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Non-spherical ball-socket joint design for Delta-type robots[☆]

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ABSTRACT

Delta-type robots are commonly used for positioning purposes in medical surgery. In such applications, the loading position accuracy of the end effector is of critical importance. However, the positioning accuracy is determined by the loading deflection, which depends in turn on the link flexibility and joint clearance within the system. Importantly, the loading deflection is posture/position dependent. This characteristic greatly complicates the task of improving the positioning accuracy using traditional compensation control methods. Accordingly, the present study proposes a non-spherical ball-socket joint design to improve the loading stiffness of the robot over the entire workspace. An analytical model is derived to quantify the loading deflection as a function of the link flexibility and joint clearance. The experimental results show that the non-spherical ball-socket joint design reduces the total variation in the loading deflection of the end effector by up to 81.04% compared to that of a traditional robot with spherical ball-socket joints when performing positioning over the entire workspace at the assigned height.

1. Introduction

Parallel manipulators have a high stiffness and a superior dynamics performance as a result of their closed-chain configuration. Among the various translation parallel manipulators available, Delta-type robots, proposed by Clavel [1], are one of the most commonly used for high-speed pick-and-place tasks and medical-assistance positioning applications. In the latter case, the medical instrument mounted on the end effector increases the load imposed on the robot structure, and therefore affects its positioning performance. In medical applications such as joint-replacement surgery [2–3], the milling plane of the bone and the positioning of the puncture operation must be precisely controlled in order to ensure the success of the operation. As a result, an extremely high positioning accuracy of the end effector is required. Thus, in designing Delta-type robots for medical tasks, accounting for the effects of link stiffness and joint clearance in a quantitative manner is a crucial concern.

The literature contains many investigations into the fundamental properties of parallel manipulator robots. For example, Laribi et al. [4] proposed a genetic algorithm based optimization method for minimizing the dimensions of a DELTA robot for a given workspace. However, as with all parallel manipulator systems, the loading deflection of Delta-type robots is dependent on the stiffness of the various links. Importantly, the stiffness is position dependent, i.e., it varies over the workspace, and therefore has a non-constant effect on the loading deflection of the end effector. Furthermore, the loading deflection of the end effector is also affected by the joint clearances in the system since anything other than a zero clearance induces a backlash effect which degrades the positioning accuracy. As a result, effective methods for quantifying the effects of the link stiffness and joint clearance on the positioning accuracy of Delta-type robots are required.

Various stiffness models of parallel manipulators have been proposed based on such techniques as Finite Element Analysis [5–6] and matrix structural analysis [7–11]. However, these models generally ignore the effects of joint clearance. Haines [12] reviewed previous studies on the two-dimensional motion and impact behavior of unlubricated revolute joints with clearances. Schwab et al. [13] estimated the peak contact force in rigid and elastic mechanical systems using continuous contact force models and an impact model. Bauchau and Rodriguez [14] presented an approach for modeling the effects of joint clearance and lubrication on the dynamic response of flexible multibody systems. Wu et al. [15] analyzed the kinematics and workspace properties of parallel manipulators and proposed a model for quantifying the effects of joint clearance on the positioning performance. However, the studies in [12–15] consider planar mechanisms, and thus the findings cannot

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be generalized to Delta-type robots, which have three (or more) degrees of freedom (DOFs). Furthermore, existing studies on the effects of link stiffness and joint clearance take only a qualitative approach. Thus, further work is still required to investigate the quantitative effects of link stiffness and joint clearance on the positioning performance of parallel manipulator systems.

The human hip joint is a classical ball-socket joint with three rotational DOFs. Over thousands of years, the hip joint has evolved into a non-spherical form in order to better support the loading pressure of the trunk [16–18]. Drawing on the human hip joint for inspiration, this study designs a non-spherical ball-socket joint for Delta-type robots in order to improve the structural stiffness and positioning accuracy. In the proposed design, the socket has a conventional semi-circular profile. However, the ball has a non-spherical contour. Thus, the clearance between the ball and the socket varies depending on the relative position between them. In particular, the geometry of the non-spherical ball is designed in such a way as to optimize the clearance between the ball and the joint in the exerted direction so as to minimize the difference in the loading deflection as the robot system performs motion in the local workspace. In determining the optimal ball contour, the coupled effects of the flexible links and joint clearance on the loading deformation are determined using a self-written MATLAB program. The optimal clearance in the exerted direction is then determined for a given workspace and positioning height using an iterative solution procedure programmed in MATLAB. Finally, the computed clearance values are used to modify the profile of a spherical ball with a nominal radius in order to obtain the geometry of the non-spherical joint.

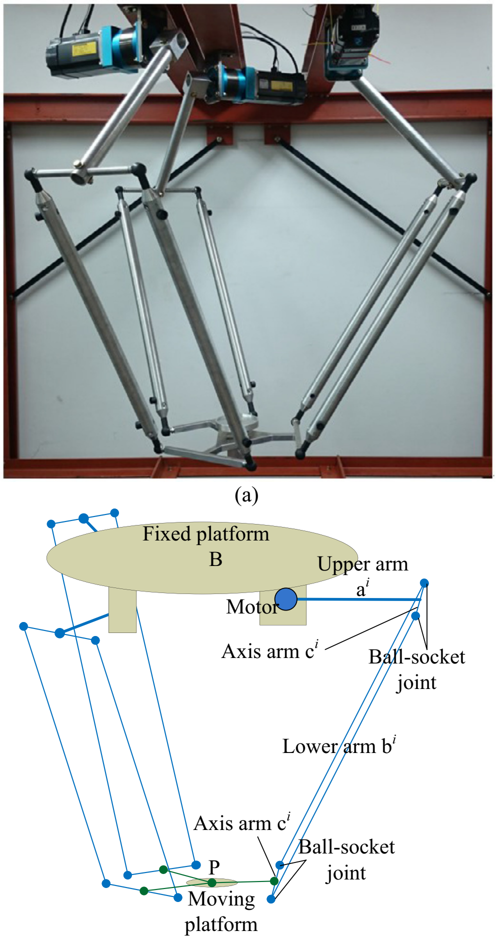
The remainder of this paper is organized as follows. Section 2 describes the structure of the Delta-type robot. Section 3 designs the non-spherical ball-socket joint based on a quantitative analysis of the loading deflection of the Delta robot end effector subject to link stiffness and joint clearance effects. Section 4 presents and discusses the numerical and experimental results. Finally, Section 5 provides some brief concluding remarks.

2. Structure of delta-type robot

The Delta-type robot considered in the present study consists of a fixed platform, three actuators (motors), three linkages, and a moving platform. The fixed platform is assumed to be a rigid body and each linkage is assumed to comprise five flexible links connected by ball-socket joints with clearances. Finally, the moving platform is assumed to be composed of three flexible links (see Fig. 1).

In the methodology proposed in this study, the flexibility of the links is modeled using a matrix structural analysis technique. As shown in Fig. 1(b), the ith linkage ($i = 1, 2, 3$) consists of an upper-arm a^i, two lower-arms b^i and two axis-arms c^i. In analyzing the loading deflection of the robot, each link is modeled as a two-nodal flexible beam element. The ith linkage is thus modeled using 12 nodes, i.e., (1) nodes 1^i and 2^i for arm a^i; (2) nodes 6^i, 7^i, 8^i and 9^i for arms b^i; and (3) nodes 3^i, 4^i, 5^i, 10^i, 11^i and 12^i for arms c^i. The ith linkage ($i = 1, 2, 3$) is connected to the moving platform at node 13^i. Finally, the center point of the moving platform is denoted as P (see Fig. 2).

For each linkage, the upper axis-arm is fixed to the upper-arm via nodes 2^i and 4^i, and the lower axis-arm is fixed to the moving platform via nodes 11^i and 13^i. In addition, the two axis-arms c^i and two lower-arms b^i form a parallelogram, in which the arms are connected by four passive rotational joints, denoted as $\mathrm{J}^i_{3,6}$, $\mathrm{J}^i_{5,8}$, $\mathrm{J}^i_{7,10}$ and $\mathrm{J}^i_{9,12}$, respectively. The joints are assumed to be ball-socket joints with either a spherical design (traditional Delta-type robot) or non-spherical design (improved Delta-type robot proposed in this study). In general, ball-socket joints provide 3-DOF motion, in



(a)

(b)

Fig. 1. Delta-type robot: (a) photograph; and (b) schematic illustration.

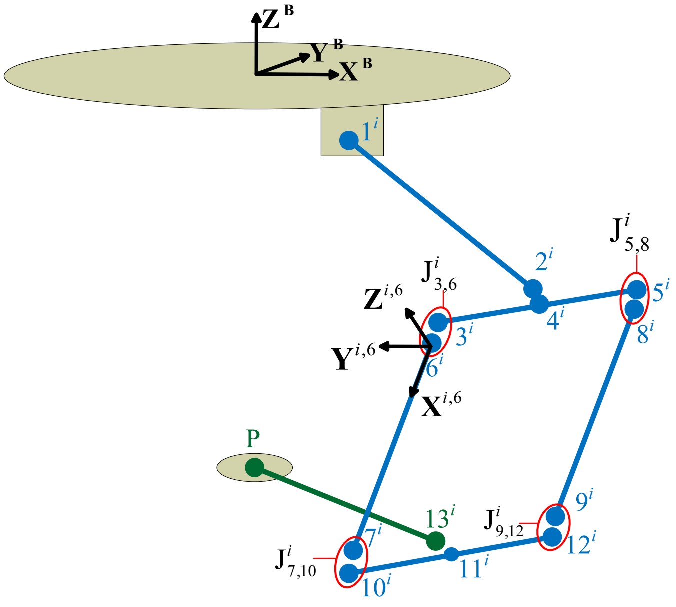


Fig. 2. Definitions of nodes and nodal coordinates.