Telesurgical Robotics and a Kinematic Perspective

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INTRODUCTION

The advent of Minimally Invasive Surgery (MIS) in surgical theaters has revolutionized the centuries-old art of surgery for various surgical procedures. After rapidly gaining its momentum in 1990s, MIS offered huge benefits over the traditional open-surgery techniques. Details of which can be found in (Satava, 2004; Lanfranco, 2004; Holt, 2004; Taylor, 2006; Kuo C. H., 2009; Nisar, 2015). Along with its revolutionary advantages, MIS proved to be a tedious and cumbersome technique for surgeons. For safety and better efficacy, it requires well-trained and skillful surgeons to carry out the surgical procedures. When compared with open-surgery, MIS techniques adversely affect surgeons' ability of direct-sight, sense-of-touch, depth perception and kinesthetic feel. These issues, along with numerous others pose serious challenges to medical doctors and surgeons when performing MIS procedures.

Surgical robotics, primarily, emerged as a very effective solution to the above-mentioned problems and many other related issues. With the passage of time, these robots started taking the role of augmenters and led to the emergence of many innovative, safer, better and user-friendly features pertaining to various MIS procedures. This gave huge impetus to the ongoing research in this field and grabbed a lot of attention from researchers of many mutually varying fields of research. While industry has played an important role, it had been the academia that remained at the forefront of the research in surgical robotics. Being in operation theaters for roughly more than two decades, surgical robots have demonstrated their potential towards the betterment of surgical procedures and general degree of efficacy (Taylor, 2006; Nisar, 2015). Enhanced precision, greater control over maneuvers, scalable movements and tremor-free tool motion with tactile feedback are some of the sublime features of today's surgical robots. Increased trust of surgeons, medical practitioners (Chitwood, 2001) and, even of the patients, on the use of robots for medical and surgical purposes is becoming a hallmark of this technology. With every new development, the overall size and weight of surgical robots is shrinking while the reliability and safety margins are expanding.

Behind every successful surgical robot, a number of technical and non-technical factors play an important role. For example, kinematics, dynamics, control and manufacturability are some of the technical aspects of a design. Kinematics - being the first and foremost manipulator design step - is considered as the lynchpin of performance for any surgical robot. It is a fundamental aspect of any mechanical design (Kuo C. H., 2012) and plays a decisive role in ascertaining its capabilities and viability vis-à-vis applications. A sound kinematic design is better posed to offer greater performance measures in terms of safety, reliability and surgical task-achievement (Kuo C. H., 2009). Kinematic design acts as a foundation block for the rest of surgical robotic system to be built over. A dismal kinematic design could severely limit the capa-

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bilities of a robot for advanced features and vice versa. Therefore, it is important to understand the kinematic design approaches in practice so far and discuss their features and potential shortcomings.

A number of well-researched and peer-reviewed surgical robots in academia and industry for various minimally invasive surgical procedures have been proposed and many novel designs are being continuously investigated. Thus a survey of the kinematic aspects of these existing designs, giving an all-inclusive consideration, can play a vital role in understanding their pros and cons and thus improving performance of the new designs.

BACKGROUND

Most of the existing surgical robotic systems are telesurgical in nature, where the surgeon operates robotic tools remotely (Nisar, 2015). This remote location could be the same room as that of the patient or anywhere outside. Given the extensive focus on telesurgical systems, the terms 'surgical robotics' and 'telesurgical robotics' are sometimes implied in the latter's sense despite of a certain distinction between the two.

A typical telesurgical robotic system constitutes of various subsystems, like master manipulator, slave manipulator, surgical tool with wrist, control unit and vision system. A system level explanation of a particular surgical robot is described at length in (Hassan, 2014). One key member, and a more interesting one from the robotics perspective, is the slave manipulator. Every manipulator is built upon some mechanism, which embodies the concept and ingenuity of its designer to achieve some specific task, for example, surgical tool movement in the case of surgery. This ability of a mechanism to achieve the design-objective in terms of links lengths and joint angles is mainly defined by the robot kinematics. Kinematics, being a study of the motion geometry of a mechanism and its bodies, provides understanding about the position of its members and change in their positions with respect to time as the mechanism changes its posture. Kinematic design plays a fundamental role and is a crucial factor in terms of its ability to achieve a given task and the overall design robustness.

A key approach to describe telesurgical robots is to classify them based on their kinematic designs. As described earlier, kinematic design defines the basic shape and function of a mechanism and dictates the terms to achieve the design goal such as surgical movements. Therefore, it is important to consider the kinematic perspective of the existing surgical robot designs in order to get a broader and clear picture of the overall progress in the field.

Historically, industrial manipulators were the first to be modified and used for surgical applications (Satava, 2004). Later on, special designs and dedicated manipulators were proposed and implemented for surgical purposes. Most of the surgical applications and majority of the surgical robots are intended for the MIS procedures (Taylor, 2006; Kuo C. H., 2009; Nisar, 2015). Therefore, before examining the available kinematic designs, it is important to understand the operational concept of MIS and its kinematic requirements.

Concept of MIS

Minimally Invasive Surgery (MIS) involves long and slender surgical tools called laparoscopes. Surgeons insert these tools inside the patient body and get visual feedback from one of the tools having an endoscopic camera at the distal end. Generally, three or more such tools are inserted inside the patient body through small holes called as incisions (Howe, 1999). A device, called trocar is used to provide a safer passage to operate the surgical tools at the incision point without causing any damage to the neighboring tissues.

DoFs Requirement

A general MIS procedure requires 4 degrees-of-freedom (DoF) for tool manipulation at the point of incision. The open-close and tool tip movements are generally obtained through dedicated distal end