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Design and kinematic analysis of 3PSS-1S wrist for needle insertion guidance☆

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ABSTRACT

In this work it is presented a complete kinematic analysis of the 3PSS-1S parallel mechanism for its implementation as a spherical wrist for a needle insertion guidance robot. The spherical 3PSS-1S mechanism is a low weight and reduced dimension parallel mechanism that allows spherical movements providing the requirements needed for the serial–parallel robotic arm for needle insertion guidance. The solution of its direct kinematic is computed with a numerical method based on the Newton–Raphson formulation and a constraint function of the mechanism. The input–output velocity equation is obtained with the use of screw theory. Three types of singular postures are identified during simulations and verified in the real prototype. The 3PSS-1S can perform pure rotations of ±45°, ±40°, ±60° along the ***x***, ***y***, ***z*** axes respectively.

1. Introduction

Contemporary medicine is toward less invasive and more localized therapy [1], mainly known as Minimally Invasive Surgery (MIS). One of this procedure is the percutaneous insertion of needles and catheters for biopsy, drug delivery and the placement of internal fiducials as surrogate for tumor location within the body.

Needle insertion intervention offers several advantages over traditional surgery, including less scarring, lighter anesthesia, reduced postoperative pain, reduced complications, and faster discharge from the hospital.

Currently, the conventional needle insertion procedure is a free-hand task with no exact reference for the entry point nor the direction of the needle. This is because the planing insertion process is based on the recognition of markers that the surgeon must place over the patient during the imagining session for further trajectory planning.

This methodology lacks accuracy and it is very common to make several erroneous insertions until the needle reaches the desired target, which may lead to internal hemorrhage and severe complications.

Robotic technologies can enhance the effectiveness of clinical procedures by coupling many information sources, such as volumetric medical images and perform complex actions in the operating room as reported in [2–6]. Particularly, a robotic device can insert needles with consistent accuracy and can overcome some of the shortcomings of the manual approach as mentioned in [7–12].

In this work we introduce the concept of a novel hybrid (serial–parallel) robotic arm for needle insertion guidance. The spherical parallel wrist is an improved version of the 3PSU-1S manipulator, whose dimensional synthesis was first reported in [13]. A discussion on the design and main attributes of the robot is presented. Then, the inverse and forward kinematics of the spherical wrist is stated, and a complete analysis of its singular configurations is detailed. Finally, the kinematic properties of the improved design are verified in the real enhanced spherical wrist prototype.

1.1. Needle insertion task requirements

During an insertion procedure, the surgical instrument must maintain a pre-planned path, defined by two points: the target point and the entry point. The first one, is where the tip of the instrument must reach, and the last one is where the needle is inserted into the patient (see Fig. 1(a)). The latter one is selected

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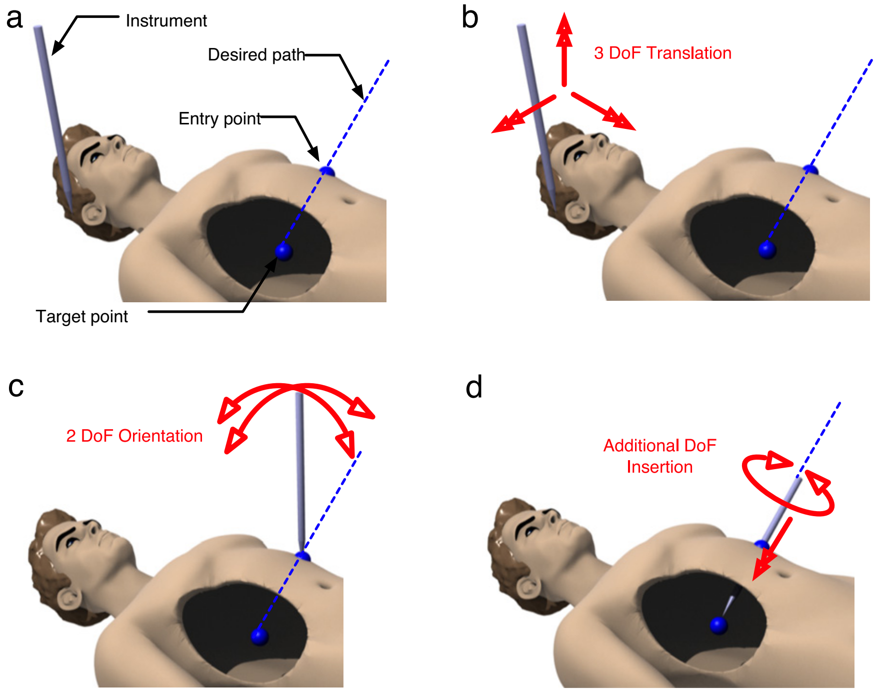

Fig. 1. Insertion procedure. 1(a): Trajectory definition. 1(b): Instrument's positioning. 1(c): Instrument's orientation. 1(d): Instrument's insertion.

in order that the desired path of insertion does not interfere with organs nor bones.

The insertion procedure can be summarized in the following steps. First, the tip of the needle must be placed at the entry point. This task requires 3 DoF (see Fig. 1(b)), then the needle must be aligned with the desired path, requiring at least 2 more DoF (see Fig. 1(c)). Once that the needle is correctly placed and aligned with the desired path at the entry point, the insertion procedure begins, generally with a twisting movement of the needle (see Fig. 1(d)).

Therefore, if the insertion is performed manually, a robotic device implemented as a guidance tool (i.e. it keeps the position and orientation) only requires 5 DoF.

However, if the insertion procedure is performed autonomously by the robot, it is preferable an additional DoF for the mechanism, since with 5 DoF only one reachable configuration is possible for each point of the desired path, resulting in a screw-like movement during insertion.

1.2. Overview of the mechanism

A robotic assistant must be carefully designed, in order to be accurate as well as rigid. Parallel mechanisms offer these physical properties, and some author have proposed them for the robotic needle insertion guidance [14–16]. However, the main drawback of a parallel mechanism is their reduced workspace. Although serial mechanisms overcome this problem [17], they present a real challenge in order to actuate the last DoFs of the mechanism without introducing backlash (due to the transmission system) or excessive load (direct transmission) at the end effector.

Therefore a better approach would be a design with a decoupled kinematic composed of a serial chain designed for the positioning and a low weight parallel wrist designed for orientation. The concept of this hybrid mechanism is presented in Fig. 2(a) (patent pending). As it was mentioned above, the mechanism consists of two main parts: the 3R serial arm and the spherical parallel wrist. The arm is mounted over a non-actuated sliding base that permits a gross positioning of the mechanism. A holding device supports the instrument at the end effector.

1.3. Design of the parallel spherical wrist

The principal criterion adopted for the design of the wrist mechanism is that, it will be coupled to the distal extremity of a serial arm. Thus, this mechanism must be compact, reduced size and light weight.

The general needle insertion procedure requires at least 5 DoF: 3 DoF for the global positioning of the needle and 2 DoF for its correct orientation.

Even though an spherical wrist is redundant for the orientation task, this characteristic is preferable since it will allow different postures of the mechanism for a given trajectory. Furthermore, in an autonomous insertion, the extra DoFs will help to overcame problems related to tissue deformation during the insertion, by correcting the altered trajectory.

The design of a spherical parallel mechanism has been largely studied [18–20] and there exists many approaches for its synthesis [21–23]. However, given the ease of its implementation, a mechanism based on a passive spherical pair and three identical controlled spatial legs is applied in this study.

The 3$\underline{P}$SS-1S is a four legs parallel mechanism, where the passive leg imposes the spherical movement pattern, controlled by three PSS type legs (prismatic–spherical–spherical chain) with the prismatic pair actuated. In a first approach [13] a PSU type leg was implemented but the universal pair had a reduced range of work, and tended to block the leg in several postures. Therefore, an extra degree of freedom was added to the kinematic chain, turning the leg into a PSS type (see Fig. 3).

2. Materials and methods

The kinematics of the 3$\underline{P}$SS-1S is essentially the same of the 3$\underline{P}$SU-1S (see [13]), since the extra revolute joint in each leg does not alter its kinematics. However, the inverse and instantaneous kinematic model of the SPM is presented again for clarity.