Development of a robotic surgical manipulator for Minimally Invasive Surgery

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Abstract

Minimally Invasive Surgery (MIS) is surgery of the chest, abdomen, spine and pelvis, done with the aid of a viewing scope, and specially designed instruments. Benefits of minimally invasive surgery are less pain, less need for post-surgical pain medication, less scarring and less likelihood for incisional complications. Since the late 1980's, minimally invasive surgery has gained widespread acceptance because of the such advantages. However there are significant disadvantages which have, to date, limited the applications for these promising techniques. The reasons are limited degree-of-freedom, reduced dexterity and the lack of tactile feeling. To overcome such disadvantages many researchers have endeavored to develop robotic systems. Even though some robot aided systems achieved success and commercialized, there still remain many thing to be improved. In this paper, the robotic system which can mimic whole motions of a human arm by adding additional DOF is presented. The suggested design is expected to provide surgeons with improved dexterity during minimally invasive surgery.

Keywords— minimally invasive surgery, articulated manipulator, and robot aided surgery

1. Introduction

Minimally Invasive Surgery (MIS) is surgery of the chest, abdomen, spine and pelvis, done with the aid of a viewing scope, and specially designed instruments. In these procedures, a slender imaging prove is typically introduced via a puncture incision. The surgical site is viewed through a videoscope equipped with a miniature video camera. A CRT screen displays the resultant camera output. In the abdomen, carbon dioxide is pumped in to create viewing a working room. Tools are fed through additional puncture incisions using trocars. The benefits of minimally invasive surgery are many. Traditional surgery often requires a lengthy hospital stay and weeks of recovery. With minimally invasive surgery, many procedures require one to two days or less in the hospital and recovery time is generally shorter. That usually means that patients can get back to their normal routines quicker. The faster recovery is possible because there are only a few small incisions requiring a stitch or two instead of a large incision through the skin and muscles. Other benefits of minimally invasive surgery are less pain, less need for post-surgical pain medication, less scarring and less likelihood for incisional complications. Since the late 1980's, minimally invasive surgery has gained widespread acceptance because of the such advantages. However there are significant disadvantages which have, to date, limited the applications for these promising techniques [1]-[3]. For example the standard laparoscopic instruments used in many minimally invasive procedures do not provide the surgeon the flexibility of tool placement found in open surgery. As the instrument slide, twist and pivot through the trocar (the point at which instruments enter the body wall), they are four–degree–of-freedom manipulators. Conse- quently the surgeon can reach points within a three-dimensional volume but cannot fully control orientation. Most current laparoscopic tools have rigid shafts, so that manipulation of delicate and sensitive can be difficult while manipulating these long-handled tools from outside the body [3]. Additionally, the fact that the port in the patient's abdomen (trocar) acts as a laterally restrictive pivot point for the body of the positioning apparatus complicates the proper positioning of the surgical tools. Because entry portal (trocar) is embedded in abdominal wall, it cannot be perfectly fixed. This allows the movement of entry portal which acts as a fulcrum and it leads to the lack of dexterity and sensitivity of endoscopic tools [4]. Moreover trocar makes the direction of the surgeon's hand motion reverse at the instrument tip. The video monitor is often located on the far side of the patient, and the difference in orientation between the endoscope and the monitor requires the surgeon to perform a difficult mental transformation between visual and tool coordinate frames. Impaired contact force reception by friction and absence of distributed tactile information also become problems. Although many abdominal operations can be performed laparoscopically at this moment in time, performance of complex minimally invasive surgery is in the hands of a limited number of experts. Therefore, researchers have started to develop new tools for laparoscopic surgery to minimize the unsatisfactory aspects of the process [5]. The launch of robotic telemanipulation system heralds this development.

Reduced dexterity and impaired visual control were considered the major burdens of endoscopic surgery and initial attempts in developing robotic endoscope support systems aimed at enhancing the surgeon's control of the scope. AESOP® (Computer Motion, Inc.) and Endoassist® (Armstrong Healthcare, Inc.) are representative works among laparoscope support systems. While developments in imaging systems clearly progressed, dexterity problems remained a crucial problem. In the early 1990s, the concept of a master-slave tele-manipulator was developed. This concept required the surgeon to control a manipulation system from a master console remote from the patient. A computer uses computing power to support the surgeon's dexterity. The surgeon moves two master devices made to resemble surgical instruments at the console, and each motion is translated to the robotic arm which scale down the movements at the end of the instruments inside the patient's body. The robotic slave arm follows all commands of the master arm in a natural way, comparable to manipulation in open surgery. Many researchers have developed robot aided minimally invasive surgery systems. Among them, da Vinci® (Intuitive Surgical, inc.) and ZeusTM (Computer Motion, Inc.) telemanipulation systems received FDA clearance. The major advantage of these newer master-slave robotic systems is the introduction of extra degrees-of-freedom at the end of the instruments, allowing surgeons to manipulate in a manner similar to that of open surgery. The ZeusTM offers five DOF and da Vinci® offers six DOF by using the Endowrist® system. In addition, the unnatural opposite response of the instruments is corrected by the robotic telemanipulation systems. Tremors and trocar resistance are eradicated by the man-machine interface. The digital processing allows the scaling down of the surgeon's hand movements to a level where micro-vascular procedures are feasible. The ergonomic and reduced fatigue features will be a great advantage [5].

2. Design Concepts

Previously described robotic tele-manipulation systems potentially offer great benefits for minimally invasive surgeries. However there still remain several points to be improved in the aspect of dexterity. In open procedure, the surgeon has unlimited flexibility in positioning his body, elbow, wrist and fingers; the operative field may be approached from various direction. The most up-to-date robotic MIS systems have six-degrees-of-freedom; four at the entry portal and two at the end of tool. These, so to speak, resemble the human arm which just has wrist and shoulder and no elbow. Some researchers reported that if we could develop either mechanical or electromechanical teleoperators which enable surgeons to move a MIS system in a manner analogous to an open instrument, we could potentially reduce the time of current laparoscopic procedures by at least 15% and we could perhaps also enable surgeons to perform procedures which are currently too difficult [6]. This result shows that the robotic system which can mimic whole motions of a human arm by adding additional DOF may have more powerful usages. This is the first and underlying premise of our design. The second premise is that the entry portal, trocar, which acts as a fulcrum is having bad effects on the dexterity and the repeatability of surgery tool. The most serious reason is that the fulcrum does not be firmly fixed. The most movements of conventional tools for minimally invasive surgery depend on that through the trocar and very few movements which are not effected by the motion of the trocar is achieved. Thus the main design concept of this research is to add two DOF rotational joint at the surgery tool so that this added joint function as a human elbow (Fig.1). By adopting this mechanism, the surgery tools can behave like a human arm because the type of degree-of-freedom of the trocar (3-rotations and 1-translation) is exactly same that of a shoulder and the type of degree-of-freedom of tool tip (2-rotations; perpendicular to the longitudinal axis) and added joint (2-rotations; one is perpendicular and the other is parallel to the longitudinal axis) are same that of a wrist and an elbow respectively. Moreover the added joint is not affected by the movement of the trocar because it is placed inside the abdomen during surgery. Thus the space where the surgery tool can move independently to the trocar is enlarged and the dexterity and the repeatability are enhanced**.**

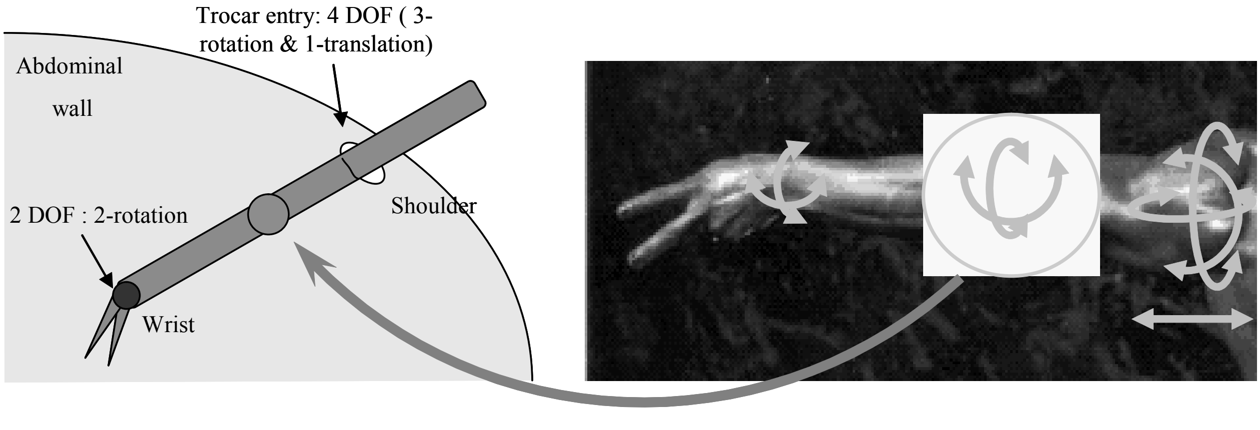

Fig 1. Design Concept

3. Design Requirements

There are several design requirements which should be satisfied for robotic tools to be used at minimally invasive surgery. Typical properties are size, force which can be produced at the tool tip, speed, repeatability, dexterity, workspace, weight, and convenience to operators.

Size : The surgery tool is inserted into the patient's abdomen through a trocar, so that the width of a tool should not exceed the size of conventionally used trocar. The size of currently used trocar is rarely above 10mm. Thus we will design the surgery tool with 10mm diameter.

Force : It is generally known that the amount of force needed for fine motion tasks such as suturing is roughly 10N at the gripper [3]. Thus we set the lower limit of required force as 10N.

Speed : In the aspect of speed we need about 3-5 Hz for the joints to achieve a speed comparable to human fingers.

Repeatability : The human's end repeatability is known about 1mm. In due consideration of practical fabrication process, our design goal for repeatability is under 0.25mm.

Dexterity : The suggested design has more joint and degree-of-freedom than conventional robotic surgery tools, it will inherently shows improved dexterity. Thus design goal is the maximization of the dexterity through whole workspace by rearranging kinematic parameters.

Workspace : As written at dexterity, workspace is also enlarged by adopting the additional joint. Thus maximization of not workspace but dexterous workspace is our design object.

Convenience to operators : Originally this parameter is the most important point to be considered during the design process. Thus the link length of surgery tool is determined by continuous simulation and consultation with surgeons.

4. Design in detail

The main idea of suggested design is to add the additional joint which behaves like an elbow. In human arm, an elbow joint moves with two rotational degrees-of-freedom; one is perpendicular to the longitudinal axis and the other is parallel to the axis. To adopt this type motion, the differential mechanism is used (Fig.2). The differential mechanism is composed of three bevel gears whose axes intersect mutually through a common point at right angle. Two gears are input (gear 1 & 2) and one (gear 3) is output device. When input gears rotate to same direction, the output gear is turned on the axis of input gear. When input gears rotate to opposite directions, the output gear is turned on the longitudinal axis. This is the exactly same motion with a human elbow. The suggested design shows 45-degrees motion range of output gear at each rotational axis. The wrist part should be able to be manipulated with two axes which are perpendicular to longitudinal axis. To this end, the universal joint may be best solution. But universal joint has a intersect axis which looks like a cross and it is very difficult to drive such a part by using a wire. To solve this problem, rotational axes are split apart and are driven separately. But this design needs one more joint than that of universal joint and it makes the manipulator become more complex and pliable. To overcome this drawback, the axis for tool tip rotation and the axis for tool opening are joined together and two parts of a tool tip are driven separately (Fig.3). In this design, the average of two rotations (pulley 1 & 2) represents the change of the orientation of tool end and the difference between two rotations does the tool tip opening angle. Thus the orientation and the tool opening angle can be controlled in one axis.

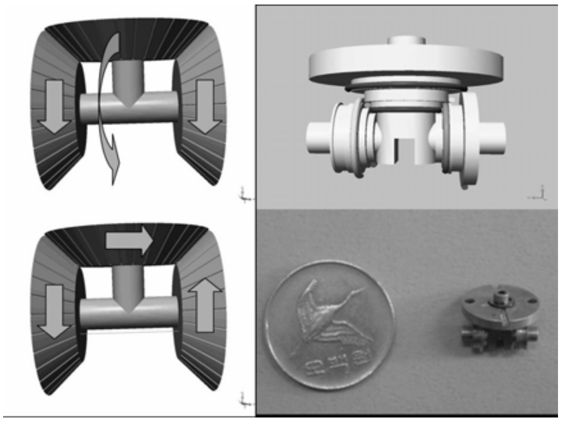

Fig 2. Differential Drive

Because wire-mechanism is only operated when tension-force work on it, wire-driven system requires 2n wires to control n-DOF motion. In our system, we need 6 wires to control 3 DOF motion of tool tip (pitching in wrist, gripping and yawing in hand). However, the space where driving mechanisms are to be installed is restricted by size of trocar, and wires must be passed

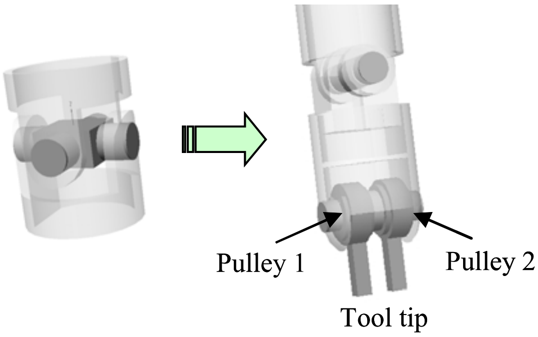

Fig 3. Universal joint and suggested design

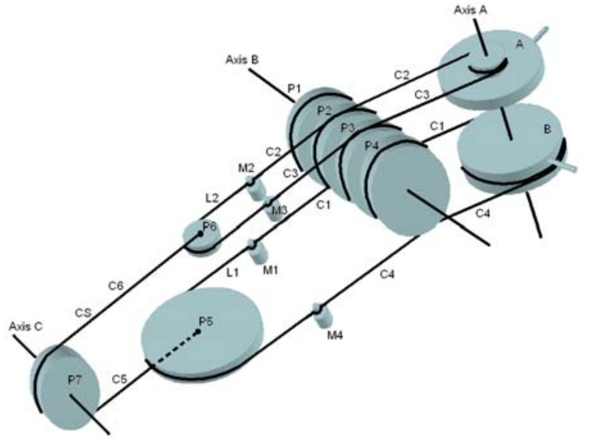

Fig 4. Schematic diagram for cabling

through axle of bevel gear of differential drive. Therefore, technique that can reduce number of wire is required. Consequently, only 4 wires are required to pass through axle of the upper bevel gear by adopting following technique.[7]

As shown in fig.4, this system is composed of 2 capstans, 7 pulleys and 4 motors. Cables C1 and C4 form two sides of a continuous loop L1. Cable C1 of loop L1 engages proximal pulley 5, drive shaft of motor M1, intermediate pulley P1, and driven capstan B. Loop L1 returns from capstan B as cable C4 and engages intermediate pulley P4, drive shaft of motor M4, and proximal pulley P5. The cables C1 and C4 are fixed to capstan A in order to pull it.

In the same manner, Cables C2 and C3 form two sides of a continuous loop L2. Cable C2 of loop L2 engages proximal pulley 6, drive shaft of motor M2, intermediate pulley P2, and driven capstan A. Loop L2 returns from capstan A as cable C3 and engages intermediate pulley P3, drive shaft of motor M3, and proximal pulley P6. The cables C2 and C3 are fixed to capstan B.

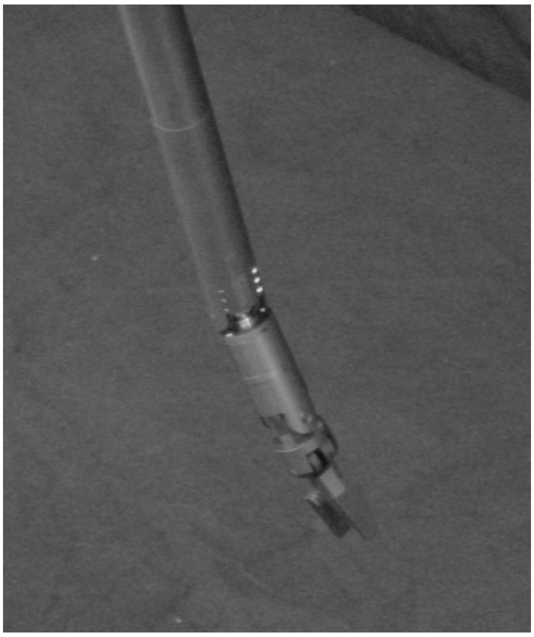

Fig 5. overall shape of surgical tool

Cable C5 and C6 form two sides of a single cable CS that engages pulley P7.

The movement of wrist and fingers acts like following. If motors M1 and M4 rotate in opposite direction, capstan A will rotate for gripping and yawing. Likewise if motors M2 and M3 rotate in opposite direction, capstan B will rotate. If motors M1 and M4 rotate in the same direction, motors M2 and M3 rotate in the same direction, but in opposition to M1 and M4, then the wrist will pitch about axis B.

The surgery tool is composed of previously described parts and is shown in Fig.5. It is expected to make the surgery tool be applied more various tasks.

5. Summary

This paper presents the design of the dexterous manipulator for minimally invasive surgery. The capability of the suggested surgery tool is enhanced by adopting additional joint which acts like a human elbow joint. The improved manipulability may contribute to performing complex tasks during surgery and popularization of minimally invasive surgery.

Acknowledgements

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