is designed to serve as the feed support system. The flexible cable-driven parallel manipulator provides the receiver with a wide range of translation and rotation [2]. However, due to the flexibility of the long-span cables, the feed support system bears a concern of possible vibration under wind disturbance in the open air [3]. The rigid Stewart platform is then used to compensate the positioning error for achieving the required accuracy.

Compensating control of the rigid mechanism, however, is challenging, especially when the platform's mass and inertia cannot be negligible in comparison with those of the base. Platform motion can induce base motion resulting from dynamic interaction. Furthermore, the base motion will alter the original trajectory of the platform. This dynamic coupling is another cause besides the wind disturbance caused vibration of the rigid-flexible manipulator. However, research on FAST mainly focused on vibration suspension [4–8], dimension optimization [9] and workspace analysis [10,11]. Dynamic coupling of the rigid-flexible manipulator has received very little investigation. This motivates the study in this paper.

Dynamic coupling problems of free floating robots have been studied by a few groups. Understanding of the dynamic coupling of the system is the first step. Dubowsky and Torres [12] introduced the disturbance mapping to relate the robot joint motion to the base attitude disturbance. Xu [13,14] defined a measure to characterize the degree of the dynamic coupling. The defined measure describes how much base motion is produced by a given robot end-effector motion. To realize zero reaction to the base, dynamic balance control was proposed by Huang et al. [15,16]. In the dynamic balance control, a space robot system consisting of two arms was developed, with the mission arm for accomplishing the capture mission, and the balance arm compensating for the disturbance to the base. To minimize the dynamic disturbance, path planning for space manipulators was also presented. Dubowsky and Torres [12] found paths to minimize the dynamic disturbance with the aid of the enhanced disturbance map. Huang et al. [17] used genetic algorithms to search for the optimal joint inter-knot parameters in order to realize the minimum disturbance. Chung et al. [18] presented new design of gaits for the space manipulator to reduce the dynamic disturbance to a space station. The above methods regarding the free floating robots have certain merit on the rigid-flexible manipulator. However, the defined metric [13,14] does not apply to the base or the end-effector with both translational and rotational freedoms because of non-homogenous dimension in the velocity vectors. Thus, it is necessary to propose a dynamic coupling index with homogenous dimension.

The dynamic coupling strongly influences control performance of the rigid-flexible manipulator. Control schemes for the macro/micro manipulators include using the rigid robot to compensate for

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Nomenclature

${}^{B}\mathbf{t}_P$	Position of the platform in $\{B\}$
${}^{B}\mathbf{R}_P$	Rotation matrix of the platform in $\{B\}$
${}^{B}\dot{\mathbf{t}}_P$	Linear velocity of the platform in $\{B\}$
${}^{B}\boldsymbol{\omega}_P$	Angular velocity of the platform in $\{B\}$
${}^{B}\ddot{\mathbf{t}}_P$	Linear acceleration of the platform in $\{B\}$
${}^{B}\boldsymbol{\varepsilon}_P$	Angular acceleration of the platform in $\{B\}$
$\mathbf{b}_i$	Coordinate of b_i in $\{B\}$
$\mathbf{p}_i$	Coordinate of p_i in $\{P\}$
$\mathbf{C}_i$	Coordinate of C_i in $\{B\}$
$\mathbf{T}_i$	Coordinate of T_i in $\{G\}$
m_B	Mass of the base
m_L	Mass of lower part of the legs
m_U	Mass of upper part of the legs
m_P	Mass of the platform
$\mathbf{r}_B$	Mass center of the base in $\{B\}$
$\mathbf{r}_L$	Mass center of lower part of the legs in $\{L\}$
$\mathbf{r}_U$	Mass center of upper part of the legs in $\{U\}$
$\mathbf{r}_P$	Mass center of the platform in $\{P\}$
$\mathbf{I}_B$	Inertia matrix of the base in $\{B\}$
$\mathbf{I}_L$	Inertia matrix of lower part of the leg in $\{L\}$
$\mathbf{I}_U$	Inertia matrix of upper part of the leg in $\{U\}$
$\mathbf{I}_P$	Inertia matrix of the platform in $\{P\}$
${}^{B}\mathbf{s}$	Unit leg vector in $\{B\}$
χ	Unit cable vector in $\{G\}$

micromanipulator position error while at the same time actively using the micromanipulator to reduce the vibration. Torres et al. [19,20] introduced energy dissipation method to maximizing the energy dissipated by commanding the actuators of the robot to behave as passive linear springs and dampers. George [21,22] developed the inertial damping control to modulate the manipulator actuators to induce the inertial damping forces by sensory feedback of the base vibration. The above control schemes have ability to suppressed high-frequency vibration of the macro manipulator instead of low-frequency vibration of the large span cable-driven parallel manipulator. The major goal of the rigid-flexible manipulator in this paper is to achieve the positioning and orientating precision. The proposed controllers were mainly based on two factors: prediction [23] and feedback [6]. The prediction deals with the base motion caused by the wind disturbance and the feedback aims to construct a closed loop system to achieve the control precision. Duan et al. [5] presented a decoupled tracking and prediction algorithm to predict the position and orientation of the base and designed an upper layer adaptive interaction PID supervisory controller. Ren et al. [4,24] used the predicted inertial motion of the base as the reference input to develop the PD control law for the six actuators. In controlling a rigid-flexible manipulator, the resultant base motion from the platform motion is undesirable and should be restricted within a limited range. If the dynamic coupling is large enough, it may result in ineffectiveness of the prediction and instability of the control system. As a consequence, the rigid-flexible manipulator may vibrate heavily and may even become uncontrollable. Therefore, it is necessary to carry on a research on influence of the dynamic coupling on the control performance.

This paper is organized as follows: In Section2, system of the rigid-flexible manipulator is described in details. In Section3, dynamics model of the rigid-flexible manipulator is established. In Section4, dynamic coupling index is proposed based on the concept of "Virtual Stewart platform". In Section5, influence of the dynamic coupling on the dynamic performance is discussed. In Section6, influential factors of the dynamic coupling are analyzed, including the configuration, the structural parameters and the inertia properties. Finally, Conclusions of this paper are given.

2. System description

In Fig. 1, the FAST is composed of a reflector and a feed support system. The feed support system is a rigid-flexible manipulator consisting of two mechanisms, which are arranged in series: a flexible six-cable-driven parallel manipulator and a rigid Stewart platform. The six-cable-driven parallel manipulator is composed of six towers, six cables and a base. $A_i(i=1,\ldots,6)$ are the connected points of the cables and the towers. $C_i(i=1,\ldots,6)$ are the connected points of the cables and the base. In Fig. 2, the Stewart platform is composed of a base, a platform and six legs. The leg is connected to the base by a universal joint b_i and connected to the platform by a spherical joint p_i. The universal joints $b_i(i=1,\ldots,6)$ are distributed in a circle of radius r_B and angle of two adjacent points is θ_B. The spherical joints $p_i(i=1,\ldots,6)$ are distributed in a circle of radius r_P and angle of two adjacent points is θ_P.

Coordinates are set up in the rigid-flexible manipulator as follows. Let $\{G\}$ be the inertial frame, with its origin at the center

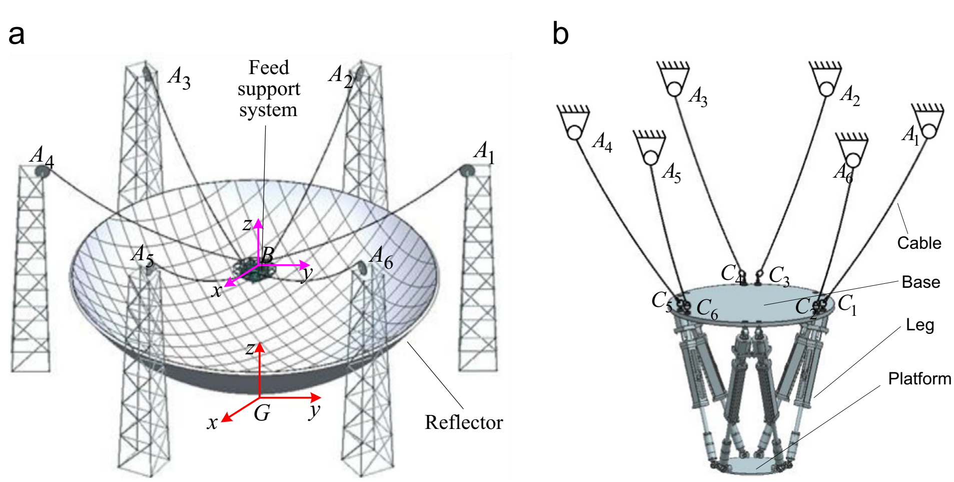

Fig. 1. 3-D model of FAST: (a) isometric view, (b) feed support system.