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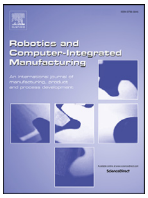

Modeling, design and experiment of a remote-center-of-motion parallel manipulator for needle insertion

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ABSTRACT

In surgical procedures such as brachytherapy, biopsies and drainages, how to precisely place the needle inside the body is crucial for the performance of such surgeries. In last two decades, robot-aided needle placement has gradually been a trend for better security and accuracy. However, existing successful medical robot systems leave some common drawbacks: expensive, bulky, and high operation complexity, which motivates the development of more compact, affordable, and functional robots. This paper introduces a novel robot based on a 2-CRRR-CRR parallel manipulator (PM) for single needle insertion with high accuracy, where C denotes a cylindrical joint and R a revolute joint. Via screw theory, the mobility of the robot is analyzed, which meets the requirement of remote-center-of-motion (RCM). Its kinematic analysis is presented and singular configurations are identified based on the Jacobian matrix. Furthermore, the link dimensions of the robot are optimized by considering motion/force transmissibility and practical limits to generate singularity-free and high-performance workspace around the incision point. The design and feasibility of the proposed robot are validated by preliminary motion experiments with a prototype. The two advantages of the proposed robot are a singularity-free workspace with good motion/force transmissibility and high rigidity due to three fixed linear actuators in parallel architecture.

1. Introduction

Medical robots have shown impressive potential because of their safety, higher efficiency, less pain, etc., compared to their human counterparts [1,2]. These benefits basically stem from exquisite design of kinematic and control system of robots [3,4]. Surgical operation such as minimally invasive biopsies, brachytherapy, and cryotherapy are done through one incision, which requires three rotational DOFs (sometimes less than three rotational DOFs in special clinical applications such as percutaneous needle insertion [1,5]) around the incision and one translational DOF for inserting the surgical tool. Besides, the surgical robot should be kept a distance from the incision entry, therefore such a motion is known as the remote center-of-motion (RCM) [6].

Theoretically, a general high-DOF serial robots provides enough dexterity and large operation workspace. However, keeping the end-effector working through a pivot and limiting unexpected motions steadily demand reliable and delicate control strategy [7,8]. When control failure occurs caused by surgeon, patient or the robot itself, security issues like tissue trauma and bacterial infection can be thorny problems.

Therefore, most medical robots such as da-Vinci [9] are mechanically constrained for safety and rely on hybrid structure: the arm is serial for large workspace while the wrist is special-designed to perform RCM. The structures of existing RCM mechanisms are diverse: parallelograms [9-11], spherical linkages [12], gear train [13], etc. More elaborate information about classifications are well documented in [1,14,15]

An alternative is adopting low-mobility parallel manipulators due to its mechanically constrained mobility to perform RCM. A RCM parallel manipulator is more reliable since the injury risk from unexpected control failures is minimized by the structure inherently. They also have lower movement inertia, higher stiffness and precision, which are good properties for efficient operations. A fully-decoupled parallel manipulator was presented in [6], where its kinematics and singularities were studied. Li et al. [16] proposed an type synthesis approach based on intersecting motion planes for RCM mechanisms. Navarro et al. [17] proposed a 3U$\underline{P}$S-1S parallel structure to generate small spherical wrist for laparoscopic surgery. Yousef et al. [18] designed a compact parallel mechanism, which realizes reorientation of the surgical tool conveniently and achieves small-scale movement for precision manipulation. Bebek et al. [19] developed a light-weight 5-DOF parallel robot, SABiR, for needle insertion on small animals. The robot is composed of a double parallelogram system and a syringe mechanism to implement dexterous alignment of needles, and it realize high accuracy through kinematic calibration procedure. Two generations of surgery robots: the parallel structure PARASURG 5 M [20] and later the parallel hybrid robot PARASURG 9 M [21] were designed in Romania by Doina Pisla et al. Besides,

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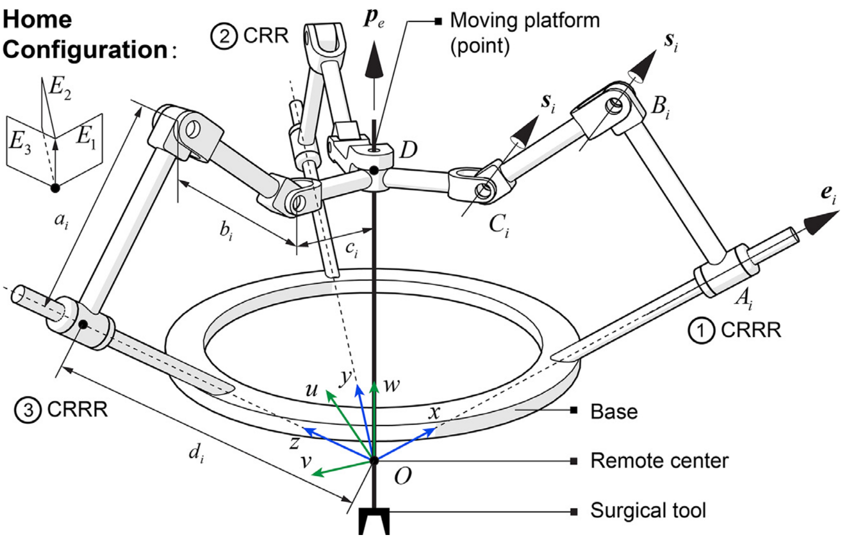

Fig. 1. CAD model of the 2-CRRR-CRR PM (at the home configuration).

they also proposed a needle placement robot with CT-scan compatible device [22]. Shao T. Liu et al. [5] presented a novel prototype of arm based on dual-triangular mechanism, by which the arm footprint is reduced with sufficient workspace guaranteed. Essomba et al. [23] proposed a compact spherical wrist for minimally invasive surgery (MIS) procedure, and then L. Nouaille et al. [24] proposed specialized indices, and applied them to present an dimensional optimization approach for the proposed MIS robots. However, most of these RCM PMs are actuated by rotational actuators or movable prismatic pairs. The number of available RCM PMs with fixed linear actuators are very limited. It is worth noting that fixed linear actuators are generally preferred in design of a parallel manipulator for reduced moving mass, higher rigidity and load capacity.

Another major concern when designing an RCM PM is to reduce singularity and improve dexterity in a prescribed workspace, which is related to dimensional parameters of links and usually done in the phase of kinematic design. Some indices have been proposed to guide dimensional optimization: manipulability (Yoshikawa T, 1985 [25]), dexterity (Klein CA, 1987 [26], Angeles J, 2002 [27]), global dexterity (Gosselin C, 1991 [28]), etc. These indices are based on the Jacobian of a robot, which either are only effective for serial structure or suffer from unit inconsistency when dealing with robots with mixed mobility. Although some literatures have provided methods for generating dimensionally homogeneous Jacobian [29,30], the use of Jacobian-based indices should be very careful in a general sense [30,31]. Another type of performance index characterizes the motion/force transmission based on the screw theory [32]. Based on the concept of instantaneous power (Ball [32]), this type of indices [33-35] concerns the interaction of velocity and force/torque simultaneously. Further, Wang and Liu et al. [36] introduced the transmission wrench screw into generating local transmission index (LTI) for configuration-dependent evaluation and global indices for design process [37]. This index is applicable to PMs with mixed DOF and can also describes the closeness to singularity of a PM. Nevertheless, there is few kinematic designs of RCM PMs which consider motion/force transmission.

In review of these considerations, the goal of this paper is to present a novel RCM PM with fixed linear actuators for single needle insertion and address its analytical modeling and optimal design focusing on motion/force transmission. A prototype was built to perform experiments to validate the theoretical results. The advantages of the proposed RCM PM are their inherent high rigidity produced by fixed linear actuators and a singularity-free workspace with good motion/force transmissibility, all of which are important concerns when designing an RCM PM. The paper is organized as follows. Section 2 gives the introduction of the RCM robot. Section 3 is dedicated to the mobility analysis of the 2-CRRR-CRR PM. Section 4 deals with the kinematic model, including coordinate setting, inverse kinematics, and velocity analysis. Section 5 investigates the identification of singularities. A design of dimensional optimization is presented based on the motion/force transmission indices in Section 6, which is followed by the generation of optimized workspace in Section 7. Section 8 presents the prototyping and the experiment results, and the conclusions are given in the last section.

2. System description

The proposed 2-CRRR-CRR PM is shown in Fig. 1. Linear actuators are installed in cylindrical joints, which provide higher stiffness and load capacity. The manipulator consists of one CRR limb, two CRRR limbs, a fixed base and a moving platform to which the surgical tool is attached.

The axes of the cylindrical joints in three legs are perpendicular to each other and intersect at a common point O. For the i^{th} limb, a plane, denoted as E_i, is generated by orthogonal links OA_i and A_iB_i. The axes of revolute joints located on points B_i and C_i are parallel to each other and vertical to plane E_i, hence three limbs are mechanically restricted in associated planes. Each plane rotates about the axis of the corresponding cylindrical joint. Three planes make an intersecting line OD, and the moving platform is degenerated to point D. The axis of the surgical tool coincides with OD and passes through the fixed point O.

Then, a novel hybrid surgical robot can be constructed by installing a 2-CRRR-CRR PM on three gantries connected to the operating table, as shown in Fig. 2. This gantry-mounted system provides supplementary positioning guidance to place a needle along three directions rather than the patient's body. What we focus is the 2-CRRR-CRR PM and the characteristics of the hybrid manipulator are out of the scope of this paper.

3. Mobility analysis

In this paper, the terminology of screw theory [32] is adopted. A unit screw, **$**, is defined as

$$\$ = (\boldsymbol{s}; \boldsymbol{s}_0)^{\mathrm{T}} = (\boldsymbol{s}; \boldsymbol{r} \times \boldsymbol{s} + h\boldsymbol{s})^{\mathrm{T}} = (l \quad m \quad n; \quad p \quad q \quad r)^{\mathrm{T}}, \tag{1}$$

where $\boldsymbol{s}$ denotes the direction of the screw axis, $\boldsymbol{r}$ the line moment of $\boldsymbol{s}$, and h the pitch.

As shown in Fig. 1, a fixed coordinate frame O-xyz (denoted as $\{M\}$) is established, with axes x, y and z coinciding with $\overrightarrow{OA}_1$, $\overrightarrow{OA}_2$ and $\overrightarrow{OA}_3$, respectively. With respect to frame $\{M\}$, the position vector of point B_i