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Compliance analysis of a 3-SPR parallel mechanism with consideration of gravity

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ABSTRACT

By taking gravity and joint/link compliances into account, this paper presents a semi-analytical approach for compliance analysis of a 3-SPR parallel mechanism which forms the main body of a 5-DOF hybrid manipulator especially designed for high-speed machining and forced assembling in the aircraft industry. The approach is implemented in three steps: (1) kinetostatic analysis that considers both the externally applied wrench imposed upon the platform and the gravity of all moving components; (2) deflection analysis that takes both joint and link compliances into account; and (3) formulation of the component compliance matrices using a semi-analytical approach. The advantage of this approach is that the deflections of the platform caused by both the payload and gravity within the given task workspace can be evaluated in an effective manner. The computational results show that the deflection arising from gravity of the moving components may have significant influence on the pose accuracy of the end-effector.

1. Introduction

The existing category of five degrees of freedom (DOF) manipulators having hybrid architectures contains two families that are composed of a 3-DOF parallel mechanisms plus a 2-DOF rotating head attached to its platform. The first family essentially comprises those with a properly constrained active/passive limb plus a number of 6-DOF active limbs having six degrees of freedom [1,2]. Here, an active limb is the limb having at least one actuated joint. A passive limb is the limb having no actuated joint. And the word ‘properly’ means that the type and number of DOF of the constrained limb are completely identical to those of the platform. Typical examples in this family are the well-known Tricept [3], George V [4] and TriVariant [5] among others [6]. Parallel mechanisms belonging to the second family are basically composed of three lower mobility limbs having 4 or 5 degrees of freedom. Typical example in this family is the Exechon robot [7]. These two families are especially designed for their applicability to light machining (such as deburring, drilling, cutting and welding), among other tasks, and they thereby have become of great interest to machine tool and aircraft builders in recent years.

Stiffness is one of the most important performance factors that should be considered for the above-mentioned 5-DOF hybrid manipulators when they are used for high-speed machining and/or forced assembling, for which high rigidity and high accuracy are crucial requirements. These requirements have led to enthusiastic and extensive investigations into stiffness modeling, evaluation and optimization. As far as the stiffness modeling is concerned the approaches available to hand can roughly be divided into two groups: numerical approaches by means of finite element analysis (FEA) or structure matrix analysis (SMA) [8,9]; and analytical or

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semi-analytical approaches [10–26] based upon the combination of fundamental robotic theory with FEA or structural mechanics. The FEA is the most accurate method because the complex 3D geometry of links, contact rigidity of joints, and distributed external forces (self-weight or gravity, for example) can be modeled precisely. However, very high computational costs arise as the FE models have to be re-meshed over and over again with the changing configurations. Consequently, comprehensive analytical/semi-analytical modeling approaches are required in order to allow stiffness evaluation to be carried out throughout the entire workspace in an effective manner either in the preliminary or in the final design stage.

Analytical/semi-analytical stiffness modeling of parallel mechanisms can be traced back to the work of Gosselin [10] in which merely the actuator compliances were taken into account. By taking into account the component compliances in terms of tension/compression, bending and torsion, a plenty of work was carried out by Zhang and Gosselin [11–13] for the stiffness analyses of Tricept robots. They also proposed the elegant concept of the 'virtual joint' to formulate the bending compliance of a properly constrained passive limb within the Tricept and its variants, resulting in a simplified bending stiffness model represented by three lumped springs. Recently, the concept of 'virtual joint' was significantly extended by Pashkevich et al. [14–16], resulting in a multidimensional lumped-parameter model formulated in terms of localized 6-DOF virtual springs for describing the link/joint compliances. The model formulated in this way is a direct map from the rigidity of links/joints to the stiffness of the end-effector.

By dividing the link/joint compliances into two groups associated respectively with actuations and constraints, screw theory based approach may serve as a useful tool for analytical/semi-analytical stiffness modeling of lower mobility parallel mechanisms. The initiative along this track was taken by Joshi and Tsai [27] in formulating the overall Jacobian. The idea was then extended by Huang and colleagues [28] into the generalized Jacobian. The difference is that the generalized Jacobian considers the theoretically inaccessible instantaneous motions between the joint space and operation space, which is an important issue in the stiffness and accuracy analysis. Based upon the overall or generalized Jacobians, the stiffness analyses of a number of lower mobility parallel manipulators have been investigated [17–26]. The advantages of the screw theory based approach is that it enables the Cartesian stiffness matrix to be decomposed into two meaningful components associated respectively with actuations and constraints, providing designers with clear and useful guidelines for taking appropriate measures to improve static performance of the system.

It should be pointed out that besides the deflections caused by the payload exerted upon the end-effector, the deflections caused by the gravity of the robot structure itself should be considered in the compliance analysis of the 5-DOF hybrid manipulators, particularly for applications that orient them primarily horizontally. Several attempts have been made to deal with this problem by treating gravity as a concentrated force [29–31], or as equivalent pairs of parallel forces applied on the adjacent joints [16]. However, these treatments are insufficient in the cases where the link compliances are not negligible, thus remaining an open issue to be investigated.

This paper presents a semi-analytical approach for compliance analysis, applied explicitly to a 3-SPR parallel mechanism which forms the main body of a 5-DOF hybrid manipulator especially designed for high-speed machining and forced assembling. Having outlined the existing challenges above, the paper is organized as follows. The system description and inverse displacement analysis are addressed briefly in Section 2. Section 3 then executes the detailed procedure for deflection analysis of the mechanism, concentrating upon: (1) formulation of a linear map between joint forces and an externally equivalent applied wrench imposed on the platform; (2) establishment of a precise model for the joint deflections; and (3) formulation of the component compliance matrices in the joint space using a semi-analytical approach. A numerical example is given in Section 4 to illustrate the effectiveness of the approach and conclusions are drawn in Section 5.

2. System description and inverse kinematics

Fig. 1 shows a 3D view of the 5-DOF hybrid manipulator under consideration, which is essentially composed of a 3-SPR parallel mechanism plus a 2-DOF rotating head attached to the platform via a trust bearing. The parallel mechanism consists of a platform, a base, and three identical SPR limbs. The major distinctions between the current design and the Exechon robot [7] are: 1) the use

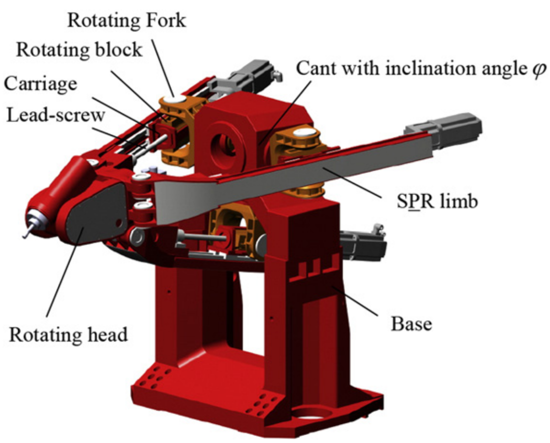

Fig. 1. 3D model of the 3-SPR parallel mechanism plus a 2-DOF rotating head.