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Kinematic sensitivity analysis of the 3-UPU parallel mechanism

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Abstract

This paper addresses the kinematic sensitivity of the three degree-of-freedom 3-UPU parallel mechanism, a mechanism consisting of a fixed base and a moving platform connected by three serial UPU chains. Although a mathematical mobility analysis confirms that the mechanism has three degrees of freedom, hardware prototypes exhibit unexpected large motions of the platform even when the three prismatic joints are locked at arbitrary configurations. Existing mathematical classifications of kinematic singularities also fail to explain the gross motions of the 3-UPU. This paper resolves this apparent paradox. We show that the 3-UPU is highly sensitive to certain minute clearances in the universal joint, and that a careful kinematic sensitivity analysis of the 3-UPU augmented with virtual joints satisfactorily explains the gross motions. Observations with a hardware experimental prototype confirm the results of our sensitivity analysis.

Keywords: Parallel mechanism; 3-UPU; Kinematic sensitivity; Kinematic singularity

1. Introduction

Despite their many advantages vis-à-vis serial mechanisms, classical 6-6 parallel mechanisms such as the Stewart platform suffer from a smaller workspace, complex mechanical design, and more difficult motion generation and control due to their complex kinematic analysis. In an attempt to overcome these and other limitations of 6-6 parallel mechanisms, many researchers have investigated various three and six degree-of-freedom 3-3 parallel mechanism designs as an alternative (e.g., [1,3,7]).

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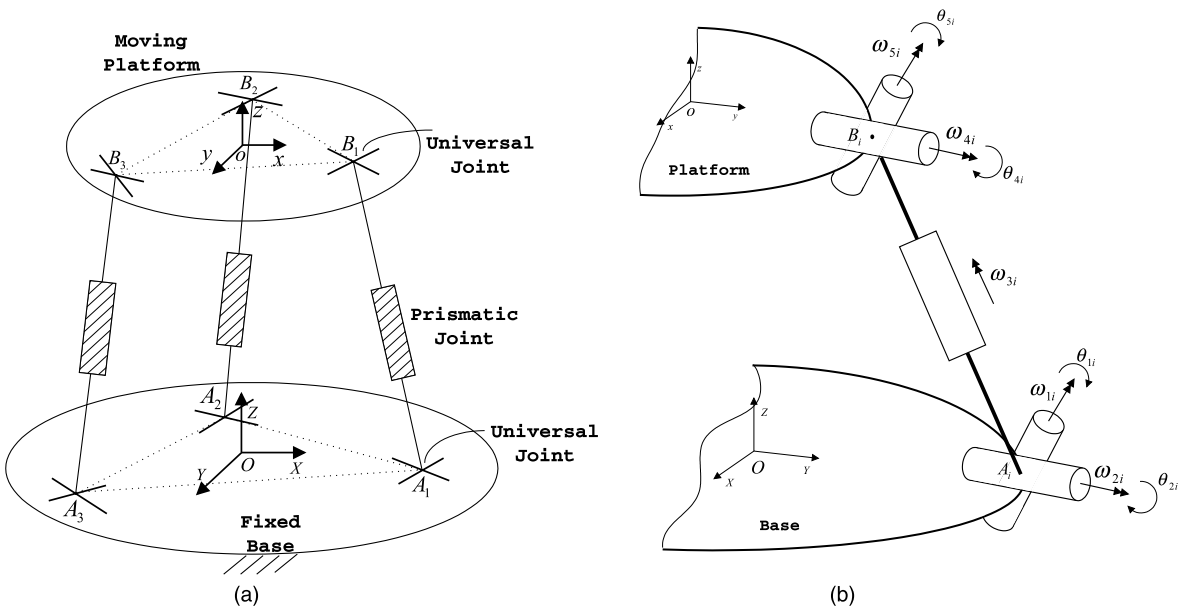

Fig. 1. The 3-UPU parallel mechanism: (a) the general 3-UPU mechanism; (b) the translational 3-UPU.

One of the more fascinating 3-3 designs is the three degree-of-freedom 3-UPU parallel mechanism; the basic structure of the mechanism is shown in Fig. 1. It consists of a fixed base and moving platform connected by three serial chains, with each chain having a universal–prismatic universal joint arranged in sequence. The universal joints are passive; only the three prismatic joints are actuated. In contrast to other 3-3 mechanisms, because the 3-UPU mechanism consists of only universal and prismatic joints, it is quite attractive from the manufacturing point of view. More interestingly, as first pointed out by Tsai [8], the universal joints can be attached in such a way that the moving platform only undergoes pure translational motion. Motivated by these results, Di Gregorio et al. [2,5] explore the conditions under which the more general 3-RRPRR mechanism (which includes the 3-UPU mechanism as a special case) can be arranged to undergo strictly translational motion.

Analysis of the kinematic constraint equations for both the general 3-UPU mechanism and the more general 3-RRPRR mechanism confirms that both have three degrees of freedom. Experiments with hardware prototypes of two representative 3-UPU designs, however, reveal an unexpected set of additional degrees of freedom—regardless of the platform configuration, when the prismatic joints are locked, the mechanism behaves as if it has additional degrees of freedom, rather than being a rigid structure as predicted by kinematic mobility analysis (see Fig. 2).

In this paper we first show that existing classifications of kinematic singularities fail to explain these redundant self-motions of the 3-UPU. We then show that this unexpected behavior can in fact be traced to minute clearances and manufacturing tolerances in each UPU assembly. Specifically, clearances in the bearing and shaft of each UPU assembly admit small torsional rotations about the leg axes, which in turn cause the gross motions of the moving platform. To show this we develop a more complete model that accounts for all possible infinitesimal motions of the