Comparison of two manipulator designs for laparoscopic surgery

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Abstract

Two kinematically dissimilar robots for laparoscopic surgery have been designed and built through a collaborative effort between IBM Research and the Johns Hopkins University School of Medicine. The two mechanisms represent two distinct design approaches and a number of different engineering design decisions. In this paper we will describe the mechanical design and kinematic structure of the two robots and report on the results of laboratory evaluations of the two mechanisms. The two systems will be compared in terms of safety, ergonomics, ease of control, accuracy, and mechanical stiffness. In each of the categories we will attempt to separate the impact of the particular design decisions made in the construction of each mechanism from the more general issue of the fundamental potential and limitations of each of the design approaches towards satisfying the particular design criterion. Based on our experience, we offer some conclusions and recommendations regarding the design of surgical robots for laparoscopy.

Keywords: surgical robots, laparoscopy, comparison

1 Introduction

Minimally invasive and laparoscopic surgeries have become increasingly more prevalent in recent years. This type of surgery offers distinct advantages to the patient in the form of less surgical trauma and shorter hospital stays. From the surgeon's point of view, however, this type of surgery presents a number of challenges. Minimally invasive procedures are characterized by restricted access to the patient's internal organs, usually resulting in a loss of direct visualization and hands-on physical access to the pathology. Instead, the surgeon operates through small skin incisions using long (usually rigid) instruments. His/her only source of visual feedback is a TV display of the view of the surgical area as seen by a laparoscopic camera inserted through one of the portals. Often an assistant is present to manipulate the laparoscope and assist with tasks such as tissue retraction.

The loss of intuitive hand-eye coordination and the need to verbally communicate desired changes in camera view to the assistant have led a number of researchers [1][2][3][4][5][6] to propose passive or actively actuated mechanical linkages to help the surgeon control the field of view of the laparoscope. Many of these efforts have focused on active, computer controlled surgical robots for manipulating the laparoscopic camera in direct response to the surgeon's commands. The means of commanding the robotic cameraman include teach-pendants[3][6], head-motions[5][2], voice[5][3], and instrument-mounted joysticks[7].

In this paper we present a comparison of two physically and kinematically dissimilar manipulator designs which have been fitted for robotic control of a laparoscopic camera. Both the Parallel-Linkage Remote-Center-of-Motion (PLRCM) robot and the Hopkins-IBM Surgical Assistant Robot (HISAR) have been designed and built through a collaborative effort between the IBM Research and

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the Johns Hopkins Medical Center. We have exercised both mechanisms extensively in a laboratory setting and pre-clinical in-vivo experiments have been conducted using the PLRCM robot.

We will compare the two mechanisms in terms of a set of key criteria determining a mechanism's suitability for use as a laparoscopic assistant. These criteria include *safety* (speed of motion, instrument force monitoring, behavior on power-off), *ergonomics* (work volume, intrusiveness, ease of manual repositioning), *control issues* (accommodation of the fulcrum, motion singularities, accuracy), and *mechanical and structural factors* (stiffness). Besides evaluating the two existing prototype mechanisms and the impact of the particular engineering and design decisions made in the construction of each, we will also address the broader issue of the fundamental potential and limitations (if any) of each of the design approaches with respect to the given criterion. Based on our experience with the two mechanisms we will offer some thoughts pertaining to the mechanical design of robotic systems for laparoscopic surgery.

The remainder of this paper is organized as follows. In Sections 2 and 3 we describe the mechanical and kinematic structure of the two arms. In Section 4 we present a detailed comparison of the two mechanisms with respect to the above set of criteria. Section 5 summarizes the results and draws some conclusions.

2 The PLRCM surgical robot

The PLRCM surgical robot consists of a 3-axis linear XYZ stage (d_1, d_2, d_3), a 2-axis parallel four-bar linkage assembly (θ_4, θ_5), a 2-axis instrument carrier (d_6, θ_7), and a motorized camera rotation stage (θ_8). The appearance and the kinematics of the PLRCM robot are illustrated in Figure 1. The instrument carrier provides for translation along and rotation about the instrument

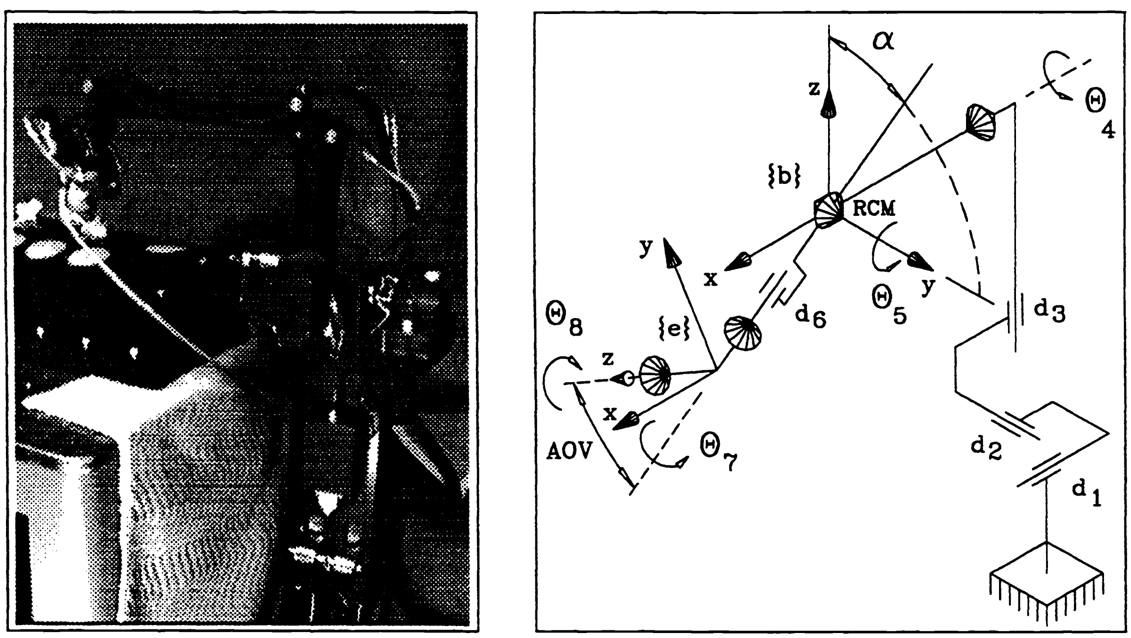

Figure 1: The PLRCM surgical robot and its kinematics (at $\mathbf{q} = \mathbf{0}$).

axis and the camera rotation degree-of-freedom (DOF) facilitates control of view orientation when the instrument is a medical telescope.

The parallel linkage structure of the distal portion of the mechanism provides a remote center of motion (RCM), distal from the linkage itself, about which all distal axes ($\theta_4, ..., \theta_8$) are decoupled. This design feature guarantees that the spatial location of the mechanism's RCM will be unaffected by the motion of the distal 5 axes of the mechanism. The PLRCM robot is also equipped with a 6-axis force/torque sensor, located at the interface between the instrument stage and the parallel linkage of the robot.

The PLRCM robot's base is mounted on a cart for easy mobility between and within the operating room. All axes are fitted with DC servo motors equipped with magnetic or optical quadrature encoders. With the exception of the instrument and camera rotation stages (θ_7, θ_8), none of the robot axes may be back-driven. The servo motors used on the robot are modest in terms of output power, and are operated at a high gear ratio in order to achieve the torque necessary to drive the mechanism.

3 The HISAR surgical robot

The HISAR arm was designed and built as a "quick" prototype manipulator to allow us to evaluate the kinematic and ergonomic trade-offs of its design. Many features which would be included in a clinical implementation (e.g., force sensing, redundant encoders, etc.) were left out of the prototype system.

HISAR is a ceiling (or support frame) mounted 7-DOF surgical robot specifically designed for laparoscopic camera holding. Its kinematic structure consists of a serial chain of torso (θ_1), shoulder (θ_2), elbow (θ_3), and wrist (θ_4, θ_5) revolute axes (see Figure 2). Mounted at the wrist is

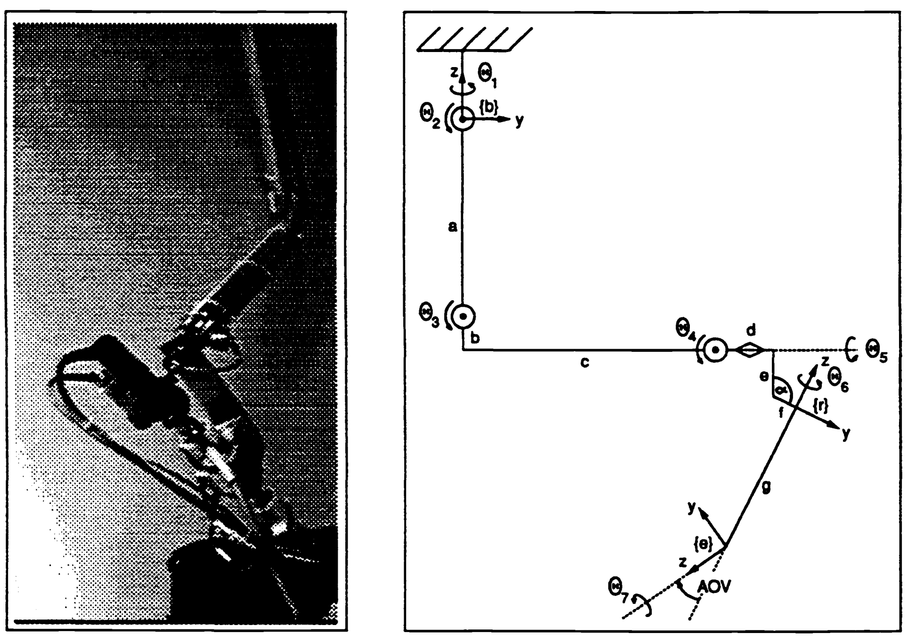

Figure 2: The HISAR surgical robot and its kinematics (at $\mathbf{q} = \mathbf{0}$).

an instrument holder, which allows rotation of the instrument (laparoscope) along its primary axis

(θ_6). Rotation of the camera with respect to the eyepiece of the laparoscope is also provided (θ_7) to accommodate control of view orientation during surgery. The instrument and camera rotation stages used by the HISAR arm are the same ones used by the PLRCM robot, described in Section 2.

A key feature of the mechanism is that the two wrist axes (θ_4, θ_5) are passive, i.e., they are encoded but not actuated. This allows the laparoscope to freely comply with the port of entry into the patient, should the patient move during the procedure. The passive axes are fitted with potentiometers, which are monitored via analog-to-digital (ADC) converters to estimate the position of the linkage. All other manipulator axes are fitted with DC servo motors equipped with magnetic or optical quadrature encoders. The gear ratios chosen for the manipulator are such that all axes except θ_1 are stiff but may be back-driven when no power is applied to the motor windings. The gear ratio and motor utilized for θ_1 is such that even with power applied to the motor, i.e. with servo action taking place, this axis may be displaced from its commanded position with relatively gentle pressure. This allows the mechanism to be somewhat compliant in case of accidental contact in the operating theater.

4 Comparison

In this section we compare two design approaches, represented by the two surgical manipulators, in terms of a set of key criteria pertaining to the suitability of a robot mechanism to assist in surgery. The set of criteria includes safety considerations, ergonomic factors, control issues, and mechanical and structural factors. Each criterion will be addressed in turn and the relevant characteristics of the two robots will be pointed out. A broader discussion of the fundamental potential and limitations of the two design approaches is included where appropriate. The conclusions of the comparison will be summarized in Section 5.

The comparison below is based on laboratory and (in the case of the PLRCM robot) in-vivo experience with the two mechanisms. Both robots have been interfaced to the same electronic hardware and were controlled by the same low-level joint controller. Also, both arms were equipped with the same instrument holder, which includes the instrument and camera rotation stages.

4.1 Safety

Since the two robots share the same electronics and control software, all safety mechanisms implemented by these system components are potentially the same for both arms. In addition to the continuous on-line checking of a number of power and status hardware lines, these safety mechanisms include hardware and software heart-beat signals and checking that voltages sensed on the motors in fact correspond to the commanded voltages.

4.1.1 Speed of motion

PLRCM: The drive trains of all axes of the PLRCM robot were designed for maximum joint velocities of 20 deg/s and 25 mm/s. These design targets were chosen for safety reasons. While a small amount of headroom exists for increasing the speed of operation by advancing amplifier gain values, the top speed of the robot was chosen so that a run-away condition may be observed and terminated by a surgeon or by the internal software safety checking before substantial motion of the mechanism has taken place.

HISAR: Maximum speed for all axes, except the torso rotation (θ_1), is 40 deg/s (the HISAR arm consists of only rotary joints). The maximum rate of rotation of the torso joint is 125 deg/s. This was found to be excessive and the joint actuator was operated in an under-powered regime to provide a comfortable, safe rate of rotation of the mechanism's arm. A consequence of this is that the arm is easily displaced from its commanded position by gentle pressure applied to the mechanism. While this behavior may be desirable from a human factors point of view, it represents a potential safety hazard, since a "full-on" failure of the corresponding power amplifier could result in a fast, large and uncontrolled motion of both the linkage and the instrument, endangering both the surgeon(s) and the patient. A second generation redesign of this mechanism would include a much higher gear-ratio on the torso joint to make it slower and stiffer.

Discussion: For surgical applications, where safety is an overriding concern, it is essential to carefully examine the requirements regarding the maximum required speed of motion of the instruments and choose the safest design accommodating these requirements. This has implications on the design of both the mechanical structure of the manipulator as well as the choice of actuators. The safest mechanical design will be one which minimizes the overall mechanical motion of the manipulator to accomplish the desired motion of the instrument tip. This consideration favors a design where the DOF of motion are decoupled about the port of entry into the patient (as in the case of the PLRCM manipulator) and the speed of instrument tip motion is thus directly related to the speed of motion of the extra-corporeal linkage. In contrast, a serial linkage may require large (and fast) motions of some of its joints to accomplish a relatively small (and slow) displacement of the instrument tip, which is clearly undesirable. As a result, for the same range of desired instrument motion velocities, the joint axes of a decoupled linkage can be powered by comparatively smaller actuators, offering an inherent degree of safety, since a high-speed run-away condition of any part of the linkage is not possible.

4.1.2 Instrument force monitoring

PLRCM: The PLRCM robot includes a 6-axis integrated force/torque sensor at the wrist, which is used for manual guiding as well as for measuring external forces exerted against the instrument. These forces could be exerted either by the port of entry or the tissue inside the patient. In the event that these forces exceed a pre-specified threshold, the control software interrupts the current task, stops all motion of the robot and alerts the surgeon via an on-screen message. In addition, all on-screen menus and graphics turn red and remain red until the condition subsides.

HISAR: No force sensor has been incorporated into the HISAR prototype. The passive wrist axes generally ensure that only minimal forces will be exerted by the instrument against the port of entry. An exception to this may occur when the instrument tip comes into contact with the tissue. Since the passive wrist tends to comply with any and all constraints on its motion, the control of the instrument is lost and subsequent motion of the instrument is in general unpredictable. If the surgeon is unaware of the situation and continues to maneuver the manipulator, spearing or gouging of the tissue may result. Clearly, this property of HISAR is potentially unsafe as the surgeon has no immediate feedback (other than visual) that the instrument is in contact with the tissue.

Discussion: The problem of uncontrolled and potentially dangerous motion of the instrument when obstructed by the tissue reflects a particular design decision in the construction of the HISAR arm and is not an inherent limitation of a passive-wrist linkage design. One solution to the problem is to equip the passive wrist manipulator with a wrist-based force/torque sensor, which could detect the instrument's contact with the tissue and allow implementation of the same safety features discussed in the case of the PLRCM manipulator above. Another approach, employed by [3], is to make use of a mechanically detachable instrument holder, which detaches from the manipulator when the force on the instrument exceeds a mechanically specified threshold. The first solution offers the flexibility of a reprogrammable or even adaptable force threshold and freezes the instrument in place when the threshold is exceeded, rather than detaching the instrument and letting it fall in an uncontrolled fashion. On the other hand, the latter approach is simpler and less expensive and may be acceptable for situations where the instrument is a laparoscopic camera. Finally, the two approaches can be seen as complementary and both could be built into the same manipulator design.

4.1.3 Behavior on power-off

PLRCM: The PLRCM arm is not back-drivable and so on power-off the mechanism "freezes" in place. This guarantees that no motion will take place following the loss of power, but also means that the robot cannot be moved out of the way manually when power is off. A quick release of the instrument from its holder can be used in this situation to retract the instrument from the patient and the robot can then be wheeled away.

HISAR: Different joints of the HISAR arm exhibit different degrees of back-drivability. The torso joint is completely back-drivable, while the harmonic drives on the shoulder and elbow joints make those joint somewhat harder to back-drive. This results in a slow "drooping" of the arm downward on power-off with the rate of droop depending on the weight of the instrument. Because the arm is essentially back-drivable, it can be moved by the surgical staff out of the way manually with only moderate effort when power has failed.

Discussion: In general, safety considerations suggest that a surgical manipulator should remain motionless following a power failure. However, the manipulator should also allow for quick removal from the operating theater, whether because of a power failure or some other consideration. While the PLRCM manipulator allows quick manual retraction of the instrument and can be wheeled away from the operating table, the linkage itself can not be back-driven in the power-off condition. A possible solution to this would be to include manually actuated clutching mechanisms on the major axes. During in-vivo system evaluations to date we have found this to be unnecessary for laparoscopic applications. However, manual clutching may be a desirable or even necessary feature for different surgical applications.

4.2 Ergonomics

4.2.1 Work volume

The range of motion of both arms is given in Table 1.

PLRCM: In-vivo surgical experiments have shown that the range of rotational motion of the existing PLRCM linkage is not sufficient to accommodate the entire range of required positions and orientations of the surgical laparoscope during laparoscopic surgery. In particular, we have found that the in-plane (θ_5) and out-of-plane (θ_4) linkage rotations would ideally require an additional

axis	PLRCM	HISAR
1	[-100,+100] mm	[-160,+160] deg
2	[-100,+100] mm	[-90,+90] deg
3	[-100,+300] mm	[-160,+90] deg
4	[-60,+60] deg	[-90,+160] deg
5	[-60,+60] deg	[-160,+160] deg
6	[-80,+80] mm	[-160,+160] deg
7	[-160,+160] deg	[-160,+160] deg
8	[-160,+160] deg	N/A

Table 1: Range of motion for the two surgical manipulators.

± 10 deg to ± 20 deg of motion in each axis. Also, the range of travel of the instrument translation stage (d_6) should be longer, with enough travel to allow complete removal and reinsertion of the instrument. This would require at least another 50 mm of travel over the existing design. Currently the instrument may be removed and reinserted by manually releasing the instrument from the instrument holder. This is not a time consuming process, but represents something of an inconvenience.

HISAR: Laboratory tests and our observations of the PLRCM system during surgery appear to indicate that the range of motion of the HISAR arm is sufficient to accommodate the entire range of motion needed to position surgical instrumentation during laparoscopic surgery. Complete removal and reinsertion of the instrument is possible by de-activating the servo control and pulling the laparoscope out while it is still in the grasp of the instrument holder. Since no in-vivo experiments have been performed with the HISAR arm, this assessment of appropriateness of the range of motion of the manipulator has not been verified in a surgical setting.

Discussion: While the existing PLRCM design lacks adequate mobility in the two rotational degrees of freedom of the parallel linkage and the instrument translation, both can be at least partially accommodated within the existing design framework. Relatively minor modifications to the design of the parallel linkage and the mounting of the instrument carrier could extend the out-of-plane rotational range of the mechanism to ± 90 degrees. The in-plane rotation, however, is fundamentally constrained by the nature of the mechanism to approximately ± 60 degrees, which has been shown to be insufficient in some situations. The range of the instrument translation axis could be extended in a number of ways. One approach would be to simply use a physically longer translation stage. However, this solution implies a larger and bulkier instrument carrier stage within the surgical working volume and is thus undesirable. An alternative would be to turn the fixed length links of the proximal portion of the parallel linkage into actuated telescoping links. The disadvantage of this solution is that it would make the linkage potentially taller (at full extension of the telescoping links) and therefore more intrusive into the surgical workspace (see Section 4.2.2). It would also make the detailed design of the mechanism more complicated. On the plus side, it would reduce the bulk at the end of the arm, where workspace is at a premium and would simplify the end-of-arm sterility issues.

4.2.2 Intrusiveness

PLRCM: Our surgical colleagues have indicated that the PLRCM arm sometimes gets in their way. Specifically, the parallel linkage was found to be too tall and occasionally interfered with the surgeon's elbows during the operation when the manipulator was located alongside the surgeon. The robot cart also has a relatively large footprint, and thus "blocks out" a large portion of floor space. This aspect of the robot's physical layout is due to the design requirement that the RCM be adjustable ($\pm$100 mm) relative to the patient, which in turn requires an XY translational stage at the base of the robot.

HISAR: No surgeon feedback is yet available on this issue for HISAR. However, laboratory experiments have demonstrated that HISAR tends to occupy less of the surgical workspace than the PLRCM manipulator and is thus less intrusive. Still, for large changes in the instrument pose, HISAR's elbow can swing around into configurations where it may interfere with the surgeon. The HISAR robot's ceiling mounted configuration and kinematics were specifically designed to avoid occupying floor space next to the surgical team. Overall, we expect the surgeons to find the HISAR system less intrusive than the PLRCM system when acting as a laparoscopic assistant.

Discussion: We found that the placement of the PLRCM robot relative to the surgeon had a big impact on its intrusiveness into the surgical workspace. While the linkage tends to interfere with the surgeon when located alongside him or her, it is much less intrusive when located on the other side of the operating table across from the surgeon. In addition, the height of the parallel linkage could be reduced by shortening the vertical links of the linkage. Similarly, the footprint of the PLRCM mechanism could be reduced by clamping the linkage to the operating table ([8]) and making the XYZ stage smaller or even passive. The overhead design of the HISAR arm appears to be preferable from a purely ergonomic viewpoint. The problem of the mechanism swinging around with its elbow towards the surgeon could be overcome by integrating a torsional degree of freedom into the "upper arm" of the linkage, making the extra-corporeal positioning linkage kinematically redundant and thus able to avoid such undesirable configurations. Alternatively, a SCARA-like kinematic design could be used with a horizontal upper-lower arm linkage placed well above the surgical area with a long vertical link descending into the surgical area to position the instrument. This would move the volume occupied by the positioning linkage outside the critical surgical volume, but poses a potential safety hazard (as do all overhead designs, in fact) in that the mass of the manipulator is located directly above the patient.

4.2.3 Manual repositioning

PLRCM: The force/torque sensor, mounted at the wrist of the PLRCM arm, can be used to reposition the robot manually by taking hold of the instrument holder and pushing the arm in the desired direction. A set of momentary switches on the instrument holder provide a means of engaging this mode. The speed of the compliant motion is proportional to the exerted effort but even at top speed it is relatively slow (e.g., 10 deg/s, 10 mm/s). The effort exerted by the surgeon is interpreted in Cartesian coordinates and the response of the system is therefore independent of the kinematics of the robot.

HISAR: The HISAR arm is back-drivable and so can be repositioned manually by simply pushing the arm. However, positional joint servoing must be disabled while the arm is being moved. This is accomplished by making use of the same momentary switches on the instrument holder, as in the case of the PLRCM. Because the arm is not being actively controlled during the repositioning and the only resistance to the surgeon's effort is due to the gear train friction, the repositioning can proceed faster than in the case of the PLRCM. The disadvantage of this repositioning method is that the manipulator is moved on a joint by joint basis rather than in Cartesian coordinates. In practice, this means that two hands are usually required to restrain some joints to achieve the desired final arm configuration.

4.3 Control

All electronics and low level control is shared between the two arms, as indicated above. The only differences in the Cartesian control of the two robots are the modifications necessary to accommodate the difference in the kinematic structure of the two mechanisms.

4.3.1 Accommodation of fulcrum

PLRCM: The PLRCM arm exhibits a fixed remote center of motion by virtue of the mechanical design of the distal linkage. This implies that the arm automatically accommodates the fulcrum constraint in hardware so long as the mechanism's RCM is aligned with the port of entry into the patient. This feature greatly simplifies the control of the mechanism as no special software considerations are necessary to account for the inversion of motion directions about the fulcrum point.

HISAR: The HISAR arm does not have a remote center of motion enforced by the mechanical structure of the mechanism. Rather, the passive wrist axes automatically comply with the port of entry into the patient. Therefore, the software control of the HISAR arm must be made "aware" of the motion inversion effect created by the fulcrum and must be able to determine the instantaneous fulcrum point on-line as the mechanism moves in order to correctly track the desired motion trajectories of the instrument.

Discussion: For passive-wrist manipulators, a simple software solution can be devised which assumes that the port of entry into the patient acts as an ideal pivot point and a control strategy can be derived which takes into account the motion constraint imposed by the port of entry and accommodates the motion inversion effect created by the fulcrum [9]. However, experience has shown that the idealized mathematical concept of a point pivot represents a poor model of the actual motion constraint created by the incision at the port of entry into the patient. As a result, the on-line estimation of the instantaneous location of the fulcrum point is numerically noisy and only asymptotically stable, which tends to degrade the accuracy of instrument positioning. While this appears very acceptable for the qualitative task of navigating a laparoscopic camera, it is likely to be detrimental in applications where precise control of the instrument motion is necessary. Clearly, more sophisticated means of tracking the fulcrum point could be developed, but some residual error will likely remain. By contrast, a system based on a mechanical remote center of motion can achieve very good precision while maintaining the fulcrum constraint. Any misalignment between the mechanism's RCM and the port of entry into the patient can be corrected on-line by measuring forces exerted on the instrument due to this misalignment and adjusting the location of the RCM accordingly.

The flexible architecture of our high-level control software has allowed us to use the same constrained Cartesian control formalism [10] to control both mechanisms. The passive-wrist nature of the HISAR mechanism and the fact that the fulcrum constraint (and the resulting motion inversion effect) had to be specified in software were easily accommodated within the framework of this control formalism [9]. This flexibility and commonality of software has enabled us to test different manipulator designs quickly and should allow us to use different mechanisms for different surgical tasks in the future with only superficial modifications to the control software.

4.3.2 Motion singularities

PLRCM: The PLRCM has no kinematic motion singularities within its reachable workspace. Mathematically the arm becomes singular when the parallel linkage is fully outstretched (i.e., $\theta_5 = 180$ deg), but this configuration is physically unattainable by the mechanism. This again simplifies control.

HISAR: The HISAR arm exhibits a kinematic singularity when the wrist of the arm lies along (or close to) the axis of the torso joint θ_1. Unfortunately, this singularity lies in a central and often traversed portion of the arm's workspace and is very undesirable. Avoidance of this singular configuration places an additional requirement on the software control and potentially sacrifices a portion of the arm's useful workspace.

Discussion: HISAR's motion singularity is inherent in the particular design of HISAR's serial extra-corporeal linkage. While most mechanisms suffer from kinematic singularities, it is often possible to match a mechanism to the task, such that no singularities exist in the portion of the manipulator's workspace required by the task. Aside from choosing an entirely different mechanism, the singularity exhibited by the HISAR arm could be avoided by redesigning the "upper arm" of the linkage to include a torsional degree of freedom as discussed in Section 4.2.2. This would make the extra-corporeal positioning linkage kinematically redundant and this redundancy could be exploited to avoid the singular configurations of the arm.

4.3.3 Precision

PLRCM: All axes of the PLRCM arm are actively controlled and are equipped with high gear-ratios and high resolution encoders. The manipulator axes are designed for near zero mechanical backlash. The mechanism has shown itself to be repeatable to better than 25 microns. The accuracy limitations are those imposed by the stiffness of the linkage and by machining tolerances. This mechanism can be used to position a surgical instrument very accurately. Use of the force sensor data to estimate mechanical loads on the PLRCM linkage and an appropriate kinematic model should allow the mechanism stiffness to be factored into precision motion tasks. It should be noted however that bending of the instrument itself in response to forces exerted by the cannula may be the limiting factor on achievable precision in laparoscopic surgical tasks.

HISAR: Since the wrist axes of the HISAR arm are passive and the location of the fulcrum point must be estimated by the software, the precision of instrument positioning is not as good as that of the PLRCM arm. In addition, the long moment arms of the external linkage, and the fact that cables are used to actuate the elbow joint, combine to create a relatively soft mechanical system. Also, as was mentioned earlier, no guarantees about the positional accuracy of the mechanism can be made when external forces are acting against the instrument. In general, this mechanism does not represent a good choice for tasks requiring high precision. It should be noted that this characteristic was, in a sense, chosen deliberately. The spindly nature of the upper and lower arms of the linkage makes them relatively unintrusive into the surgical work space, and the camera holding task for which this robot was specifically designed is by nature somewhat imprecise.

5 Conclusion

Two design approaches, exemplified by two kinematically dissimilar prototype mechanisms, have been compared in terms of a set of critical criteria determining a mechanism's suitability for use as a surgical assistant. The set of criteria included safety, ergonomics, ease of control, and structural factors. This comparison was based on laboratory and in-vivo (PLRCM only) experience with the two arms.

We have found that the two arms present an interesting set of trade-offs with respect to the selected set of criteria. Both arms perform well for the simple task of maneuvering a laparoscopic camera inside the patient (or abdominal simulator) and either arm would therefore be suitable for this application. The key differences between these two arms are their ability to execute precise motions in the presence of external disturbances, their working volumes, and their footprint in the operating room (OR). The PLRCM robot excels at precise positioning and instrument manipulation, but has a working volume and OR footprint that make it less desirable as a laparoscopic camera holder. The HISAR robot does not allow precise positioning, but has a working volume and footprint which are a better match to the requirements for holding a laparoscope. Besides precision, the key advantages of the PLRCM surgical robot are its ability to measure forces exerted by the tissue against the instrument (and warn the surgeon if necessary), and the ease of control of the arm — the fulcrum constraint and motion inversion effect are taken care of in hardware, the arm has no motion singularities in its reachable workspace. On the other hand, the light-weight construction of the HISAR arm and its approach into the surgical workspace from above make it less intrusive into the surgeon's working volume and able to accommodate a larger range of instrument positions and orientations. Being back-drivable, it is also easier to move out of the way in the event of power failure or simply when it is no longer needed.

The experience of having designed and tested these two mechanisms has led us to a number of conclusions and guidelines regarding the kinematic and mechanical design of surgical robots. The PLRCM was designed to be a fairly general purpose surgical robot. Since we saw (and continue to see) its primary use in applications where motion accuracy is necessary, we designed the mechanism to be able to deliver a fairly high degree of kinematic accuracy. This design goal tended to "bulk up" the robot structure, thus affecting the ergonomics of the system in the surgical workspace. While the system is clearly suitable as a laparoscopic camera holding robot, it may get in the way in procedures which require that it be located alongside the surgeon or which require that a large number of surgical personnel (and the robot) be present around the operating table at the same time. It is probably best suited to laparoscopic or percutaneous procedures requiring a high precision targeting device, potentially guided by pre-operative and intra-operative image data of the patient. Also, in some situations it may be possible to roll the robot to the operating table only for those parts of the procedure where it will be needed and keep it out of the way the rest of the time. The HISAR robot, on the other hand, was designed specifically to hold a laparoscopic camera and ergonomic factors were an overriding design goal. It appears to be well suited to the task of laparoscopic camera holding, but would be very difficult to apply to precise pointing applications. The overhead design keeps it light-weight and out of the way, but the use of a passive wrist makes precise control a challenge.

It is difficult to design a general purpose surgical robot. The workspace, ergonomic and precision requirements associated with different procedures vary greatly. Once a promising class of applications for robots in surgery is identified, a specific mechanism and design approach may be required to adequately address the application requirements within cost constraints. However, the manipulator itself is only one part of an overall system which includes control electronics, computers and software, human-machine interfaces, surgical end-effectors, and much more. Although these components clearly affect (and are affected by) manipulator design, it is very valuable to provide as great a degree of reusability and kinematic independence as possible, since their development (and clinical qualification) can easily dominate the total time and resource expenditure required for applications. We have found that developing two very different manipulators within the same overall system has been an especially valuable experience in helping assure an appropriate degree of independence.

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