ROBOT CONSTRUCTION FOR SURGICAL APPLICATIONS

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Abstract: This paper presents a robot design for use in robotic-assisted surgery. The requirements of a medical robot emphasize the advantages of parallel robots for this task. Based on laparoscopic surgery, specifications for workspace, velocity, force and accuracy of the robot were determined. Following computer simulations, an RSPR parallel robot was designed and constructed. This extremely compact and lightweight robot meets design specifications and exceeds the accuracy of manually manipulated surgical tools. It is currently being implemented for knee arthroscopic surgery and as an integrated tool for registration and surgical assistance in TKR (total knee replacement surgery).

Keywords: Robotic manipulators, Medical applications, Master-slave systems, Robot kinematics, Telerobotics.

1. INTRODUCTION

Robotic-assisted surgery is a new trend in medicine that aims at using robots in the operating theater for helping surgeons with routine tasks and in performing accurate and delicate procedures. By using the robot's capabilities, surgeons can complement their own skills with accuracy, motion steadiness, and repeatability.

Kavoussi, (Kavoussi *et al.*, 1996), compared the performance of a human assistant *vs* a robotic assistant in manipulating a laparoscope and showed the superiority of the robot in terms of motion steadiness. In another study (Kazanzides *et al.*, 1995), experimental results of robotic milling of cavities for hip replacement surgery indicated clear preeminence of robotic milling over manual broaching of implant cavities.

From the point of view of structure, most of the robots employ a serial chain as their basic kinematic structure. This is true in either special-purpose robots (Taylor *et al.*, 1995) or in modified industrial robots (Kienzle *et al.*, 1995; Kazanzides *et al.*, 1995). However, as will be shown in this paper, these serial-type robots suffer some drawbacks, resulting in a large and heavy robot design.

A search for a typical task-oriented robot reveals that the parallel robot architecture better suits a class of medical applications as described in several reports (Grace *et al.*, 1993; Jensen *et al.,* 1994; Brandt *et al.*, 1995; Simaan *et al.*, 1998; Shoham *et al.*, 1998). Before listing the characteristics of a parallel robot, we first discuss basic guidelines for the design of medical robots and compare a parallel architecture with a serial one in terms of adequacy for medical applications.

2. REQUIREMENTS OF A MEDICAL ROBOT

This section lists the basic requirements of a medical robot in terms of robotic structure only. It disregards the requirements for data acquisition and registration, or for the pre-operative computer-based system. Some of the requirements have been presented previously (Khodabandehloo *et al.*, 1996; Brandt *et al.*, 1997).

In order to insure the successful implementation of a medical robot, four fundamental requirements must be fulfilled. The first and most crucial one is safety.

The following seven criteria constitute the safety requirement:

1) Effective control. The robot must permit, in all configurations, effective control of the tool from the point of view of both speed and force.
2) Limited Workspace. The robot must have limited workspace in order to prevent hazardous collisions between its moving parts and the medical staff or the patient.
3) Limited forces or force feedback. In applications where the robot is active in performing surgical procedures that include tactile tasks, the force applied by the tool must be limited. Alternatively, in applications where the robot acts as a slave, the robot must convey the maximum amount of data to the surgeon of the forces exerted on the tool. This requirement is essential when cutting bone, as different levels of force are required during various stages of the cut (Harris *et al*., 1997).
4) Immunity against magnetic and electric interference generated by other surgical tools.
5) Full control option. In applications where the robot performs automated tasks, the control program must allow the surgeon to interrupt the automatic execution process and take over control at any stage of the procedure.
6) Fail-safe features. The most reliable systems will inevitably fail at some stage of their service. The robot must, therefore, utilize a fail-safe mode that includes holding the tool position if power supply is lost, as well as limiting the speed and force of the end effector, even when the control program fails.
7) Safe behavior near singular configurations. The path planning of the robot or its inherent design should avoid passing near singular configurations.

The second requirement for a medical robot is compactness, both to save space in the already crowded operating room, and to facilitate its use at different locations and for various tasks.

The third requirement is simplicity and user-friendly operation so that operating room staff can quickly learn to use the robot. The last, but not least, requirement is for ease of sterilization.

To deduce its adequacy for medical applications, a comparison between a serial and a parallel type of robot is next made.

3. KINEMATIC ARCHITECTURES OF ROBOTS

This section presents the two basic kinematic architectures of robot manipulators, i.e., the serial and the parallel architectures. Each architecture is characterized by the type of kinematic chain connecting the base and the output link of the manipulator.

3.1 Serial Architecture

Figure 1 depicts the classical (anthropomorphic) serial architecture of robotic manipulators. In this architecture, the output link is connected to the base link by a single open-loop kinematic chain composed of a group of rigid links, where each pair of adjacent links is interconnected by an active kinematic pair (controlled joint).

Serial manipulators feature a large work volume and offer high dexterity, but have several inherent disadvantages, which include low precision, poor force exertion capability and low payload-to-weight ratio. Their motors are not located at the base and the large number of moving parts result in a high inertia.

To overcome the low precision and low payload-to-weight ratio of serial robots, extremely accurate gears and powerful motors are used.

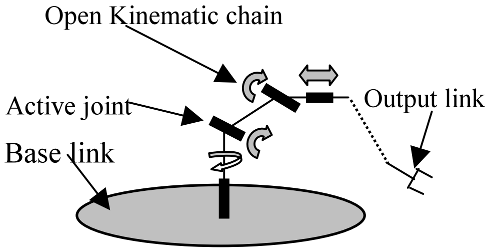

Fig. 1. Serial (open-chain) robot

3.2 Parallel Architecture

The parallel robot architecture is composed of an output link connected to a base link by several kinematic chains, Fig. 2. The simultaneous actuation of kinematic chains produces movement in the output link. By contrast to open-chain serial robots, parallel robots consist of closed kinematic chains with both active and passive joints.

Parallel robots have advantages and disadvantages. The parallel architecture provides high rigidity and a high payload-to-weight ratio, high accuracy, low inertia of moving parts, and a simple solution to the inverse kinematics problem. Because the load is shared by several kinematic chains, there is a high payload-to-weight ratio and rigidity. High accuracy results from sharing and not accumulating, joint errors. The disadvantages of parallel manipulators are limited work volume, low dexterity, complicated direct kinematic solution, and singularities that occur both inside and on the envelope of the work volume. The inverse kinematic solution–the one needed for control purposes–is, in general, much simpler in parallel robots than in serial robots. Table 1 compares the physical characteristics of serial and parallel manipulators.

In contrast to the bulky serial robots, the compactness and lightness of parallel robots simplifies their relocation in the operating room, economizes on space, and facilitates sterilization. If correctly designed, their relatively small work volume provides an important safety factor. The same accuracy level can be achieved at a lower cost than serial robots (certain accuracy levels may not be achievable with serial robots).

These features show the merits of parallel robots for medical applications that require a small workspace, compactness, high accuracy and high rigidity.

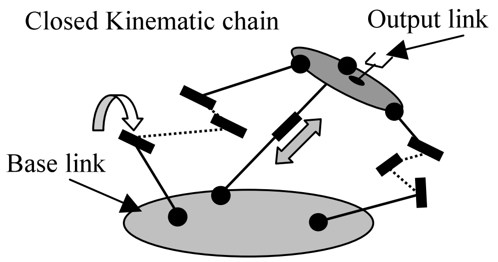

Fig. 2. Parallel (closed-chain) robot

4. TASK REQUIREMENTS

For the manipulation of a surgical tool in a minimally invasive laparoscopic surgery there are constraints on the workspace, velocity, force and accuracy envelopes. The design task is therefore to synthesize a robot that supports a given load and manipulates it with a given velocity and accuracy in a required workspace. From considerations in the previous section, the choice is to synthesize and construct a mini parallel robot for this application.

The load and the required workspace were set by physical and geometric estimates of the needs of the laparoscopic procedures.

Table 1: Comparison between Serial and Parallel manipulators

Property	Serial manipulator	Parallel manipulators
Type of kinematic chains	Open	Closed
Type of Joints	Active only	Active and Passive.
Role of active joints	Twist applicators	Wrench applicators.
Direct kinematics problem	Simple single-valued solution	Complicated, with up to 40 solutions (Lazard, 1993).
Inverse kinematics problem	Complicated with multiple solutions	Relatively simple.
Joint errors	Cumulative	Non cumulative.
Positional accuracy	Poor	Average
Payload-to-weight ratio	Low	Very high.
Singularity	Loss of freedoms	Gain and loss of freedoms.
Singularity domain	On the envelope of the work-space	Both inside and on the work-space envelope.
Jacobian mapping	Maps joint speeds to end effector linear/angular velocity	Maps the end effector linear/angular velocity to active joints' speeds.
Work volume	Large	Small
Moving parts inertia	High	Low

The required workspace is a rectangular cube with sides 40 × 40 × 20 mm, in which a minimum of 20° rotation of the tool must be maintained. The external forces are equivalent to supporting a weight of 1.2 kg with a lever of 0.1 m. The speed of the laparoscope tip should vary between 2.5 to 25 mm/s. With these design specifications, other functions of this robot are possible, such as for knee arthroscopy and total knee replacement surgery in a semi-active mode.

The above design specifications were used in (Simaan, 1999) for comparing several parallel robot architectures and for the type and dimensional synthesis of the robot.

5. THE RSPR PARALLEL ROBOT

Following an extensive series of kinematic simulations, we chose an architecture of a mini parallel robot (that will be referred to as the RSPR parallel robot–a name that is explained below) as the one that best fits the previously stipulated requirements. This manipulator consists of three identical kinematic chains, connecting the base with the moving platform, shown in Fig. 3. Each chain contains a lower link rotating around a pivot perpendicular to the base platform, offset from the center of the base. At the other end, each chain is connected by a spherical joint to a prismatic actuator. The upper end of the prismatic actuator is connected to the moving platform by a revolute joint whose axes form an equilateral triangle in the plane of the moving platform. This arrangement of joints and links provides the moving platform with six degrees-of-freedom. If we denote revolute, spherical, and prismatic joints by the letters R, S, P, respectively, Fig. 3, we can call this robot RSPR by following a convention among robotics researchers in which symmetric parallel robots are characterized by stating their kinematic chains' joint types starting from the base to the moving platform.

This manipulator is distinguished by the location of the revolute axes of the lower links that are offset from the center of the base platform. Alizade in (Alizade, Tagiyev, and Duffy, 1994) presented a robot with RRPS kinematic chains and we found that the RSPR robot requires less actuator effort for a corresponding task. This robot also eliminates some of the singular configurations that are present in the RRPS robot. However, use of the swept volume analysis presented in (Zhiming, 1994) reveals that when eccentricity is eliminated in RSPR robots, both RSPR and RRPS robots have the same swept volume for the upper extremities of the kinematic chains. Since the RSPR robot has a revolute joint at the end of each kinematic chain, which imposes additional perpendicularity constraints, there is a smaller vertex space and smaller work volume than for a RRPS robot.

The aim of the synthesis was to find the minimal size of robot that provides the required work volume and end effector forces. Details of this work have been previously presented (Simaan, Glozman and Shoham, 1998). The synthesis is based on computer simulations that use the inverse kinematics and the Jacobian formulations of the robot to evaluate the work volume, the actuator forces and ranges, and the spherical joint limits. The synthesis eliminated robots that possessed singular configurations within the required work volume as it yielded 22 possible RSPR robots having different characteristic dimensions. Additional design considerations for the actuator size and construction feasibility led to the selected robot.

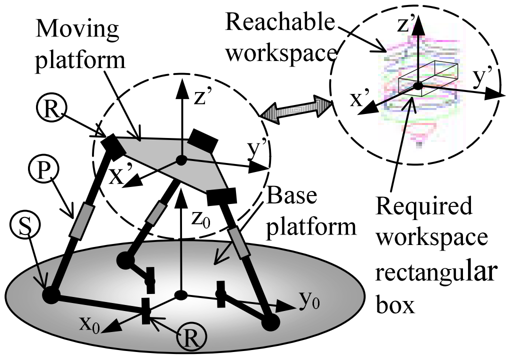

Fig. 3. The RSPR robot, its reachable workspace and the required workspace rectangular box.

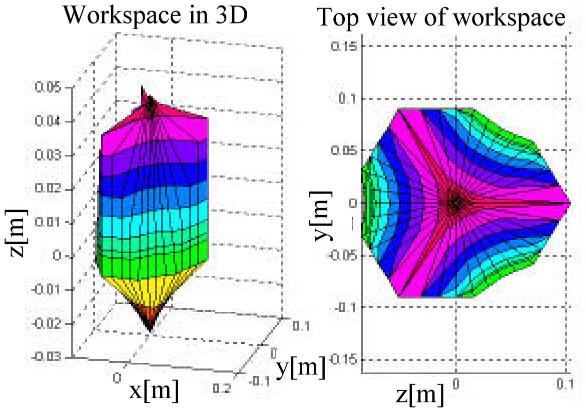

Fig. 4. The RSPR robot work volume with parallel platforms.

Figure 3 shows the work volume of the selected robot, which is better than the design goal. Its attainable workspace is shown in Fig. 4. Figure 5 depicts the actuator forces of the selected RSPR robot when the moving platform is subjected to an external six-dimensional wrench [7, 7, 7 N, 0.7, 0.7, 0.7 Nm]. These forces and moments are maintained along a path from the lower corner of the workspace volume (point [-20, -20, -10] mm) to the upper corner of the volume (point [20, 20, 10] mm), while keeping the moving platform with an orientation of 20 degrees about [1,1,1] axis in [x', y', z'] coordinate system (see Fig. 3).

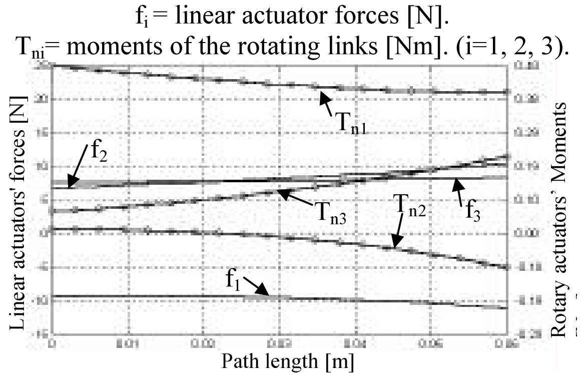

Fig. 5. RSPR selected robot actuator forces along the diagonal path

6. THE RSPR PROTOTYPE ROBOT

Based on the above results, an experimental robot was constructed which weighs less than 3 kg and can be stored in a cylinder 250 mm in diameter and 200 mm in height, Fig. 6.

The prototype is currently being prepared for preliminary experiments in knee arthroscopy. Figure 7 shows the experimental setup of the robot in the surgery. In this setup, the robot is used for manipulating an arthroscopic camera under the surgeon's commands and this relieves him from having to continuously manipulate the camera.

The motion of the prototype robot is controlled in master-slave mode. Our experimental system includes the computer control program in its core, a 12-bit 8-channel digital-to-analog D/A converter, input-output I/O card, six power amplifiers, and a power supply unit. The robot is shown in Fig. 8. The system includes a six-dimensional force sensor, and is attached to the end effector for moving the robot in compliance mode. This mode will give the surgeon the ability to move the arthroscope for the initial setup of the surgery. The master-slave mode is then used to allow the surgeon to perform slow and accurate motions of the camera while the arthroscope tip is inside the knee cavity.

The computer program reads the desired position/orientation of the moving platform as an input signal initiated by the user (the master). The control program calculates the positional error and uses a PID control algorithm to compute the control signal, which in turn is converted by the D/A card to an analog signal. This signal is fed to the power amplifiers and translated into a PWM signal for the DC motors M_1 .. M_6 .

The control program checks the inverse kinematics solution and assesses whether an actuation limit has been reached. The program also prevents collision between the linear actuators and the centrally located motors.

7. CONCLUSIONS

The RSPR prototype was designed, constructed, and controlled successfully to meet the design goals. The compact dimensions and weight of the robot, as can be seen in Fig. 6, promise easy setting-up and portability in the operating theatre. The accuracy of the robot is better than can be achieved by manual manipulation of surgical tools. This indicates the potential inherent in this robot for a whole class of surgical procedures, such as knee arthroscopy and total knee replacement.

Fig. 6. The RSPR prototype robot

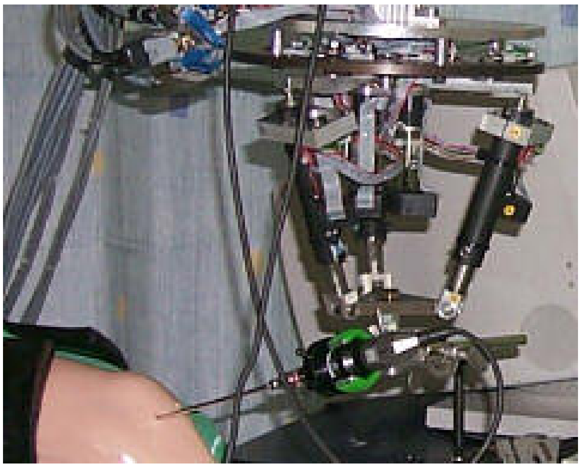

Fig. 7. Preliminary experimental setup for knee arthroscopic surgery

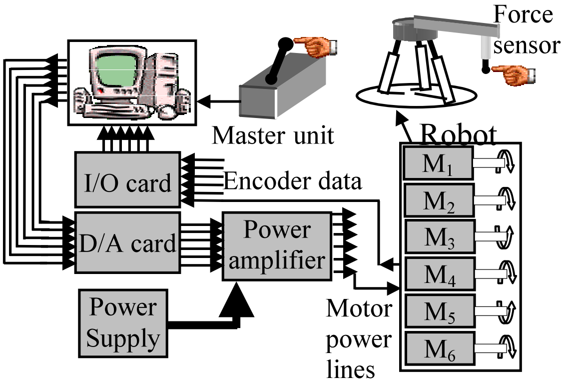

Fig. 8. Block diagram of the robot's control units

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