Second Israeli Symposium on Computer-Aided Surgery, Medical Robotics, and Medical Imaging (ISRACA'S 99).

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 point to the advantage of a parallel robot structure for this task. Based on laparoscopic surgery, specifications for workspace, velocity, force and accuracy of the robot were determined. Following a large number of kinematic and dynamic simulations, an RSPR parallel robot was designed and constructed. The extremely compact and lightweight robot meets the design specifications and exceeds the accuracy of the manually manipulated surgical tools.

1. Introduction

Robotic-assisted surgery is a new trend in medicine that aims at using robots in the operating theatre to help the surgeon in routine tasks and to carry out accurate and delicate procedures. By using the robot's capabilities, the surgeon can complement his or her own skills with accuracy, motion steadiness, and repeatability. Kavoussi *et al.* [1996] compared the performance of a human assistant and a robotic assistant in manipulating a laparoscope. The results of this comparison emphasized 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 were reported. A comparison with the manual operation showed clear preeminence of the robot in performing accurate milling of the

Acknowledgment:

The Authors thanks Dr. S. Goldberger of Meir Hospital, Kfar Saba and Dr. M. Roffman of Carmel Hospital, Haifa for assistance in defining the medical task of the robot. This project is partially supported by Afirst Program and the Fund for Promotion of Sponsored Research at the Technion.

implant cavities. On account of these features of the robot, a steadily increasing number of researchers have invested efforts in assimilating the robot into the surgical arena.

From point of view of structure, most of the robots employ a serial chain as their basic kinematic structure. This is true either in special purpose robots [Taylor *et al.*, 1995] or in modified industrial robots [Kienzle *et al.*, 1995; Kazanzides *et al.*, 1995]. However, as is described in the sequel, 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 is described in several reports [Grace *et al.*, 1993; 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 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 a maximum amount of data to the surgeon about the forces exerted on the tool. This requirement is essential in the process of bone cutting where

different levels of force are required during different 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, at any stage during the task, to interrupt the automatic execution process and take over the control.

6) Fail-safe features: The most reliable systems will inevitably fail at some stage of their service. Based on this premise, the robot must support a fail-safe mode. This includes retaining the position of the tool when the power supply is lost, 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 in size and lightness. This ensures that the robot does not consume a large amount of the already crowded space in the operating room and facilitates the relocation of the robot to different positions for different tasks. The third requirement is simplicity and user-friendly operation so that staff can learn quickly how to use the robot. The last, but not least, important requirement is ease of sterilization. This requirement is critical since any tool in the operating room must either be sterilized or covered with sterile drapes.

A comparison between a serial and a parallel type of robot is given next, from which the adequacy of the robot for medical applications can be deduced.

3. Kinematic Architecture of Robot

This section presents the basic two kinematic architectures of robot manipulators — serial and parallel architecture. 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 serial (anthropomorphic) architecture of robotic manipulators. In this architecture, the output

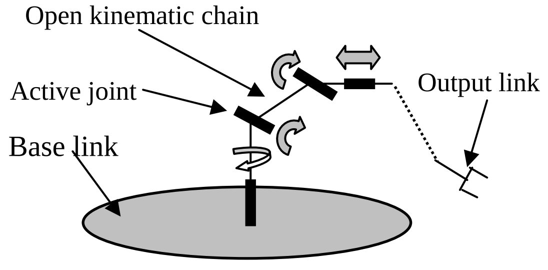

Figure 1: Serial robot

link is connected to the base link by a single open-loop kinematic chain. The kinematic chain is 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 high dexterity, but suffer from several inherent disadvantages. These disadvantages include low precision, poor force exertion capability and low payload-to-weight ratio, and they have motors that are not located at the base and large number of moving parts, which leads to high inertia.

The low precision of these robots stems from cumulative joint errors and deflections in the links. The low payload-to-weight ratio stems from the fact that every actuator supports the weight of the successor links. The high inertia is due to the large number of moving parts that are connected in series, thus forming long beams with high inertia.

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

3.2 Parallel Architecture

The parallel robot architecture is composed of an output link connected to a base link by several kinematic chains. Motion of the output link is achieved by simultaneous actuation of the kinematic chains. In contrast to the open-chain serial robot, the parallel architecture is composed of closed kinematic chains and everyeach kinematic chain includes both active and passive kinematic pairs.

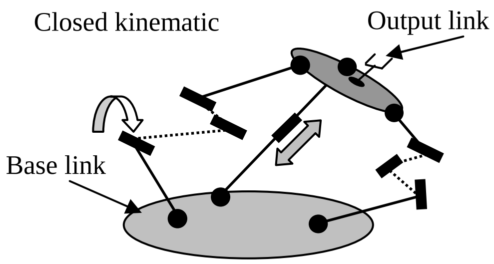

Figure 2: Parallel robot

Parallel manipulators exhibit several advantages and disadvantages. The parallel architecture provides high rigidity and high payload-to-weight ratio, high accuracy, low inertia of moving parts, and a simple solution to the inverse kinematics problem. The fact that the load is shared by several kinematic chains results in high payload-to-weight ratio and rigidity. The high accuracy stems from sharing, not accumulating, joint errors. The disadvantages of the parallel manipulator are limited work volume, low dexterity, complicated direct kinematic solution, and singularities that occur both inside and on the envelope of the work volume.

Parallel manipulators are classified into fully parallel and non-fully parallel manipulators. Fully parallel manipulators are characterized by having a single-valued solution for the inverse kinematics problem, namely to find the joint motion for a given end-effector location. The non-fully parallel robot described in this study has eight solutions for the inverse kinematics problem. The inverse kinematic solution - the one needed for control purposes - is in general much simpler in parallel robots than in serial ones.

Table 1 specifies the physical characteristics of serial and parallel manipulators. The table also presents a brief summary of the differences between fully parallel and non-fully parallel manipulators.

Table 1: Comparison between Serial and Parallel manipulators.

Property	Serial manipulator	Parallel manipulators	
		Fully parallel	Non-fully parallel
Type of kinematic chains	Open kinematic chain	Closed kinematic chains	
Type of Joints Used	Active joints	Active and Passive Joints	
Role of active joints	Twist applicators	Wrench applicators	
Direct kinematics problem	Simple and single-valued solution	Complicated with up to 40 solutions	Complicated, but with less solutions
Inverse kinematics problem	Complicated with multiple solutions	Simple and single-valued solution	Simple with multiple solutions
Joint errors	Cumulative	Non-cumulative	
Positional accuracy	Poor	Average	
Payload-to-weight ratio	Low	Very high	
Singularity	Loss of freedoms	Gain of freedoms	Gain and loss of freedoms
Singularity domain	On the envelope of the workspace	Both inside and on the envelope of the workspace.	
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	

In contrast to the bulky serial architecture, the compact and lightweight nature of parallel architectures simplifies the relocation of the robot in the operating room, economizes on space, and permits easy sterilization. The relatively small work volume of the parallel robot, if correctly designed, introduces an important safety factor. The parallel robot provides accuracy at a lower cost when compared to similar serial robots with the same accuracy level (certain accuracy levels may not be achievable at all with some robots).

Based on the above arguments, one may conclude that the parallel robot better suits the types of medical applications that require a small workspace, compact design, high accuracy and high rigidity.

4. Task Requirements

The particular application concentrated on here is the manipulation of a surgical tool in minimally invasive laparoscopic surgery. This determines the workspace, velocity, force and accuracy envelopes. The design problem is therefore to synthesize a robot that supports a given load and manipulates this load with given velocity and accuracy in a required workspace. Based on the conclusion of the previous section, we have chosen to synthesize and construct a mini parallel robot for this task.

The given load and the desired workspace were defined according to physical and geometric estimates of the requirements for certain laparoscopic procedures. The desired workspace is a volume with sides 40 × 40 × 20 mm, whereby a minimum of 20° rotation of the tool can be maintained throughout the workspace. The required external forces are equivalent to supporting a weight of 1.2 kg with a lever length of 0.1 m. The speed of the laparoscope tip should vary between 2.5 to 25 mm/s. Based on these design specifications, other implementations of this robot are possible, such as for knee arthroscopy and total knee replacement surgery in a semi-active mode.

The design specifications listed above were used for comparing several parallel robots architectures and for type and dimensional synthesis of the robot.

5. The RSPR Parallel Robot

Following a long series of kinematic and dynamic simulations, we choose the RSPR parallel robot as the one that best fit the requirements set out above. This manipulator consists of three identical kinematic chains connecting the base with the moving platform. Each chain contains a lower link rotating around a pivot perpendicular to the base platform, and is 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 constitute an equilateral triangle in the plane of the moving platform

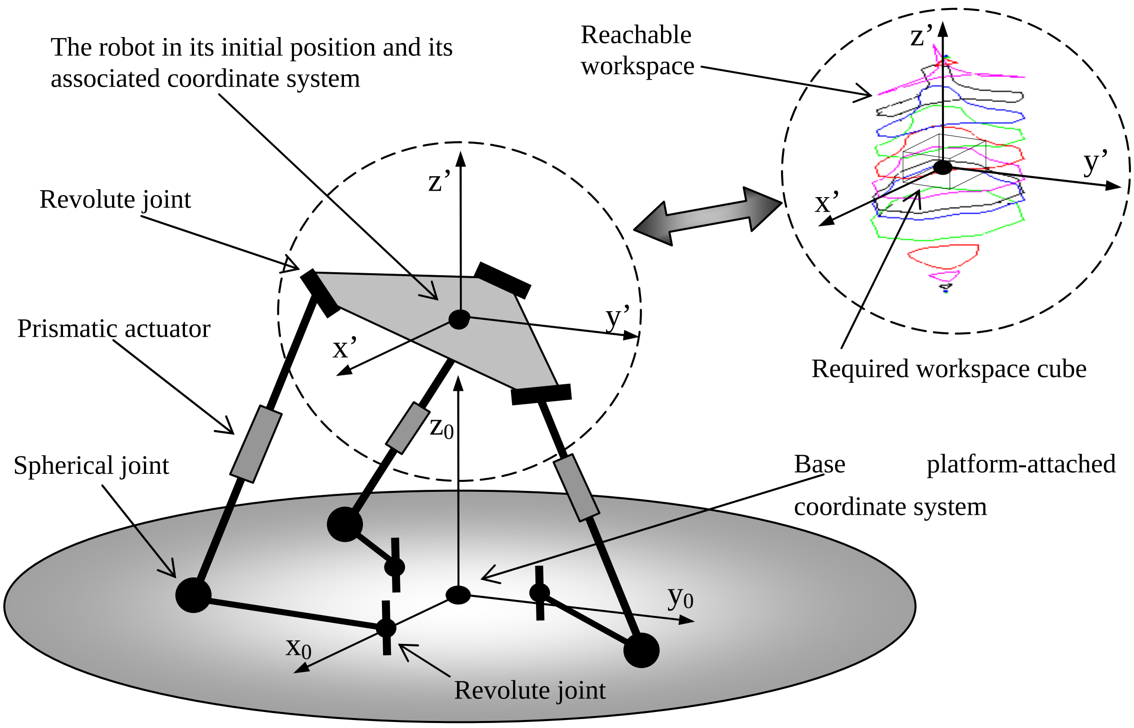

Figure 3: The RSPR robot, its reachable workspace, and the required workspace cube.

(see Fig. 3). This arrangement of joints and links provide the moving platform with six degrees-of-freedom.

This manipulator is distinguished by the location of the revolute axes of the lower links being placed offset from the center of the base platform. Alizade, Tagiyev, and Duffy [1994] presented a robot with **R**R**P**S kinematic chains. We found that the **R**S**P**R robot requires less actuator effort for the same task. Also, this robot eliminates some of the singular configurations that are present in the **R**R**P**S robot. However, use of the swept volume analysis presented in Zhiming [1994] reveals that when eccentricity is eliminated in the RSPR robot, 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 constrains, it results in a smaller vertex space and smaller work volume than a RRPS robot.

The aim of the synthesis process is to find the minimal size of the robot that provides the required work volume and end effector forces. The details of this work were presented previously in Simaan, Glozman and Shoham [1998]. The synthesis process 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 of the robots eliminated robots that possessed singular configurations within the required work volume. The synthesis process yields 22 possible RSPR robots having different characteristic dimensions. Additional design considerations for actuator's size and construction feasibility led to the selected robot.

Figure 3 shows the work volume of the selected robot which exceeds the design goal.

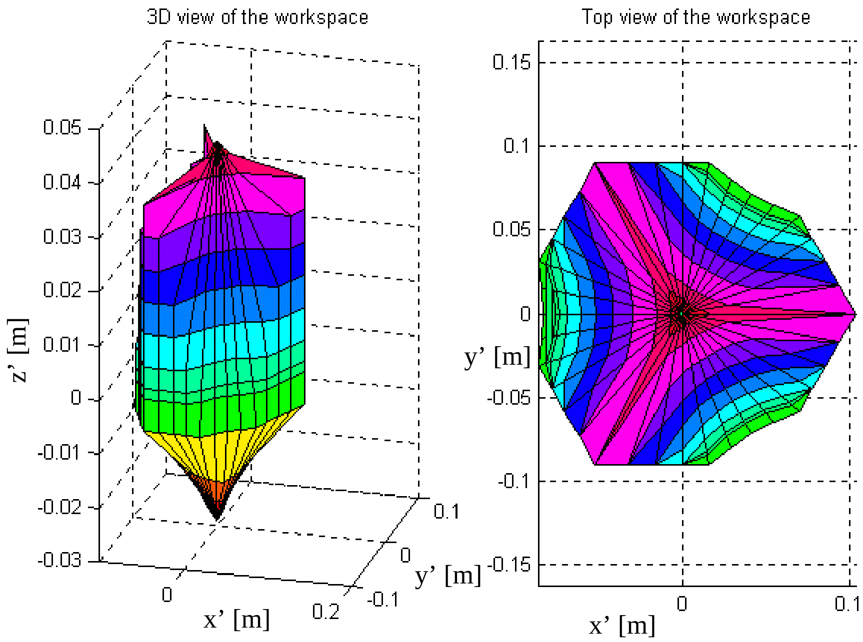

Figure 4: The RSPR robot work volume boundary surface with parallel platforms and an initial position of [0, 0, 0.16] m.

The reachable workspace is also shown in Fig. 4.

Figure 5 depicts the actuator forces 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).

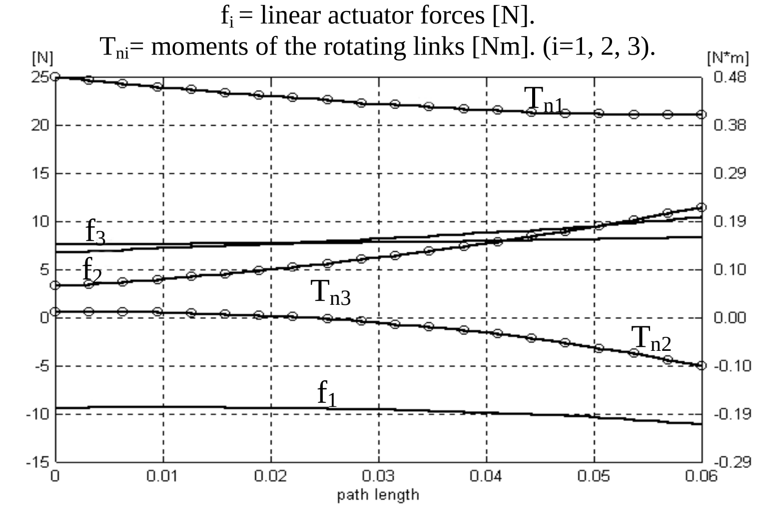

Figure 5: RSPR selected robot actuator forces along the diagonal path.

Based on the results mentioned above, an experimental robot was constructed. The constructed system which weigh less than 3 kg and can be stored in a 250 mm diameter by 200 mm height cylinder, is shown in Fig. 6, and its control diagram is shown in Fig. 7.

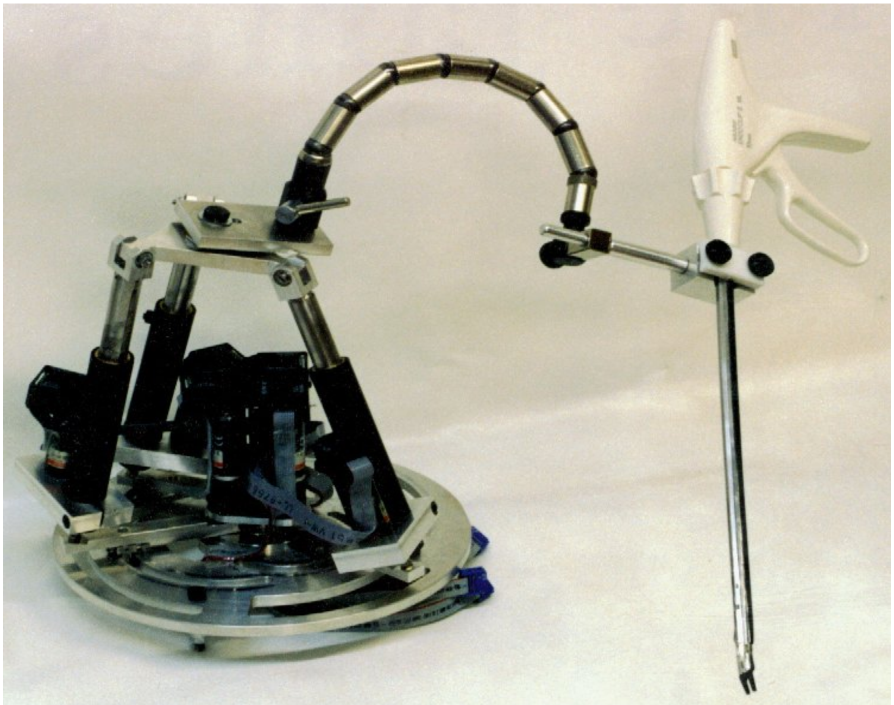
Figure 6: The RSPR prototype robot demonstrating surgical tool positioning.

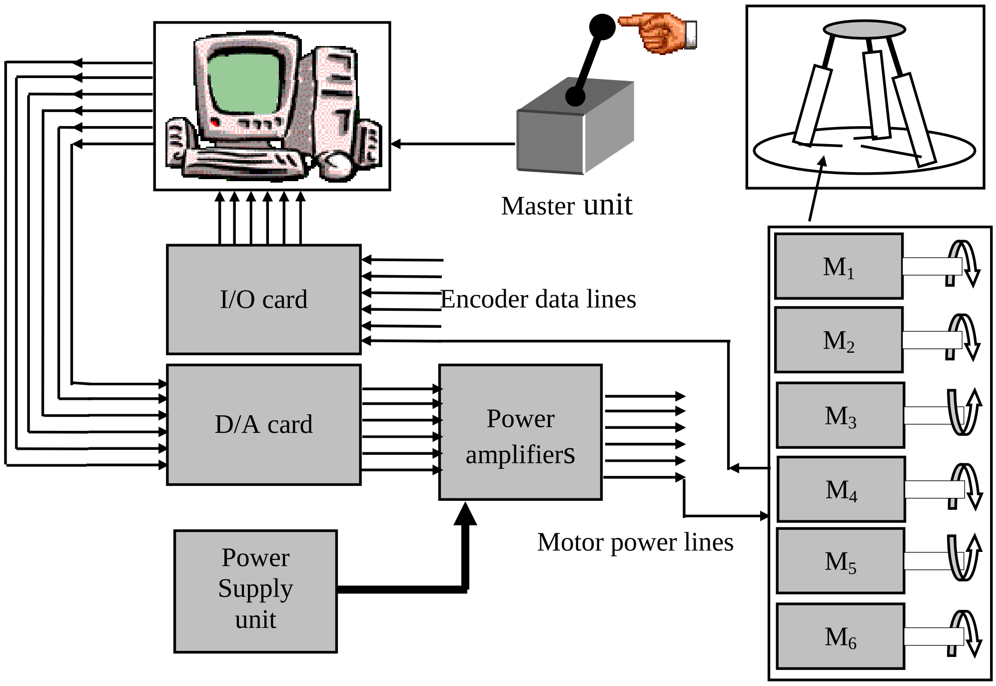

Figure 7: A block diagram of the robot's control units.

6. Conclusions

The RSPR prototype was designed, constructed, and controlled successfully to meet and the design goals. The compact dimensions and weight of the robot, as can be perceived relative to the laparoscopic tool in Fig. 6, promise easy setting-up and portability in the operating theatre. The accuracy of the robot exceeds the accuracy achieved by manual manipulation of the 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.

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