Design of a Robotic Manipulator for Minimally Invasive Surgery

Abstract

With the integration of Minimally Invasive Surgery (MIS) and Robotics, the capabilities of a surgeon became far better than with MIS alone. It is learnt that a double parallelogram-based remote center-of-motion (RCM) mechanism is most widely used for the realization of MIS robots. In the present research work, it is noted that the mechanical design of these devices needs to be improved further by addressing the problems arising because of the inevitable constraints of their manufacturing and assembly, and refining their transmission design. While modeling the kinematics of such mechanisms, classically, it is assumed that the opposite sides of constituting parallelograms are equal. Consequently, the modeling procedure becomes simple and the RCM remains invariant with the in-plane motion of the mechanism. In addition, the surgical instrument does not exert any force on the incision site, during an MIS procedure. However, in actual practice, it is not true on account of the mentioned constraints which deliver erroneous (unequal) link parameters. It leads to the RCM deviation which in turn results in the surgical instrument tip deviation as well. Thus, instrument force at the entry point to the patient's body becomes non-zero and hence, degrades patient safety. Further, it is important to add that in control-based RCM mechanisms, RCM adjustment is possible using various control strategies. However, it is not feasible for mechanically constrained RCM devices as the error gets enforced into the physical structure (closed-loop) of the mechanism. In addition, the combined use of spring and screw elements in the tendon-based actuation of such devices is missing in the literature. And, the concept of invariant tendon length demands an investigation to quantify the effect of said constraints. Furthermore, there is a need for the improvement of tendon drive design to avoid sharp bends of the tendon element. Moreover, there is a strong demand for cost-cutting design techniques without any compromise with desired device features such as safety, accuracy, and precision. The present thesis has systematically addressed all of these issues and proposed solutions that not only enhance the device design but also offer several ways to realize an economic design. The concept of link parameters inequality and an accurate kinematic modeling technique have been introduced for the parallelogram-based RCM mechanisms. It is followed by the compliant mechanism-based design of an integrable and hysteresis-free RCM Adjustment System for mechanically constrained RCM devices. In addition, a systematized method/algorithm of RCM adjustment has been proposed. Further, a dedicated mechanism for tension adjustment in tendon-driven RCM mechanisms has been introduced, characterized, and demonstrated. The analytical and physical validations have been performed which justified the effectiveness of the introduced concepts. Furthermore, the effect of the prescribed constraints on the transmission design of distal DoFs has been investigated. Moreover, the present research work has adopted and enhanced the cable drive design of the proximal DoFs of the mechanism under consideration. Finally, the design of a double-parallelogram-based RCM mechanism has been revealed by incorporating the above-reported design improvements. The actuation of the devised manipulator has demonstrated its capabilities.