Spatial configuration of a Manipulator for Laparoscopic Telesurgery.

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Abstract This paper presents the spatial configuration aspects and observations in the research work of an experimental laparoscopic surgery performed remotely with a manipulator. The telesurgery was performed in a live pig to which the gall bladder was successfully extracted, the pig survived the surgery with no complications at all. To perform the procedure, a careful study with simulation of the spatial configuration, limitations and advantages of the manipulator were performed, resulting in a successful operation. Additional interesting aspects where found on the mechanical adaptations made to the robot to enhance its spatial suitability. The results obtained with this experience have shown that approaching the problem by imitating as much as possible the human spatial and dynamic characteristics, is not always the best thing to do. Key Words - *Tele-Operation, Applied Robotics, Robotics in Medicine.*

1. INTRODUCTION.

Telemedicine is being applied into more and more aspects of modern medicine. Telemedicine involves a communications means by which a medical skill is practiced by an expert(s) interactively with patient(s) and/or colleagues in a remote location relative to each other. Contrary to the belief that technology dehumanizes the processes in which it gets involved, telemedicine is exactly for that, to humanize medicine for people that otherwise would have some limitations with this service.

Some applications of telemedicine are:

- Take the skills of medical experts to a remote site that has a limited coverage of specialized health services.
- Provide highly skilled medical services in war zones with out the need to have those medical doctors within the military troops.
- Expand the educational coverage of medical experts by means of teleconference in which examples and practical training can be provided interactively through telemedicine.

This work involves a telemedicine project, studied and developed to a practical experimental implementation. The project consists of a telesurgery procedure performed with a robotic manipulator being remotely commanded by a skilled surgeon.

By using a telecommunication means to transmit video and voice between the surgeon and the patient and assistants in the remote operating room, and additionally to transmit data to control a robot system, a Telesurgery can be performed. Telesurgery does not mean that the robot alone can perform an operation under the remote control of a surgeon, there must be a group of qualified medical assistants supporting the procedure, but the main skills and the most critical decisions are provided by the remote surgeon.

Telesurgery does not have to be restricted to long distance applications. At present, many new diseases and situations in an operating room make the work risky or difficult to surgeons. Even if the Root is a few meters away, or a few steps with a security glass in the middle, telesurgery has many applications:

- To operate without infection risk to the surgeon, patients with dangerous diseases such as AIDS.
- To perform the extraction of hazardous projectiles from wounded patients.
- To perform high precision micro-surgery procedures, obtaining more accurate results with less fatigue and stress to the surgeon.

To perform a successful telesurgery three components have to be present:

- An expert surgeon.
- The adequate technological tools.
- The correct adaptations between the robot, the surgical tools, and the patient.

This paper presents the work performed and the experience gained in the last aspect of the project: the spatial configuration aspects involved between the manipulator, the surgical tools and the patient

2. WHY LAPAROSCOPIC SURGERY.

For surgeons, one of the most important aspects of surgery is the sense of touch. With his/hers hands the surgeon feels the patient's organs and gets a very important feedback.

In Laparoscopic surgery the situation for the surgeon changes dramatically as compared with a classic procedure.

- The surgeon no longer looks directly at the patient or his/hers own hands. He/She is looking at a video monitor that is placed at one side and above the patient, quite out of the way of his/hers hands.
- The size of the image is distorted (normally amplified).
- There is no direct touch sense with the organs. Some amount of texture feedback can be felt through the tool, but is like comparing the feeling of touching with the fingers with the feeling of poking with a stick.

The fact that for this procedure the surgeon is already forced to look at a monitor and has already lost most of the sense of touch makes this procedure easier to learn when done remotely with a teleoperated robot.

An additional advantage is the existence of a large number of commercial tools which are easier to adapt to a robot's grip than the classic surgery tools.

Looking from the point of view of the particular surgery to perform, two options are routinely performed in our Hospital using the laparoscopic procedure:

- The Gall Bladder extraction (when it is affected by stones).
- Knee ligament reconstruction (usually after an sports injury).

The Knee ligament reconstruction is a very complex operation performed only by the most skilled surgeons. It is not very adequate for an experimental work at this stage.

The Gall Bladder extraction is a relatively simple procedure performed in our Hospital even by final year medicine students making the surgery practices. It implies little risks to the patient, and if a problem arises, it can be solved by performing an emergency open surgery. Another characteristic of the Gall Bladder extraction is that the patient can lead a nearly normal life without it, this means that if the surgery is performed in a live animal, it is possible for it to live a normal life in captivity, specially if its life expectancy is low compared with its longevity (such as the case of pigs for human consumption).

Given the mentioned characteristics, the Laparoscopic extraction of the Gall Bladder was chosen as the procedure to use for our experimental work.

3. DEVELOPMENT OF THE SYSTEM.

Initially, the group performed a series of observations in routine Laparoscopic Cholecystectomy surgeries, performed in the San Ignacio Hospital, in Bogotá. At this stage the objective was to analyze and determine the minimum characteristics needed for the system to perform the operation. This led to the initial integration of the PUMA type, 6 degrees of freedom robot arm with the laparoscopic tools, the communications system between the robot's control computer and the remote control system, and video and audio communication systems.

Once the system was integrated, the first tests where performed using a rubber model of the abdomen, practicing the procedure on fruits and clay organs. During these tests it was determined that the best maneuverability was achieved when the tool entered the *skin* in approximately the same angle as it enters in a procedure performed by a person. The position of the different tools relative to the abdomen of the patient has to remain the same as in a normal procedure since they are determined by the position of the organs and the way in which they have to be approached in order to perform a safe operation (Figure 1).

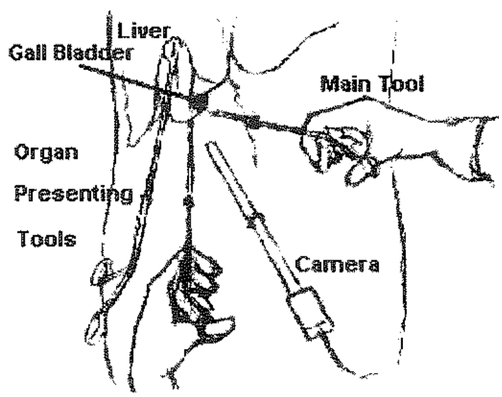

Figure 1

The main tool entrance position is determined by the relative position between the gall bladder, the liver, the hepatic artery, the portal vein and the bile duct. Approaching these organs from the patient's right in the abdomen (as shown in figure 1) gives the best position to separate the artery, vein and duct, as well as giving the best clearance from the liver. The position of the camera is also critical, since a wrong or ambiguous view could lead to fatal mistakes (confusing the artery with the vein or mistaking a ramification), observing the organs from below gives the best view to differentiate the vein, artery and duct and its ramifications in the moment of clipping and cutting.

The position of the middle auxiliary tool (the one nearest the camera in figure 1) is not very critical. In the case of a normal surgery this tool is usually shared between the surgeon's left hand (as shown in figure 1) and the surgeon's assistant's right hand, thus the middle position is normally the best. In the case of the telesurgery this tool is going to be used always by the surgeon's assistant, thus its position can be somewhere around the middle to the lower left.

Keeping this tool topology, the manipulator will get in charge of the main tool (Figure 2) and the surgeon will be remotely controlling the it. The camera and the organ presenting tools will be used by the surgery assistants.

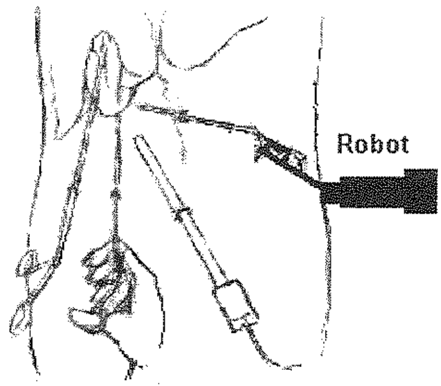

Figure 2

With this spatial configuration in mind the tools where adapted for the robot. The sixth degree of freedom of the manipulator (the opening and closing of the gripper) was used to grasp the modified tools, thus it was converted to a rigid grip, therefore leaving 5 d.o.f. from

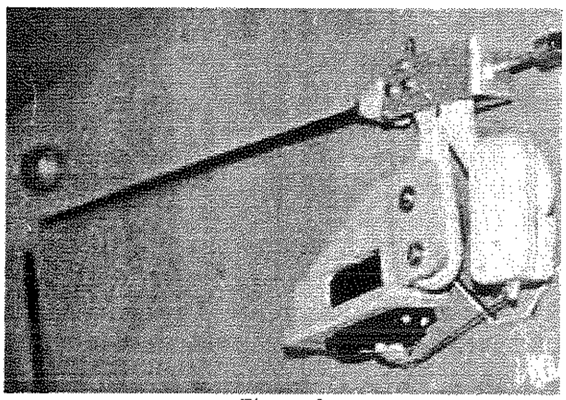
Figure 3

the robot's base to the skin entrance of the tool. The tool was opened and closed with a hobbyist servo mechanism providing the sixth d.o.f. at the tip of the tool. A photograph of the modified tool is shown in Figure 3.

Using the rubber model of the abdomen a complete procedure was simulated. The manipulator was located in the approximate position where the surgeon would be relative to the patient, and the tool entering in approximately the same angle.

3.1. D.O.F. Limitation.

After several trials in the rubber model the first problem appeared. The shaft of the tool forced the skin to the sides too much, it was very difficult to make it pivot in the correct place, so it was displacing in the same plane as the skin in most of the movements. The first option to solve the problem consisted in analyzing the mechanical possibility of the manipulator to move the tool so that it would pivot around the entry point in the skin, and to design an algorithm to achieve this.

According to classic manipulators kinematics, for a PUMA type manipulator to be able to locate the final tool in any position in space (with in its movement range envelope) it is possible with 4 or more degrees of freedom. With six or more degrees of freedom it is possible to include any desired orientation to the tool in any desired position. The manipulator used has 5 d.o.f. from its base to the skin surface, and since in this application the tool has a restricted orientation, it is possible to achieve any desired position at the skin surface. But it is a very difficult task.

Although there are many such algorithms in use in industrial manipulators, they are used in 6 d.o.f. robots, are used with off-line training and for repetitive tasks, not in teleoperation real time tasks. For this application a new algorithm or method would have had to be developed. While working in possible mathematical solutions, other methods were explored also.

3.2. Indirect control of free joints.

The analysis for developing a control algorithm that would enable pivoting the tool at the skin's entry point in an on-line, real time, teleoperated application proved to be very complex. While work was being done in this aspect, a *temporal* solution was used to be able to at least continue tuning the rest of the system. This solution turned out to be the answer to the problem.

An universal joint was inserted between the gripper and the tool so that it would bend freely in any direction just below the site into which it was anchored to the manipulator. As it was explained earlier, the gripper was converted into a rigid union between the manipulator and the laparoscopic tool, the universal joint would then add 2 new degrees of freedom after this point and before reaching the skin's entry point. This provided a total of 7 d.o.f. from the robot's base and the skin, but with the constraint that the last 2 d.o.f. are not directly controllable (they do not have motors or any type of actuator that can be controlled directly), those 2 d.o.f. present in a single joint are free to move and would do so depending on the forced exerted by the robot's other joints and the force exerted by the skin were the entry point would act as a pivot. A photograph of the modified tool can be seen in Figure 4.

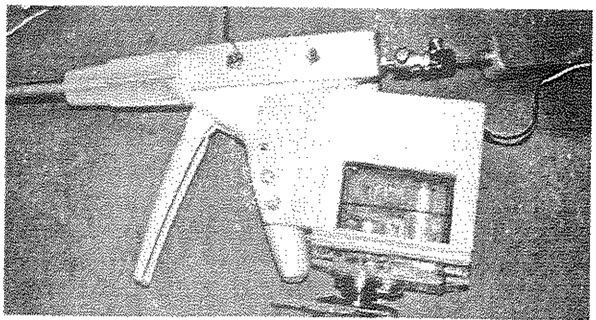

Figure 4

In figure 4, the detail of the universal joint can be seen. The L shaped part at the right of the joint is the one that locks into the gripper of the robot when it closes, the tool is attached to the other side of the joint. When the robot *takes* the tool it hangs freely from the grip, the surgeon's assistant guides the tip of the tool to the opening of the trocar and after this the robot can control the tool by pivoting it on the skin's opening. The photograph in Figure 5 shows an assistant guiding the insertion of the tool.

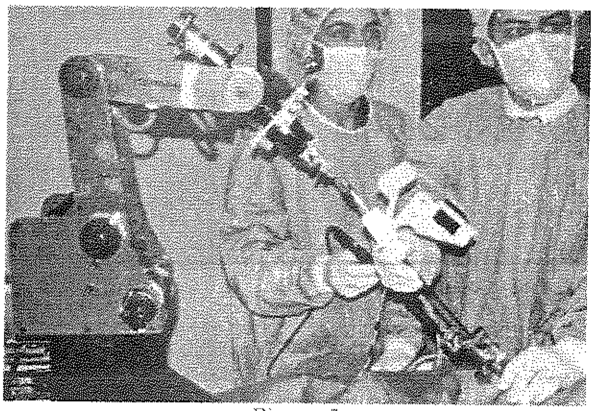

Figure 5

With this joint, the final movement of the tip of the tool is inverted relative to the original movement with the rigid system. The surgeons quickly learnt to control the manipulator in the inverted mode.

Contrary to what was expected, these 2 additional free degrees of freedom made the system easier to control, in addition to providing more versatility to the movements. The fact that there were a redundant number of degrees of freedom with 2 of them indirectly controlled, did not complicate the inverse kinematics of the system as mathematically would have been predicted. This was due to the inherent constraint of the orientation of the tool, which enables the preceding joints to remain in the same basic configuration.
An additional constraint is the position change of the robot, which has to avoid any type of singularities. This limits the solution space to a given tool movement. This constraint means that since a kinematics singularity would most probably be fatal to the patient, the joint configuration for a given tool position, relative to the previous state, *must* keep the current joint spatial topology in order to avoid out of range movements. At this respect it is interesting to notice that a human operator (the surgeon for instance) can handle kinematics singularities by moving the body, while the robot can not do this since it has an anchored base.

3.3. Final Spatial Configuration.

After the final adjustments on the rubber model, the spatial configuration to be used in live animals tests was determined as follows (see Figure 6):

- The trocars positions were kept similar as shown in Figure 1 which is one of the most commonly used in normal surgeries.

- The robot's base was anchored to the left side of the patient, at a distance equivalent to the length of the *arm* of the robot (without considering the *wrist's* length), at an angle of about 130 degrees from the axis of the body lengthwise (the axis parallel to the spinal cord).

- The surgeon assistant stood at the right side of the patient, looking the monitor placed a little to the right of the head of the patient. With the functions of handling both auxiliary tools (Endo Grasp tools), and helping to change the tools in the robot arm.

- The instrument assistant stood behind the surgeon assistant, handling the camera as well.

4. TESTS IN LIVE ANIMALS.

After the final validations in the laboratory models, the system was used to perform Laparoscopic Cholecystectomy to a number of live Pigs. The pigs were between 4 to 6 months old. The surgeries took place in the amphitheaters of a Veterinary school, and the surgeon was in a staff office in a nearby building.

The surgeries were performed with all the procedures used in a human operation. An all-medical staff was in charge of the surgery, having only as back up a group of Veterinary surgeons.

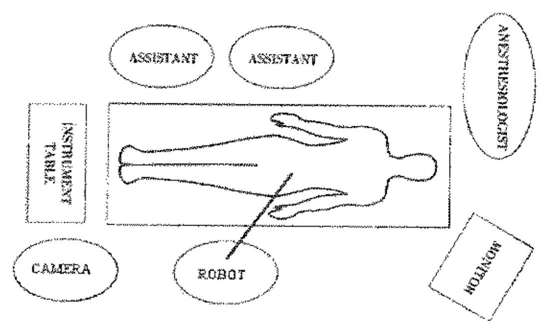

Figure 6

Figure 7 shows a photograph of the trocars in the abdomen of the patient (the pig). The middle tool entry point is a little higher than the leftmost tool, as done in usual surgeries, but displaced to the left to optimize the orientation for the surgeon assistant that will be in charge of this tool all the time.

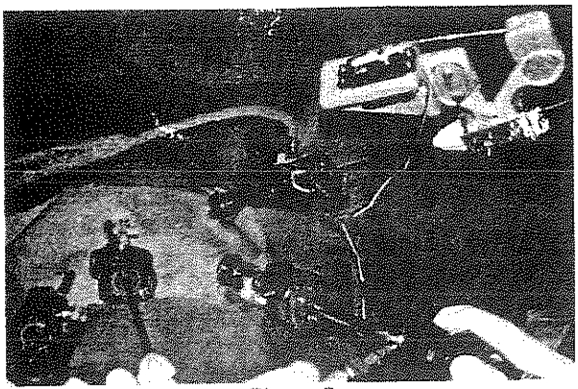
Figure 7

Figure 8 shows a global view photograph of the spatial configuration used. Since the pig is smaller than humans, the instruments and camera assistant is actually standing at the feet of the patient (in can also be seen in Figure 5 for another operation). In the background a tripod can be seen. It holds an overhead camera which is transmitting a global view of the operating room to the remote surgeon. This global view is important so that the surgeon can be sure that he/she is not trying to perform a movement that could result in a kinematics singularity.

In his office, the remote surgeon is looking at two Video Monitors, one that shows the view of the laparoscopic camera, and the one that shows the view of the overhead camera. In addition there is a bidirectional voice link between the surgeon and the assistants in the operating room.

The overhead camera is located behind the robot but at more than 160 degrees from the axis of the body lengthwise (the axis parallel to the spinal cord, see Figure 6) so that the robot can be observed slightly from the side to have a better judgment of its kinematics configuration at any given moment.

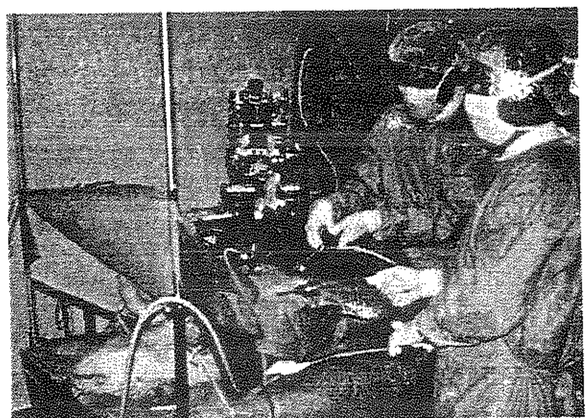
Figure 8

All of the operated animals survived and the surgeries where a success.

After these experiments it was confirmed that the spatial study performed yielded successful results and guidelines for this type of remote surgeries. Although the user interface to control the robot remotely was not the most appropriate (since it was also under study), the fact that a careful analysis of the spatial configuration was made, permitted the surgeon to perform the surgeries successfully. The manipulator was efficiently controlled during the complete operation and the two assistants had no trouble in performing all the tasks they were responsible for.

5. ANALYSIS OF RESULTS.

The success obtained in the surgeries are very encouraging in the field of telemedicine. Two main aspects are important for the system: the slight modifications to the traditional spatial configuration made to accommodate the tools for the robot, and the modifications to the tools kinematics made so that the control of the robot can be achieved more efficiently.

When the project was started, the initial approach was to start from the configuration used by human operators and trying to accommodate the manipulator to it. With this approach a working system was achieved, but the control of the system resulted very difficult and it seemed that a complex algorithmic scheme would have to be developed to aid in the telecommand of the manipulator.

After several training trials and a careful analysis of the kinematics of the manipulator-tools-organs system, a simpler and more efficient solution was achieved by modifying the basic topology of the spatial configuration. The use of the universal joint to provide two additional degrees of freedom, even though that the five degrees of freedom already present were redundant for the kinematics needed, proved to be a very efficient solution. Although at the beginning it seemed that it would complicate the manual control of the system by the surgeon.

With the universal joint solution it was found that the learning curve of the surgeons (in the remote control of the manipulator) was much faster than without the joint, and of course it was possible to achieve a much precise control of the tool with less stress to the skin of the patient (and therefore with lest stress and energy consumption for the individual motors of the robot's joints). The fact that the movement of the tip of the tool was reversed with respect to the initial (5 d.o.f.) configuration did not have any adverse effect on the final proficiency in the control achieved by the surgeons.

The most interesting observation about this additional free joint aspect is that from the point of view of the robot's control computer and its kinematics, the use of a free moving joint complicates greatly the control of the system. This makes it look as if the manual tele-control of the system by a human operator would be even more difficult, but actually it was easier and more versatile. From a careful revision of the videos taken in a normal laparoscopic surgery, and also analyzing ourselves doing the procedure in a laparoscopic tools trainer, it was noticed that humans actually move the wrist so that the tools pivot freely over the skin's entry point, rather than trying to pivot them on purpose. In other words, if the tool was used over a hole in a tighten rubber surface (or over the patient's skin) the movements and the mental attitude is completely different from trying to pivot the tool on a virtual fixed point in the air were no resistive force feedback could be sensed (as when using the robot in tele-control operation). It was even amusing to do the experiments and see how the mental and *kinematics* situation changes so dramatically in these two different *modes* of control. After these analyses it looks obvious that the final configuration used for the system is a much more efficient from the human operator point if view, than trying to assist the control with complicated algorithms that, apart from being difficult to develop, would add electronic complexity to system, and therefore, reduce its reliability (the more parts a system has, the more probability there is for a failure to occur).

Another additional point observed during this stage of the project was that because of the many adaptations done to the robot and the tools, in conjunction with the fact that the robot is a didactic type, there was a slight overshoot at the tip of the tool when performing small precise movements. When this was first observed there was concern that it could impair the capacity of the system to perform surgeries, after all surgeon are supposed to have perfectly firm hand movements. But when the surgeries where performed it was found that the nearby tissues (to the handled organ) were not affected by this overshoot of the tool, in addition, this vibration made more efficient the dissection of the adipose tissue around the organs that were being exposed. The vibration obtained from this *error* of the robot-tool system was not equivalent to a trembling hand movement, rather, it was like giving to a precise tool an enhanced ability to separate tissues more efficiently. Again, a mechanical analogy to humans does not corresponds with the manipualtor.

With the experience obtained from this first stage, a more reliable and efficient system is under development. The results are encouraging and show the feasibility to perform these type of procedures in the near future. The spatial configuration of the system is already developed to an advanced stage, the electronic control system, the user interface, and the reliability aspects of the system are now under further development.

6. CONCLUSIONS.

The simulation and real tests of the system developed showed that approaching the control of a mechanical system by imitating the human movements is very difficult since it is assumed that all parts of the system must be *under control*. Analyzing carefully the system shows that many human movements are indirectly controlled by relying on external reaction to the movements, rather than consciously controlling every part of it. This can validate even more the new techniques of reactive control and emergent behaviors used in robotics, which to many, are rough bypasses to formal mathematical methods, but after all, it could be the real or *natural* way to do things efficiently.

Two (apparently) similar errors: the trembling of a human hand and the overshoot of the robot's tool; can really be quite different in the effect over the handled object, specially if it is not rigid, such as organic tissues. The difference lies in the temporal dynamics characteristics of each system. A trembling human hand is a steady state chaotic oscillation (forever trembling) around a non-fixed attractor, while an overshoot in the robot's tool is classic 2^{nd} order damped oscillation that rapidly stops at a precise (and controlled) point.

Performing laparoscopic telesurgeries has proven to be feasible even if the system is not constructed using high cost high precision equipment, given that the optimal mechanical and spatial configuration is used.

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