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Design and optimization of a 2-degree-of-freedom planar remote center of motion mechanism for surgical manipulators with smaller footprint

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ABSTRACT

This paper presents a new remote center of motion (RCM) mechanism design for Minimally Invasive Surgery (MIS) robotic manipulators, capable of providing two important degrees of freedom (DoFs) — pitch and translation — purely through its mechanism design. Novelty of the proposed design is that it offers a significantly smaller footprint compared to the existing state-of-the-art 2-DoF planar RCM mechanisms. We describe the design, perform kinematic analysis, and use simulation to validate its RCM capability. The design is also optimized using manipulability and tool translation to achieve maximum kinematic performance with smallest size of the proposed mechanism. A comparison between the mechanism workspace and the required workspace shows that the proposed design meets the MIS workspace requirements. Optimization results demonstrate that the proposed design offers same kinematic performance as of an exiting design, but with a significantly smaller footprint. Compact distal-end and smaller footprint make the proposed design ideal for applications requiring multiple manipulators to operate in close proximity.

1. Introduction

Minimally Invasive Surgery (MIS) is an innovative surgical technique which involves use of long and thin surgical tools. These tools, called laparoscopic instruments, are inserted in the patient body through small holes, called *incisions* (Fig. 1). MIS is widely practiced in modern operation theaters due to its minimally invasive nature which provides numerous advantages over the traditional open surgery methods [1–4]. However, surgeons find MIS challenging to perform mainly due to the unintuitive tool movements and the uncomfortable posture required to hold the surgical tools [5,6]. The unituitive tool movements are caused by the fact that the surgical tools remain constrained at the *incision* point during the operation.

To help surgeons perform MIS with ease and greater control, robotic manipulators have been used as a means to increase dexterity and ergonomics. For this purpose, researchers have developed a special kind of mechanical mechanisms, called remote center of motion (RCM) mechanisms, which provide a virtual hinge point on the distal-end of a robotic manipulator. This virtual hinge (called RCM point) mimics the *incision* constraint present in the manual MIS.

Since the advent of surgical robots in 1980s, planar remote center of motion (RCM) mechanisms have been a popular choice for MIS robotic manipulators [7]. A number of surgical manipulators [8–14] have been designed and developed using

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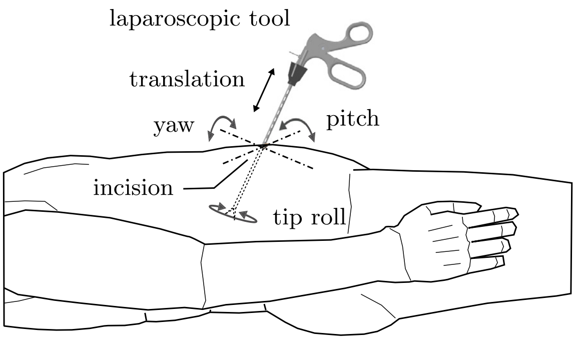

Fig. 1. DoFs required at the incision point in a typical MIS procedure: pitch, yaw and translation. Another DoF, roll, can be implemented at the tip of surgical tool, as shown in the figure.

a particular planar RCM design, called Double-Parallelogram (DP) RCM mechanism. A well-known example of this is the da Vinci surgical robot [8], which has been successfully used for various MIS procedures around the world [15,16].

From kinematics view point, MIS requires at least three DoFs (pitch, yaw and translation) at the *incision* point, as shown in Fig. 1. Among these, pitch and translation are considered as the most-important DoFs [17] due to a number of reasons. Both DoFs are executed more often than the yaw, and require larger execution forces and higher resolution of the surgical tool movement. Especially, the translation DoF demands highest forces (up to 20 N), and largest travel distance (15–30 cm) [11,18]. By virtue of its location, which forces it to always pass through the incision (RCM point), translation DoF also bears the reaction forces caused by tool operation in other DoFs as well. This makes translation DoF further critical in a surgical manipulator design.

However, the widely used traditional planar RCM mechanisms, including the DP mechanism of the da Vinci surgical robot, offer only one degree of freedom (DoF) — pitch — purely through their mechanism design [17]. The other important DoF — translation — is often realized by installing some *external means*, such as cable-pulleys or actuators directly mounted on the distal-end of a manipulator [17]. In case of da Vinci surgical robot, for example, the translation DoF is implemented using a complex web of cables and pulleys. These cables run from the proximal-end (base) right up to the distal-end of the manipulator [8]. In other designs, such as [11,12], it is realized by mounting actuators directly on the distal-end of manipulator. In both design approaches, the pitch DoF is achieved through RCM mechanism, but the translation DoF is realized using one of the *external means* mentioned above.

Use of these *external means* to realize translation DoF has several negative effects on the manipulator performance. It increases the design complexity, and (depending on the nature of external means used) may affect the overall compactness of the distal-end. For example, use of cable-pulley scheme complicates the overall design and reduces the operational life of a manipulator. It also increases the joint friction and makes it challenging to maintain an appropriate tension in the metallic cables for longer operational periods. Use of cable-pulley scheme also decreases the power transmission capabilities of the robot [19]. On the other hand, actuators mounted directly on the distal-end increase its size and weight. This consequently increases the torque and energy requirements of a surgical manipulator. A heavier distal end could easily induce vibrations at the tool tip.

To avoid the problems discussed above, a number of new 2-DoF planar RCM mechanisms [13,17,20] have been proposed in recent years. These mechanisms (described in next section) provide pitch and yaw DoFs at the incision point purely through their mechanism design. Contrary to the 1-DoF RCM mechanisms, these designs achieve translation DoF by virtue of their mechanism design and, therefore, do not rely on the *external means* discussed above. However, with capability to produce translation DoF through their design, the 2-DoF RCM mechanisms have a significantly larger footprint (space required to setup and operate) than the 1-DoF RCM designs. Larger footprint means more space is required to setup and operate a manipulator. This issue becomes even more significant in the case of MIS, where multiple (three or more) manipulators are required to complete a surgical procedure in a relatively confined space.

To solve this problem, we propose a new RCM mechanism design which offers the two most important DoFs — pitch and translation — through its mechanism design, but with a considerably smaller footprint. Novelty of the design lies in the fact that it achieves the pitch and translation DoFs by virtue of its mechanism design, and offers a smaller footprint without sacrificing the kinematic performance. As the proposed design does not rely on any *external means* to achieve translation DoF, it is supposed to offer a better operational performance than the existing state-of-the-art 2-DoF RCM designs. We also validate the RCM capability of the proposed design through simulation. To achieve the maximum kinematic performance with smallest size of the manipulator, an optimized design of the proposed mechanism is also presented.

To describe the proposed design and its optimization, this paper is divided into six sections. After a brief introduction in Section 1, Section 2 describes the existing state-of-the-art 2-DoF planar RCM designs. Their features are highlighted and limitations are identified. The proposed mechanism design is described in Section 3, which includes the its kinematic analysis, validation of the RCM capability, mechanism singularities, and the workspace analysis. Section 4 describes the optimization procedure to achieve maximum kinematic performance inside the required surgical workspace. Section 5 summarizes the