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A cable linkage with remote centre of motion

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ABSTRACT

Mechanical remote centre of motion (RCM) mechanisms are often used to construct robotic minimally-invasive surgical manipulators, such that potential damage on the incision ports is eliminated. Current parallelogram-based RCM linkages (PB-linkage) typically have large footprints that compromise optimal surgical operations. A novel cable system with remote centre of motion is proposed to reduce the footprint. The RCM function of the cable system is proven mathematically. A new approach based on constraint analysis is conducted to determine the magnitudes of tension. The results are validated by finite element analysis, hence proves the use of constraint approach and the functioning of the cable system. Upon verification, the footprint of the cable linkage is compared to that of a PB-linkage in a simplified surgical scenario through three approaches. The quantitative analysis shows that the cable linkage has a smaller footprint in more than half of the design points in all approaches. A prototype is built for proofing the concept of the cable linkage.

1. Introduction

In a minimally-invasive surgery (MIS), the surgical instrument is constrained to have four degrees-of-freedom (DOF) through the incision port [1]: pitch, yaw, translation along the longitudinal axis and roll. The first three DOF in combine function as a spherical coordinate system to define the position of end-effector inside the patient's body. Remote centre of motion (RCM) mechanisms provide the two rotational DOF while permitting the surgical instrument to pivot around the incision port, hence eliminate potential damage to the incision port and promote the safety of MIS procedures [2].The RCM function refers to the capability of a mechanism to rotate its link(s) around a remote point without having a physical revolute joint at the point [3,4]. A remote centre (RC) can be constrained virtually or mechanically [5]. Mechanical RCM mechanisms are more reliable and considered suitable for clinical applications [3]. Mechanical RCM mechanisms that generate single RC and are applied on robotic MIS systems include isocentres [6], circular tracking arcs [7,8], parallelograms [9–14], synchronous transmissions [15] and spherical linkages [16]. In addition, there are RCM mechanisms that generate multiple RCs [17].

A commonly used approach to synthetise a two-DOF RCM mechanism is to combine a planar RCM mechanism with a revolute joint [3]. The axis of the revolute joint coincides with the one-DOF RC to add the second DOF. Such approach results in fully

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decoupled rotational DOF, whose benefits include reduced complexity in control, promoted level of confidence in safety as well as rapid and intuitive manual positioning of the entire mechanism or individual DOF [1].

The translational DOF required in the MIS applications is often achieved by mounting an independent translational mechanism on the two-DOF RCM mechanism. A typical example of such three-DOF mechanism is the clinically-approved da Vinci series robotic surgical system [11,18,19]. In other approaches, various types of RCM mechanisms that also provide translational DOF are explored [20–22]. However, these mechanisms have coupled DOF [20], or are relatively bulky in terms of the transverse dimension [21], or have large sweeping volume upon rotation of the planar RCM mechanism around the revolute joint, due to the large enclosed area by the outer boundary of the planar RCM mechanism [22].

The parallelogram-based structure is widely used as the planar RCM mechanism in the robotic MIS systems [3]. However, there are footprint issues associated with the parallelogram-base linkages (PB-linkage), which the consequences being poor access for bedside assistance [19] and the compromise in optimal surgical functioning [23]. The term “footprint” is mostly referred to as the sweeping volume of the RCM mechanism, which is generated by the rotation of the planar RCM mechanism around the revolute joint. The sweeping volume is thus related to the area enclosed by the outer boundary of the planar RCM mechanism.

When the output link of the parallelogram is short, the output joint of the PB-linkage is positioned closely to the incision ports. Given that the space around an incision port is often crowded with robotic or manual surgical tools, the collision-free workspace is reduced and the chance of interference is increased. The transmission for the translational mechanism mounted on the output link of the PB-linkage goes through the output joint, causing further expansion in size.

In opposite case where a longer output link is used to displace the output joint away from the mechanism, the size of the parallelogram and thus the enclosed area is increased. The consequence being the increase in the sweeping volume, which again leads to increase in chance of interference. Apart from the sweeping volume, longer links occupy more space even when the linkage is stationary. It also increases the weight and inertia of the system. Quantitative analysis on the footprint of the PB-linkage though three approaches is presented in Section 5.

This paper proposes a cable linkage with RCM, in the attempt to address the footprint issue associated with the PB-linkage. The entire RCM mechanism is kept relatively faraway from the RC, when the distance between the input joint and the RC is given. A cantilever is rigidly mounted on to the output link. It is the only part of the entire RCM mechanism that is operated near the RC. Therefore, the cable system can leave more collision-free workspace for the neighbouring robotic surgical arms or human surgeons to operate. In addition, the enclosed area of the planar RCM is relatively small, resulting in a smaller sweeping volume. Further, the links are relatively short, which reduces the space taken by the links when stationary, and potentially reduce the weight and inertia of the mechanism. A comparison between footprint of the proposed linkage and the PB-linkage is presented in Section 5.

Cable-pulley mechanism provides advantages such as structure simplicity, compactness, light weight, low friction and low backlash [24]. Therefore it is widely applied on serial and parallel robotic manipulators, as summarised in [25] and [26], respectively. In MIS applications, the evolution from linkage-based da Vinci system [11] to cable-based da Vinci systems [18,19] shows significant deduction in the size of linkage. As such, the proposed planar RCM mechanism is developed based on cable-pulley mechanism.

Cable tension analysis is essential for proof of functioning of the cable linkage. Approaches for describing cable tension of cable-constrained open-chain linkage and multi-link parallel manipulator are available in [27] and [28], respectively. However, a more generalised approach based on mechanical constraint [29] is used in the analysis. The reason being that the proposed linkage is based on four-bar linkage and is affected by the singularity of an unconstrained four-bar linkage. The constraint approach provides indication on the constraint status of the mechanism, thus enable justification on the removal of singularity. The cable tension is solved as generalised force along mechanical constraints. Numerical solution of cable tension is obtained using QR decomposition and verified with static finite element simulation in ANSYS.

The rest of the paper is arranged as follows. Section 2 describes the design of the cable linkage and the proof of the RCM function. Section 3 applies the constraint-based analysis. Constraint equations are derived. Cable tension is solved and verified with finite element analysis. The functioning of the cable loops is hence proven. Section 4 calculates the minimum required cable stiffness to achieve a given overall stiffness of the linkage. Section 5 compares the footprints of the cable linkage and PB-linkage in a simplified surgical scenario. Section 6 introduces the prototype of the cable linkage.

2. The cable linkage with RCM

In this section, the design of cable linkage with RCM is presented, along with the proof of RCM under the condition that the cable is in tension.

2.1. Design of cable linkage

The design of the cable linkage with RCM is illustrated in Figs. 1 and 2, where the schematic diagram of links (without cable loops) and the full schematic diagram are presented, respectively. The cable linkage consists of eight links and seven pulleys that are arranged in three cable loops. As illustrated in Fig. 1, the links are AF, AC, CE, EH, BG, DG, CI and IG, respectively. Joint I is a passive prismatic joint while all other joints (indicated by the small circles) are revolute joints. Note that joints B and D do not divide links AC and CE, respectively. For convenience, links CI, IG and passive prismatic joint I are grouped and termed “diagonal link CG” in the later descriptions. Different configurations of the cable linkage are presented in Figs. 3 and 4. ROM in