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Research article

Design and implementation of a novel modal space active force control concept for spatial multi-DOF parallel robotic manipulators actuated by electrical actuators

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ABSTRACT

Robotic spine brace based on parallel-actuated robotic system is a new device for treatment and sensing of scoliosis, however, the strong dynamic coupling and anisotropy problem of parallel manipulators result in accuracy loss of rehabilitation force control, including big error in direction and value of force. A novel active force control strategy named modal space force control is proposed to solve these problems.

Considering the electrical driven system and contact environment, the mathematical model of spatial parallel manipulator is built. The strong dynamic coupling problem in force field is described via experiments as well as the anisotropy problem of work space of parallel manipulators. The effects of dynamic coupling on control design and performances are discussed, and the influences of anisotropy on accuracy are also addressed. With mass/inertia matrix and stiffness matrix of parallel manipulators, a modal matrix can be calculated by using eigenvalue decomposition. Making use of the orthogonality of modal matrix with mass matrix of parallel manipulators, the strong coupled dynamic equations expressed in work space or joint space of parallel manipulator may be transformed into decoupled equations formulated in modal space. According to this property, each force control channel is independent of others in the modal space, thus we proposed modal space force control concept which means the force controller is designed in modal space. A modal space active force control is designed and implemented with only a simple PID controller employed as exampled control method to show the differences, uniqueness, and benefits of modal space force control. Simulation and experimental results show that the proposed modal space force control concept can effectively overcome the effects of the strong dynamic coupling and anisotropy problem in the physical space, and modal space force control is thus a very useful control framework, which is better than the current joint space control and work space control.

1. Introduction

Robotic spine brace is a novel spine brace concept, and it will be exploited to realize the treatment of scoliosis [1], by applying accurate 3-D rehabilitation force on the spine of patients, but no limitation on the movement of the upper body. A parallel-actuated structure, Stewart type platform, is chosen to develop robotic spine brace in our research, because this kind of structure has many advantages such as high accuracy, high ratio of load to weight, and the required multi-dimensional output force [2–4]. However, the inherent properties, strong dynamic coupling and anisotropy in task space, greatly affect and restrict the performances of active rehabilitation force control, including big error in the direction and the value of the output force. It is very difficult to cancel coupling and anisotropy problems with the current control strategies in joint space control or workspace control, because these problems just appear in joint space or workspace [5–7]. It is excited that we find a modal space control which can rightly solve these boring problems. Hence, the research of modal space active force control of parallel manipulators is quite important and significant to implement accurate force control, via eliminating the effects of strong dynamic coupling and anisotropy in DOFs.

Parallel mechanism has attracted wide research interest [8–10], and it has been extensively used in different areas [11,12]. In the

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system and control community, many effective control methods have been proposed for parallel manipulators [13–15]. These control strategies are designed based on two frameworks [16]: the work space control framework, controller designed in task space [17,18]; the joint space control framework, controller designed in joint space [19,20]. Generally, each link of parallel manipulators is viewed as an independent SISO system in joint space control framework. Kim et al. [21] designed a robust tracking control in joint space for parallel manipulators in presence of nonlinearity and fast time-varying uncertainty based on Lyapunov redesign method. Pi et al. [22] proposed a sliding model control with discontinuous projection-based adaptation law in the joint space for parallel robots, considering the uncertain load disturbances. Nevertheless, the work space control framework has a potential to supply better DOF control ability [18]. Meng et al. [23] developed an adaptive sliding mode fault-tolerant control in task space for an uncertain Stewart platform in presence of loss of actuator effectiveness, based on offline multi-body dynamics. Khosravi et al. [24] studied a composite control for a fully-constrained parallel cable robot with elastic cables in task space, taking into account the asymptotic stability of fast dynamics. Although many literatures on control of spatial parallel manipulators can be easily found, only motion trajectory tracking of parallel manipulators is the focused topic in these reports.

Research on force control of spatial parallel manipulators is far later than motion control for its complexity. For the most current application of parallel manipulators, such as rehabilitation robots, surgery robots, biomechanics testing systems of human body, control and estimation of the contact force between device and environment become quite important. Force control of robotic system can be divided into two aspects [25]: the direct force control and the indirect force control. Aiming to directly control the contact force, the direct force control takes the actual contact force as its feedback and a desired force as its input. The indirect force control aims to realize force control by controlling dynamic relation of force and position, with the information about motion as its input. Nguyen et al. [26] reported a virtual force control for the six-DOF parallel manipulator. Kosuge et al. [27] designed an indirect control in joint space to realize force control of a hydraulic parallel link robot used for assembly. Takaiwa et al. [28] developed an indirect control belonging to impedance control in workspace for a pneumatic parallel manipulator applied in wrist rehabilitation. Li et al. [29] proposed a direct force control, hybrid position/force control, in joint space for a cable driven Stewart parallel manipulator. Onodera et al. [30] studied the force control of a Stewart-platform-type ankle-foot rehabilitation device, by using the indirect control in joint space. Mao et al. [31] and Vashista et al. [32] developed a direct force control in the joint space of cable driven parallel manipulators utilized in rehabilitation. Although the indirect control in force field is more popular in the case of position & force control together, the direct force control may be a wise choice for the case that only force control is required. However, the current force control schemes with both direct and indirect force control are designed in joint space or task space. Because of the negative influences of the strong dynamic coupling and anisotropy in DOFs of spatial parallel manipulators, force control designed in both joint space and task space will greatly lost its control performances in force control field. For solving the strong dynamic coupling effects in control, Yang et al. [33,34] analyzed the dynamic coupling problem and proposed a novel control concept, modal space control framework, for motion trajectory tracking. Unfortunately, the control framework is developed only for motion control of parallel manipulators in our previous research. In this research, we will try to develop a novel but effective control framework in force control field, which owns all the advantages of the joint space control and the task space control but no shortcoming of them.

The main contribution of this research is to propose a novel control framework named modal space force control for parallel manipulators, which has the function of eliminating the negative effects of the strong dynamic coupling and anisotropy in DOFs. This proposed framework is like joint space or task space control framework, but the most difference is no dynamic coupling exists in the proposed modal space. Moreover, the isotropy within the concerned bandwidth can be implemented in the modal space, which is also the key contribution in force control of parallel manipulators.

This paper is organized as follows. Section 2 issues the key problems of coupling and anisotropy for force control of parallel manipulators via experiments in both time domain and frequency domain. The mathematical model of parallel manipulators will described in Section 3, and the modal space active force control will developed in Section 4 as well as the decoupling and isotropy control. Section 5 evaluates the control performances of proposed modal space force control applied in an experimental parallel manipulator, and the conclusion is made in Section 6.

2. Problem description

Robotic spine brace is a novel concept in both the field of spine brace and rehabilitation robotics. We design the first prototype named 'SproB' for the scoliosis patients with 'C' type scoliosis by adopting spatial parallel robotic manipulator (PRM), which is shown in Fig. 1 [1]. The middle ring is used to apply accurately rehabilitation force/moment to patients for correction of abnormal spine, and the top ring is static compared with bottom ring under passive motion control. Obviously, active force control of PRMs plays an important role in SproB. In addition, force control usually shows more difficult than motion control in the area of system control. Hence, active force control becomes the key issue except for optimal design of SproB. However, the accuracy of force control, involving direction and value of force, is greatly degraded because of the strong dynamic coupling and anisotropy problem, common problems of all parallel mechanisms.

2.1. Anisotropy problem

PRM is usually an anisotropic system, which means the properties are not in all directions of DOFs or joint space. Anisotropy is a negative property of a PRM especially from industrial viewpoint, and many efforts have been reported from design point [7,35]. The effects of anisotropy property in force control will be discussed in this section.

To clearly describe the effects of anisotropy property in force control field, a desired combined force, 8 N/0.06 Hz in both surge and sway directions, is applied to a real PRM, the lower platform in

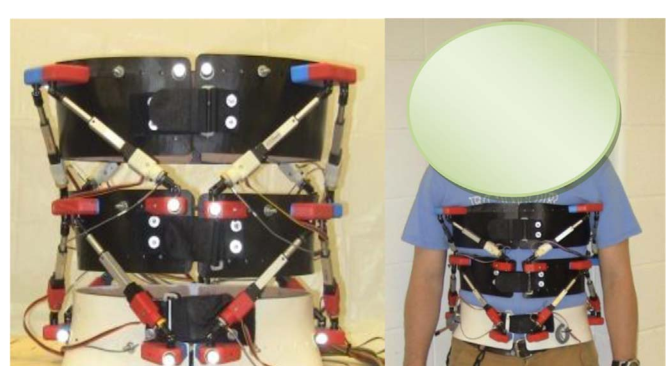

Fig. 1. 'SproB' robotic spine brace used for treatment and sensing of scoliosis.

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