Journal of Engineering Research & Education
Vol. 3, 2006 (43-52)

The Design of Mechatronics Manipulator for Surgical Purposes: Approach and Challenges

ZOL BAHRI RAZALI[1] AND ZAHEREEL ISHWAR[2]

[1]*Department of Mechanical Engineering*
The University of Western Australia, 35 Stirling Highway, Crawley, PERTH, WA 6108.
E-mail: razalz01@mech.uwa.edu.au *Tel: (00614)11529726*

[2]*School of Computer and Communication Engineering*
Kolej Universiti Kejuruteraan Utara Malaysia, 02600 Jejawi, Perlis, MALAYSIA.
E-mail: zahareel@kukum.edu.my Tel: 04-9798149

Received : 14 January 2006 / Accepted : 22 November 2006

ABSTRACT

This paper discusses the preliminary study of improving the development of mechatronic manipulator for surgical aided system, i.e. in MIS procedures. Realizing the importance of robotic and computer technology for surgical field in Malaysia, a study of the application of mechatronic in medical has been set forward. The intended outcome of the study is to develop a surgical assisted system that could increase the quality of surgical service performance. Therefore, the aim of this study is to investigate and develop a kinematics model with all the necessary details to be used for mechanism analysis and preliminary control system design. The objective is to determine the optimal geometric configuration for the develop model. This information will be used for the detailed mechanical design and manufacture of the physical device. The final product which should be an aided surgical manipulator would be best applied to endoscopic surgeries. Parallel mechanisms which is more complicated to design, but offer a relatively smaller workspace and lower overall handiness were chosen for the design of mechanism topology. To their benefit, parallel topologies result in stiffer mechanisms, with the ability to transmit higher forces at the tool with greater accuracy.

Keyword: Mechatronics surgical manipulator, kinematic model, mechanism topology, surgical simulation.

INTRODUCTION

At present, robotic systems for computer-assisted surgery have gained paramount initial interest and are being actively investigated by several research groups, but are rarely found in clinical practice [1]. Recent advances in computer hardware and software have made it possible for the computers to play important role in human health care including in medical environment [3]. Similarly robotics, which is integrated with computational and mechatronics system, has played a significant role in serving the medical sector [4], especially in surgery. Many surgical procedures such as orthopaedic surgery for milling linear paths for cavities in total hip replacement, in neurosurgery for tool holding functions, in endoscopes surgery for automatically movement of the camera, and so on, have involved robots in performing the tasks [5]. There are other robotic solutions for surgery, including telemanipulator systems like the daVinci system from Intuitive Surgical, and robots for endoscope guidance in abdominal surgery like the AESOP system (developed by Computer Motion) or the EndoAssist from Armstrong Healthcare. On the other hand, the concept of commercial systems like Robodoc and CASPAR which have been introduced for milling the stem cavity in total hip replacement surgery has turned out to be not convincing and many systems have been removed from the OR [2].

Simultenously, the using of surgical simulation can provide great benefit to medical environment [6,7] including computer-assisted surgery which is dominated by use of navigation systems. Originating from first applications in neurosurgery, ENT and spinal surgery, such systems have found wide acceptance in most bone-related surgical interventions. However, surgical instruments are still guided manually. The same advances in technology are also making it possible to develop better and faster realistic computer simulation [1] for surgical procedures. However, there are many technical challenges associated with the development of a robust simulation system, including the requirement on the human-machine interface [6, 7]. The medical application has unique needs that drive the design of the mechanism, the control scheme, the tissue deformation engine, and the overall system architecture and distribution of computation [5]. Another challenge is to produce user friendly and realistic feel of surgical process simulation system.

Looking at the possible significant contribution that mechatronics manipulator technology could offer, the study on the application of mechatronic in medical field has been launched in the spirit of developing a surgical assisted system that could be used to increase the surgery quality of service. Therefore, the objective of this study is to concentrate on the application of mechatronics aided system in designing manipulator for assisted basic surgery. It includes the tasks of researching, designing, developing and examining the suitable manipulator for the purpose. As a start, literature reviews on mechatronics manipulator and surgical simulator are being conducted to study the application. Apart from that, the sources for application of surgical manipulator system are also being studied.

Next, significant research and development efforts on aided basic surgery manipulator could be uphold to develop a suitable system. The irrefutable valuable contribution it could provides proves that this research is highly significant to be carried out. It is hope that the developed system could contribute extensively to surgeon in demonstrating and achieving high precision and excellent quality of service.

APPLICATION OF MECHATRONICS AND ROBOTIC IN SURGERY

Robots have played an increasingly important role in the recent decade in the field of surgery. It is a new intersectional study field, which composed of medicine, bio-mechanics, mechanics, materials, computer graphics, computer vision, mathematical analysis, robotics and many others [8]. This would not only promote the evolution of the traditional surgery, but also bring new robotic technologies and theories [2]. It is also found that, the robot applied a more consistent retraction pressure and less overall retraction pressure than human. Thus, this seems to be an instance, where a robotic device can perform a boring, repetitive task in a more consistent, and perhaps safer, manner [5]. On the basis of describing the status of surgical robots, this paper wills analyze the key technologies of surgical robotics manipulator, as well as future orientations.

Although surgical intervention assisted by a robot was initially performed in 1985 [9] surgical mechatronic systems up to this point are only used for "simple" trajectories e.g. as toolholding functions. For example, the actual main preliminary applications in orthopaedical surgery is for milling linear paths for cavities in total hip replacement [10], in neurosurgery for tool holding functions [11], in endoscopic surgery for automatic movement of the camera and in interventional radiology for setting the angles for the incision direction of the instruments [12].

The design of mechatronic assistance system should achieve a lower complication rate, a shorter duration of the surgical procedure and an improved ergonomic for the surgeon. This new system has to be superior to the actual standard procedure concerning criteria of efficiency and in the economic point of view. The development should precede over four steps [13];

1. The first assistance system follows passively the positioning movement of the surgeon and takes over the final position.
2. Thereby the system controls the intermittent forces and warns by trespassing of defined limits.
3. Later the system should approach positions order, which were defined at the beginning of the operation.
4. In the last step of development the system should follow tracked surgical instruments or laser automatically within of a predefined space and including force control.

In the other words, the design of the system should be done for an already realized and given 'processes'. Often modeling, simulation and identification is done for systems that already exist. But in case of a full design the system does not yet exist, which not only means that there is a large initial uncertainty, but also that there is much more freedom to modify the design, not just the manipulator and controller, but the complete 'process' [14], including the mechanical construction. Therefore, this study aims in conception and prototypical realizing of such a mechatronic assistance system.

PREVIOUS RESEARCH ON THE DESIGN OF MECHATRONICS SURGICAL MANIPULATOR

The first machine or robot assisted device for surgery was approved for use by the United States of America Food and Drug Administration (FDA) on June 16, 1999. This ushered in a new and exciting age of surgery, with potential limited only by surgeons' dreams and engineers' capabilities. Robotic technology has been used to great advantage in non-medical applications for a long time. Surgery has been slower to take advantage of this technology for obvious reasons. But engineers and forward-thinking surgeons have been thinking, dreaming, and working toward the introduction of robotic technology into the world of surgery [5].

Regarding to [5], one of the first devices used clinically in human surgery was the "Robo-doc" system for orthopedic surgery. Its aim was to improve on a task performed by surgeons using bare hand. The task, in this instance, was bone drilling to fit a hip prosthesis, to create a more ideal fit between prosthesis and bone. This system continues to be used clinically. Experience has rapidly accumulated since the approval by the FDA of the daVinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) and reported that the prospective analysis of 211 robotically assisted procedures performed between June 2000 and June 2001 using the daVinci system. The procedures undertaken included antireflux surgery, cholecystectomy, heller myotomy, bowel resection, donor nephrectomy, left internal mammary artery mobilization, gastric bypass, splenectomy, adrenalectomy, exploratory laparoscopy, pyloroplasty, gastrojejunostomy, distal pancreatectomy, duodenal polypectomy, esophagectomy, gastric mass resection and lysis of adhesions [5].

The world of surgery is rapidly changing. The current generation of robotic systems for general surgical applications is only a beginning, but it is an impressive start [5]. At the same time, the application of computer software and programming also plays an important role in this field. Many research and development of surgical simulation was undertaken especially for the purpose of education or training. Some of the study is to show the possibilities opened up by three-dimensional (3D) computer-based models of the human body for education in anatomy, training on radiology and endoscopic examinations, and simulation of surgical procedures. The models provide a means for realistic training in interpretation of radiological and endoscopic images of the human body. Furthermore, certain surgical procedures may be simulated realistically [19]. Used as a complement to the current curriculum, these models have the potential to greatly decrease education period and costs.

Furthermore, in current miniature technology, mili-robotics tools have been developed for mili size medical purposes, such as for minimally invasive surgery [4]. Milli-robotics for this surgery needs new kinds of robots, tactile and visual sensors, and human-machine interfaces. Several research devices for whole hand force feedback [8], touch, and slip feedback [4] have been developed to study these issues.

Current Challenges in Mechatronics Surgical Manipulator

The primary focus of this research is to investigate better positioning system for the mechatronics manipulator to assist surgical, especially for minimal invasive surgery. The current challenge to be identified is to acquire better positioning systems. For the method of tools positioning, active motion control with a robot will be chosen. The positioning will be identified by mechanism analysis, which shall focus on kinematics analysis (i.e method for representing position, orientation, velocity, etc.)

Minimally Invasive Surgery

Minimally Invasive Surgery (MIS) has revolutionized many surgical procedures over the last few decades. MIS is a class of surgical procedures that minimizes patients' wounds incurred during an operation. It is the result of a natural progression guided by the medical philosophy nil nocere suprema lex, the highest rule is to do no harm [22]. MIS is performed using a small video camera, a video display, and a few customized surgical tools. MIS is also termed keyhole surgery because of the small incisions [8,9,21,22]. In procedures such as gall bladder removal (laparoscopic cholesystectomy), surgeons insert a camera and long slender tools into the abdomen through small skin incisions to explore the internal cavity and manipulate organs from outside the body as they view their actions on a video display [9]. The advantage of MIS over traditional procedures is obvious. Small, localised wounds heal quicker than larger wounds and cause less scarring. Reduced healing periods can also reduce the overall expense of the operation, both for the hospital and patient.

Better Assistance Tools for Mis Surgeon

MIS procedures are classified based on the body location where they are performed and the type of viewing apparatus used. The viewing instrument is generally termed an endoscope, and is further classified by the part of the body it is designed to examine. The most common type of viewing apparatus is the laparoscope, a long, thin hollow tube, with a small camera affixed to the end [22]. This is directed though a small incision in the abdominal wall to allow imaging of the target. From surgeon perspective, it is stated that most of the weaknesses in laparoscopic surgery are caused by the unmanageable instruments and limited vision [16]. In this case, the final image is displayed on a cathode ray tube or liquid crystal display. Improvement on controlling or managing the endoscope tools to get accurate image of the target area, can be achieved by the usage of mechanism or robot [21]. A finding in literature stated that medical error caused lack of skill can be reduced by the usage of manipulator to assist the task of controlling and managing the endoscope tools.

Application of the Mechatronics Surgical Manipulator

The typical duty of a surgical assist manipulator or robot is to assist the surgeon, in tools placement (in this case, a surgical tool). In term of design, the manipulator can be designed utilizing various fashions to perform every aspect of a surgical procedure; however this is not the design goal for most surgical robot. The design goal of the manipulator is to assist the surgeon in tool placement, as motion guidance and reduce surgeon tremor during the operation. Referring to [21] the application best suited endoscopic surgeries. These includes surgeries in the chest (thorascopic), joint (arthroscopic) and abdominal (laparoscopic) regions. Brachytherapy (radiation treatment for prostate and other types of cancer) and cryotherapy (a treatment that freezes a cancerous tumour) are also well suited to endoscopic procedures. The mechatronics surgical manipulator can also be used as a static mechanism such as an abdominal wall retraction device or a self-retaining arm when the repositioning of an instrument is irregular.

THE DESIGN AND MECHANISM ANALYSIS OF MECHATRONICS SURGICAL MANIPULATOR

Research Objective

The objective of this study to investigate mechanical designs to develop a kinematic model detailed enough to be used for mechanism analysis and preliminary control system design. An additional objective was to determine the optimal geometric configuration for the given model. This information can be used for the detailed mechanical design and manufacture of the physical device.

Design Phases

Referring to [14], in a design process the following iterative phases can be distinguished;

Phase 1: A conceptual design is made of the kinematic model, which has to be constructed, taking into account the tasks that have to be performed and identifying and modeling the major components.

Phase 2: The model's concepts can be evaluated on the basis of this simple model.

Phase 3: When the model's evaluation is successful, the different components in the system can be selected and a more detailed model can be made.

Phase 4: When phase 3 has been successfully completed, the model can be realized mechanically. This hardware can be tested with a hardware-in-the-loop simulation that mimics the physical system (plant) still to be built.

Phase 5: Finally the physical system itself can be built. As this is usually the most cost intensive part of the process, this should be done in such a way that those physical parameters that proved to be most critical in the previous phases are open for easy modification as much as possible, such that final tuning can lead to an optimal result.

Mechanism Analysis

The goal for kinematic study is to predict and analyse motion using a model of reality. The model is mathematical in construction and based on observed physical phenomena. Numerical approximations are often necessary in order to obtain results from the mathematical model [22]. The mechanism analysis will be done for this research includes rigid body notation to find position, orientation, linear and angular velocity; mobility analysis to investigate the mechanisme topology, joints and mobility; kinematic modeling by using jacobian matrix to find virtual work and assembly mode; kinematic analysis including position anlysis, jacobian analysis, manipulability, error analysis, workspace analysis and other performance functions.

Mechanism Topology

The topology, or type, of a mechanism is determined by the relationships between links and joints, irrespective of geometry. Thus, a mechanism can be modeled as a undirected graph composed of nodes and vertices. The topology of a mechanism has wide and varied effects on its possible motions. Therefore, type selection is considered as the first, and arguably most important, however, the feasibility of these methods is questionable for real-world applications. Mechanisms can be classified into three broad types, serial, parallel or hybrid, based on their topology [22].

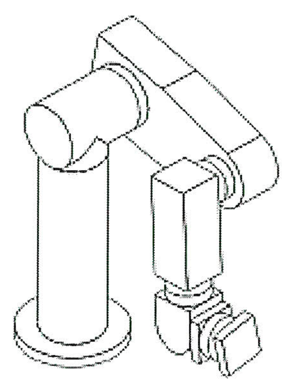

Figure 1. PUMA-like serial arm robots.

A serial robot is usually given the name arm, undoubtedly because of the "arm-like" working qualities of many common industrial serial robots. An example of serial robot with the principle of "arm-like" working quality is as Figure 1 [22]. A parallel linkage has multiple closed-loops in its graph, distinguishing it from a serial linkage. The closed loops arise from multiple connections from the base to the tool, called the manipulator's legs. Each leg is a serial linkage with no loops existing in its sub-graph. A fully parallel mechanism has the same number of legs as degrees of freedom [23].

Parallel mechanisms are more complicated to design, have a relatively smaller workspace and lower overall handiness. To their benefit, parallel topologies result in stiffer mechanisms, with the ability to transmit higher forces at the tool with greater accuracy. Also, fully parallel mechanisms can be designed with all actuators fixed on the base and is useful for high-speed robots [24]. Figure 2 shows the proposed design of serial manipulator, which will be studied, designed, analyses and constructed to achieve the objective of this research.

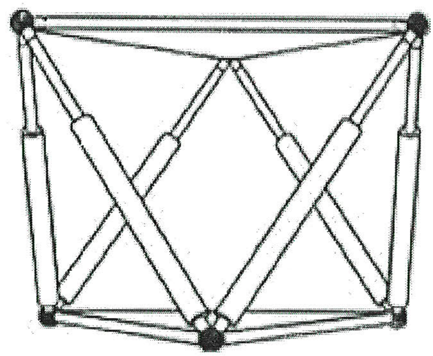

Figure 2. Parallel manipulator (side view).

SUMMARY

Robotic technology has been used to great advantage in medical applications including in surgery, although it has been slower to take advantage of this technology. For that reason, the preliminary review shows the important of the robot or manipulator to assist surgical process. Through the review, the authors found that the design of parallel manipulator are more complicated but have a relatively smaller workspace and lower overall handiness. These advantages give benefit to surgical environment because it need only a small working area and will not disturb the operating working area. In the other word, this manipulator can be installed to the operating area without rearrangement of previous setting.

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