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Novel design solution to high precision 3 axes translational parallel mechanism

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The paper presents a 3 degree of freedom UPU mechanism having an excellent practical feasibility. The mathematical model and the design considerations of the 3-UPU mechanism are discussed. A detailed sensitivity analysis is carried out and the results are discussed in a new perspective. A novel design solution for a high precision three axis translation parallel mechanism is presented. We describe and validate the theoretical observations with the prototype model. The capability of the 3-UPU mechanism in performing fine motion manipulation, high precision trajectory following and metrological measurement is demonstrated. The performances of the 3-UPU mechanism concur with the theoretical observations in contrast to what is presented in previous works.

1. Introduction

Spatial 3 degree of freedom pure translational mechanisms are mostly employed in the industry. Most of them are serial based mechanisms and widely applied in 3-axis cranes, machining centers, coordinate measuring machines, etc. Only recently, 3-axis parallel mechanisms are making their entry in the industry through Delta robots in high speed pick and place applications. Tsai et al. [1] first proposed a 3-DOF based universal–prismatic–universal (UPU) kinematic chain. The fully parallel mechanism can exhibit high stiffness in most of the mechanism workspaces. The geometric conditions for a pure translational motion for a 3-UPU mechanism and workspace analysis are presented in [2] and [3]. Mobility analysis was well analyzed by Gregario and Parenti-Castelli [4]. Work on stiffness and deformation of a 3-UPU mechanism was carried out by Hu and Lu [5]. These interesting theoretical analyses made a strong case for feasibility of the simple and practical 3-DOF, fully parallel mechanism and have come to be known as the 3-UPU parallel mechanism. The 3-UPU mechanism is the particular mechanism of the most generalized 3-RRPRR mechanism, wherein in the first two and last two, the RR revolute joints are replaced with universal joints. There are very few research reports based on experimental results for a 3-UPU mechanism. The observations and negative results presented in Han et al. [6] and a reference to this in a survey by Merlet [7] raised the questions regarding the feasibility of 3-UPU parallel mechanisms. Later it was shown that the geometry of a 3-UPU mechanism developed by Han et al. [6] is in singularity by Walter et al. [8]. The theoretical models of Venanzi and Parenti-Castelli [9] and Meng et al. [10] came out with the results showing that the end effector position is very highly sensitive to the joint clearances. They have reported very high positional errors acknowledging the results of Han et al. [6] even in a non-singular geometry.

These results largely shifted the focus away from 3-UPU based parallel mechanisms despite sound theoretical assertions [1–5,8,11–14]. In an accuracy analysis with the joint clearance model given in Venanzi and Parenti-Castelli [9], the absolute sum of maximum of clearance of all the individual joint pairs constituting the mechanism is a highly unlikely scenario. The model does not consider the effect of geometry of the mechanism to arrive at the error at the output link. Adding the absolute values of the maximum errors in all the joints of the mechanism is an improper estimate and results in an unrealistically exaggerated value in closed loop mechanisms. Going by the conflicting results in theory and very fewer observations based on practical models, we chose to revisit the

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mechanism and build a theoretical model and validate it with stage wise prototype models and experiments. From the results, we show that the 3-UPU mechanism proposed by Tsai et al. [1] can have an excellent practical feasibility.

The paper deals with two important aspects of the 3-UPU mechanism. First is the sensitivity analysis of the mechanism and the second deals with the design, development and experimental validation of the 3-UPU mechanism. The kinematic model and sensitivity analysis are given in Sections 2 and 3. The design and development of a 3-DOF UPU mechanism based on the theoretical model is discussed in Section 4. Several sets of experiments are conducted to measure the performance characteristics of the 3-UPU mechanism. We discuss the experiments and results in detail in Section 5. We conclude the paper with an observation of excellent practical feasibility.

2. The 3-UPU mechanism kinematic model

Simple kinematic analysis suggests that the mechanism based on parallel architecture can possess high accuracy and repeatability. This is because, the end effector motion is generated by actuated links directly connected to the base. The simple kinematic analysis does not reveal the design challenges because of the high number of passive joints present in the mechanism. Therefore the influence of passive joint selection or design has to be critically considered in a manipulator design. It is shown in [2] that the 3-RRPRR, 3-DOF UPU mechanism under some geometric conditions results in pure translational motion. Each of the three legs of the manipulator connected to the base through two revolute joints and the platform through two revolute joints has to meet the following conditions

$$q_{i2} = q_{i4} \text{ and } q_{i1} = q_{i5}, (i = 1, 2, 3), \tag{1}$$

where, q_{i1} and q_{i2} are the unit vectors of passive revolute joint axes at the base and similarly q_{i4} and q_{i5} are the unit vectors of passive revolute joint axes at the platform. It can be seen in the later sections that the above conditions attained within the realm of practical considerations can result in a high precision manipulator.

Figs. 1 and 2 show the kinematic sketch and describe the manipulator parameters. The three base connection points are chosen to form an equilateral triangle and so are the connection points at the platform. The coordinates of all the points are defined with respect to a global coordinate system fixed at the geometrical center of the base O (XYZ) as shown in Figs. 1 and 2. The above straight forward choice is based on the symmetry. The plane formed by the connection points at the platform is parallel to the base. Let '*b*' be the side of the base equilateral triangle, and '*a*' be the side of the platform equilateral triangle. l_1, l_2, l_3 are the leg lengths connecting base connector point B_i to the corresponding platform point A_i, $i = 1, 2, 3$. $\hat{i}, \hat{j}, \hat{k}$ are the unit vectors along X, Y and Z axes. $(x, y, z)^T$ are the coordinates of the center of the platform from O (XYZ). The coordinates of the leg connection points at the base and the platform with respect to O (XYZ) are given by

$$B_1 = \left[\frac{b}{\sqrt{3}}, 0, 0\right]^T B_2 = \left[\frac{-b}{2\sqrt{3}}, \frac{b}{2}, 0\right]^T B_3 = \left[\frac{-b}{2\sqrt{3}}, \frac{-b}{2}, 0\right]^T \tag{2}$$

$$A_1 = \left[\frac{a}{\sqrt{3}} + x, y, z\right]^T A_2 = \left[\frac{-a}{2\sqrt{3}} + x, \frac{a}{2} + y, z\right]^T A_3 = \left[\frac{-a}{2\sqrt{3}} + x, \frac{-a}{2} + y, z\right]^T. \tag{3}$$

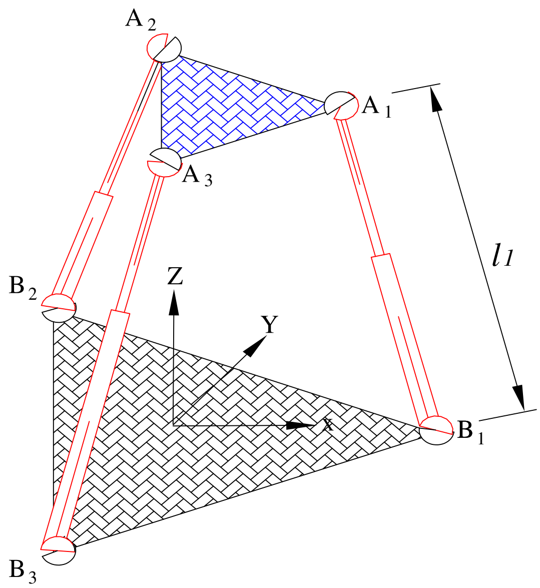

Fig. 1. 3-DOF UPU mechanism.