Developing a Low-cost Seven Degree of Freedom Minimally Invasive Surgical Manipulator

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Minimally invasive surgery (MIS) gives surgeons the ability to operate through a few small incisions made in the patient's body. Through these incisions, long rigid instruments are placed into the body and manipulated to perform the necessary surgical tasks. Conventional instruments are constrained, however, through having only five degrees of freedom (DOF), as well as having scaled and mirrored movements, thereby limiting the surgeon's dexterity. Surgeons are also deprived of depth perception and hand-eye coordination through having only two-dimensional visual feedback. Surgical robotics attempts to alleviate these drawbacks by increasing the dexterity, eliminating the fulcrum effect and providing the surgeon with three-dimensional visualisation, therefore reducing the risks to patients as well as to the surgeons. However, existing robotic MIS systems are hugely expensive and bulky in operating rooms, preventing their more widespread adoption. In this paper, a new, inexpensive seven DOF primary slave manipulator (PSM) is presented. The four DOF wrist is actuated through a tendon mechanism driven by five direct current motors. A repeatability study on the wrist's joint position showed a standard deviation of 0.38 degrees and the strength test demonstrated that the manipulator is able to resist a 10 N opposing tip force and is capable of a theoretical gripping force of 15 N.

Additional Keywords: Minimally invasive surgery, laparoscopic instrumentation, robotic manipulator, surgical robotics

Nomenclature

Roman

d	gripper length
F_a	axial force
F_m	exerted force
F_n	normal force
T_g	grasping torque
x_o	projected arm distance
x	Pythagorean extension length

Greek

γ	angle difference between gripper and cable
φ	angle of gripper actuation cable
φ_{max}	maximum value of φ

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1. Introduction

Minimally invasive surgery (MIS) is an operating technique whereby surgeons use specially designed instruments to operate through small incisions made in the patient's skin. Several surgical specialities have benefited greatly from this operating technique; one such example is a laparoscopic cholecystectomy, which was first performed by Professor Erich Mühe on September 12, 1985[1]. Benefits in using MIS techniques rather than open-surgery methods include quicker recovery times, reduced discomfort to the patient and reduced incidence of post-surgical complications, such as adhesions (abnormal fibrous connections which join tissue surfaces abnormally)[1, 2]. Reduced hospitalisation time and therefore procedural costs are also major benefits to the patient as well as to the health care system.

MIS, however, has its drawbacks in that the commonly used conventional instruments have only five degrees of freedom (DOF) through the entry port (figure 1), preventing arbitrary orientation of the instrument tip[2]. MIS is also technically more difficult for the surgeon in that the tool tip moves in the opposite direction to the surgeon's movements due to the pivoting of the tool around the entry point (known as the fulcrum effect)[3]. Furthermore, the image displayed on the CRT monitor is a two-dimensional one and therefore deprives the surgeon of depth perception and hand-eye coordination, making the procedure more difficult to perform due to the surgeon having to continuously correlate hand motions to the end effecter's motions.

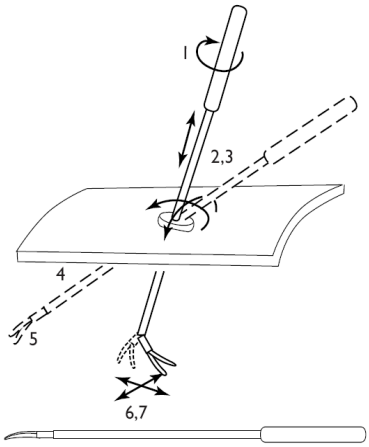


Figure 1: Conventional 5 DOF laparoscopic instrument (dashed) versus proposed 7 DOF manipulator by Ruurda[4]

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Because of these dexterous and visual constraints related to conventional MIS instrumentation, robotics is used in surgery in an effort to alleviate these constraints, making robotics a promising and exciting field for innovations to improve the capabilities of surgeons in MIS[5].

Minimally invasive robotic surgery (MIRS) systems (such as those discussed by Lanfreanco *et al.*[6], Sim *et al.*[7] and Lobontui and Loisance[8]) use state-of-the-art technologies to directly address the drawbacks of conventional MIS instrumentation. These systems attempt to improve surgical dexterity and visual feedback through features including articulating end effectors, tremor filtering, motion reversal correction, stereoscopic vision and motion scaling[9]. Existing robotic master-slave systems are, however, not without shortcomings. The main factors preventing more widespread adoption of such systems are their prohibitive cost and the high maintenance costs involved in keeping the system in continuous working condition[7]. Furthermore, the employment of additional staff to maintain the system and possibly even the development of new and bigger operating rooms to accommodate the sizable system are required in some instances[7]. For these reasons alone, most medical centres discard the consideration of such a system and continue using conventional instrumentation, accepting their associated drawbacks.

The design proposed here has many similarities to existing systems[7;8;10-16], however, since the focus is on a low cost system, some simplifications were made. One of the most significant differences is the design of the wrist. Some commercial systems, such as the Da Vinci system[7;8;15;], use the patented EndoWrist[14] which has a complex design with many internal pulleys. Our system does away with the pulley design, thereby minimising the number of parts and hence the cost. The Da Vinci system system[7;8;15;] has active feedback control that compensates for patient and organ movements. Other systems use haptic feedback for the surgeon. Our system has no such feedback; all feedback will be visual through the endoscope.

This paper presents the design of a new, inexpensive primary slave manipulator (PSM). The seven DOF manipulator aims to increase the surgeon's dexterity. Another design challenge was to have an outside diameter of the manipulator of less or equal to 10 mm, in order for it to be used with standard laparoscopic instruments.

2. Design of the Mechanical Manipulator

The ability of surgeons to work through a few small incisions presents a number of benefits to the patient as well as the surgeon. Therefore, over the last two decades, many minimally invasive surgical enhancements have been researched and developed at research institutes across the world[10-12] to further advance MIS. Among these enhancements are many robotic manipulators that were designed with applications in MIS[13, 17-21]. Among these are the Da Vinci's *EndoWrist*, the wrist discussed by Seibold *et al.*[21], as well as the manipulator from Peirs *et al.*[18]. These are all actuated using direct current (DC) motors.

Table 1 compares a number of different actuator technologies that were considered to actuate the manipulator. From this table it can be seen that the amount of work per unit volume, or work density, is high for Smart Alloys (Thermal) or Shape Memory Polymers (SMPs) and piezoelectric actuators. However, the actuator efficiency for Smart Alloy actuators is very low and large power is required. Smart Alloy actuators also have low speeds and small stroke lengths, whereas piezoelectric actuators have higher speeds, but also short stroke lengths. A hybrid actuator using Smart Alloy wires and DC motors was used by Kode *et al.*[5].

Actuator Type	Strain (max %)	Pressure (max MPa)	Efficiency (max %)	Relative speed (full cycle)	Power Density
Electromagnetic	50	0.1	>90	fast	high
Piezoelectric					high
ceramic	0.2	110	>90	fast	
single crystal	1.7	131	>90	fast	
Polymer	0.1	4.8	N/A	fast	
Electrostatic devices	50	0.03	>90	fast	low
Shape memory polymer	100	4	<10	slow	medium
Thermal	1	78	<10	slow	medium
Magneto-restrictive	0.2	70	60	fast	very high

Table 1: Comparison of various actuating technologies[5]

Table 1 shows that electrostatic actuators have a low power density[2], or low output torques; however, advances in miniaturisation and the production of miniature DC motors with small gearheads make the actuating technology feasible for use in miniature manipulators[5]. These actuators work with high efficiency, giving large stroke lengths at high speeds[23]. Also, placing the motors outside the manipulator or human body (allowing more space for the motors) and driving the manipulator wrist using cables allow for high gripping forces while still keeping the manipulator's diameter small[5].

2.1 Design criteria

Taking the abovementioned research and the identified advantages and disadvantages into consideration, a number of design criteria were formed and are summarised in Table 2. The manipulator should be 10 mm in diameter so that it can fit through a standard Ø 10 mm trocar (a hollow cylinder with a sharply pointed end that is used to introduce implements into blood vessels and body cavities). The manipulator should be able to rotate 360° about its elongated axis and the wrist able to deflect 55°. The tool tip should also rotate a minimum of 90° about the wrist axis.

Parameter	Value
Overall instrument diameter	≤ 10 mm
Rotation about instrument axis	360°
Wrist deflection	> 55°
Tip rotation about wrist axis	> 90°
Gripper opening angle	> 60°
Gripping force	≥ 5 N
Opposing tip force	> 10 N

Table 2: Chosen and required manipulator design requirements to achieve full motion[3]

Furthermore, the literature[3, 24] indicates that a gripping force of at least 5 N is needed for grasping the needle during

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suturing or pulling and stretching tissue during an MIS procedure. The manipulator should also be able to resist a 10 N opposing tip force, as determined in an additional study conducted in our laboratories[25], which is also in accordance with other devices of a similar nature.

The functional requirements of the control electronics of the primary slave manipulator are as follows:

- Five motors need to be driven bi-directionally and positional feedback needs to be processed simultaneously. For future implementation of auto-calibration and tactile feedback, current feedback from the motors should also be provided for.
- The control board should be capable of connecting to a PC-based host using HyperTerminal to allow the user to interact with the electronics by checking various parameters as well as to set parameters such as the reference position or the upper and lower positional limits.
- The controller should also do 'on-board' diagnostic checks on start-up, as well as failsafe checks periodically, to ensure that all hardware is working properly and that all communication links are up and running.

2.2 The mechanical manipulator

The seven DOF manipulator includes a wrist capable of three DOF that is attached to an extension arm that can roll around its own axis, therefore giving the wrist a fourth DOF. The additional three DOF of the manipulator are made possible by sliding the instrument in and out, and by pivoting it about its centre of rotation, which is defined roughly by the point of insertion into the abdomen; the entry DOF into the abdomen is illustrated in Figure 1. This is made possible through the use of an additional robotic manipulator or secondary slave manipulator (SSM). Figure 2 shows a diagrammatic depiction of the complete system.

The PSM's wrist includes a revolute joint, a rotation joint and the gripper. These joints are actuated by means of a tendon mechanism that uses five DC mini-motors (Faulhaber 3242G012CR mini-motor with IE2-16 encoder and a 1526:1 planetary gear head) to actuate the cables. The cables are Ø 0.1 mm stainless steel fibres woven into Ø 1.1 mm cables, giving them an estimated tensile strength of 1000 N and an estimated bending radius of 2.5 mm. And the prototype manipulator diameter was constructed with a diameter of 10 mm.

Three DOF are shown in figure 2 for the primary manipulator. In addition to the rotation of the manipulator, there are four DOF actuated by the five motors in the housing. There are three additional DOF that will be added in future. These are, firstly, a movement up and down the trocar and, secondly, a pivot around the point of insertion. The five motors and their control electronics are all fixed to an actuator hub situated inside the actuator drive housing.

2.3 The control electronics

The control electronics of the PSM were implemented in a master-slave configuration. Briefly, the master receives instructions from a host controller. The master controller then processes these instructions and passes them on to the relevant slave controller. Each slave is then responsible for controlling an H-bridge to drive the motors while simultaneously receiving positional feedback. The master is also able to request a status report from the slave to send to the host controller. Figure 3 shows the master-slave configuration conceptually.

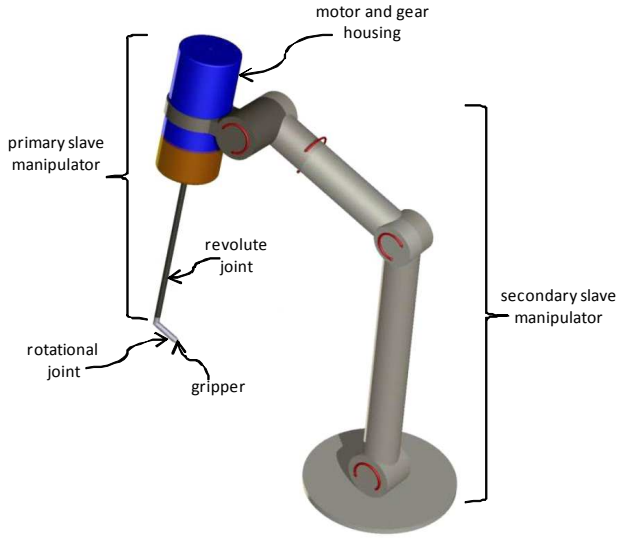


Figure 2: Diagrammatic depiction of system

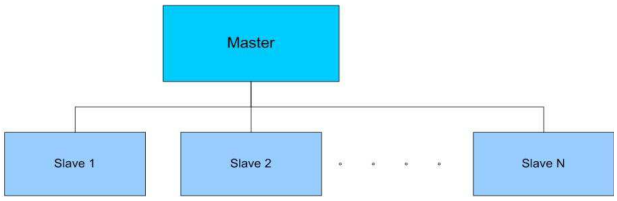


Figure 3: Master-slave configuration shown conceptually

The main advantage of such a configuration is that, if one slave malfunctions, it should not influence the other slaves. In fact, the master could try resetting the faulty slave and reloading it with its previously backed-up data. Also, each slave can concentrate on those tasks directly related to its activities, leaving other unimportant and time-consuming tasks to the master. The master also acts as a shield for the very important slaves in case the host should malfunction and send invalid instructions or data.

Figure 4 shows the control electronics for the primary slave manipulator. In the working, each slave microcontroller (a PIC18F2431 from Microchip Technology Inc.) on the digital board controls an H-bridge, which in turn drives a motor. The motor's encoder is connected to the digital board to allow the slave microcontroller to monitor the motor's 'current' position. Using this 'current' position and subtracting it from a reference position (typically received from the master), the microcontroller can then drive the motor to any desired position, thereby forming a proportional closed-loop system controller. Also, current feedback from the motor is sampled using the slave's control module. Furthermore, each slave is responsible for managing its own hardware, e.g. motor position and motor current.

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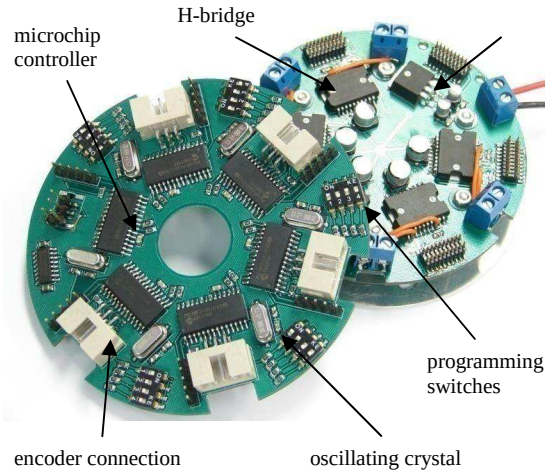


Figure 4: Primary slave manipulator control electronics

The master (a PIC18F2550 from Microchip), on the other hand, receives instructions from the PC-based host through an RS-232 communication protocol. These instructions are processed and if, for instance, a new reference position is received, the master would then send this new reference position using the I2C bus to the related slave(s), which will then drive the motor(s) to a new position or set any one of the parameters.

3. Manipulator Experiments

Two experiments were done to verify the manipulator's capabilities with respect to the literature and the design criteria. These were the repeatability test and the strength test experiments. Neither of these experiments was intended to be destructive, but instead proved that the manipulator can achieve the design criteria.

3.1 Repeatability study

Repeatability is the ability of the end effecter to move back to a previous position again and again. The system, however, is an open loop system. In other words, the position of the end effecter is unknown to the control electronics. Only the position of the shaft of the gearhead output is known through the encoder mounted on the back of the motor. Therefore, the intention of this experiment was aimed specifically only at the mechanical repeatability (the position of the end effecter with respect to the position of the gearhead output shaft). This was achieved by moving the manipulator to certain positions repeatedly, moving from different directions, and measuring the manipulator links with a coordinate measuring machine (CMM).

Table 3 shows the results for a typical repeatability experiment. The results shown are for the angle between the short and the long arm, i.e. the two manipulating arms of the PSM. The position value is a motor position and is not the same as the angle, the value is the command position set by the controller, and the acronyms 'ext' and 'flex' refer to whether the arm was in an 'extension' or a 'flexion' motion when the measurements were taken.

The results are broken up into two sets of data, namely 'samples 1 to 4' and 'samples 5 to 10', due to a malfunction after the fourth series of tests, causing a new 'zero position' to be stored in the controller – thereby requiring the results to be considered separately.

Position	Samples 1 to 4		Samples 5 to 10	
	mean	*std.dev.*	*mean*	*std.dev.*
55 start	58.3°	0.031°	58.2°	0.108°
35 ext	47.1°	0.158°	48.2°	0.177°
20 ext	30.1°	0.185°	31.6°	0.380°
0	4.3°	0.076°	5.4°	0.196°
20 flex	23.7°	0.156°	24.3°	0.159°
35 flex	40.7°	0.170°	41.2°	0.171°
55 stop	58.3°	0.054°	58.2°	0.126°

Table 3: Mean and standard deviation for short arm [°]

From the results shown in table 3 it is clear that there is a maximum standard deviation of 0.38 degrees (sample 6 to 10, 20 ext) over a number of samples with no recalibration between samples. Furthermore, the 20 ext and 35 ext manipulator positions are the same motor positions as those for the 20 flex and 35 flex positions respectively. From the table we notice, however, that the measured manipulator positions for these same motor positions are not the same and have an error of nearly seven degrees. This hysteresis error is believed to be due to friction inflicted on the cable by the bronze cable guides and other components, causing the cable to stretch and therefore not move the manipulator arm to its desired position. Figure 5 shows the hysteresis error for the distal part of the wrist while moving from an extreme deflected position to an extended position and back to an extreme deflected position.

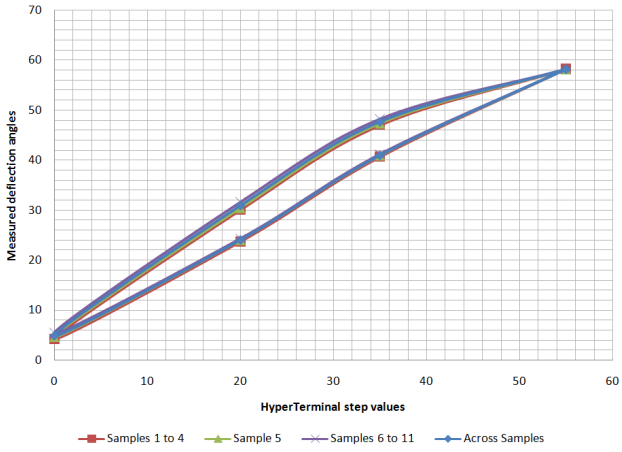


Figure 5: Hysteresis error graph found in repeatability study

3.2 Strength test

A manipulator strength test proves that the designed PSM is strong enough to perform the necessary tasks during a typical MIS procedure. One of the design requirements was that the manipulator should resist a 10 N opposing force at the manipulator tip. Also, according to the literature[3, 24], a gripping force of at least 5 N is needed during an MIS procedure for grasping a needle while suturing or pulling and stretching tissue.

Figure **6** shows the experimental setup for determining whether the opposing or gripping forces were able to

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achieve the required level rather than what the maximum of the parameters are. The reason for this was that there was no real way to quantify how successfully the manipulator was able to oppose a certain force. It either could or it could not. Also, because of the expense of the manipulator the authors did not want to break the cables and possibly damage the components while trying to oppose forces that were much higher than what can be expected during an MIS procedure.

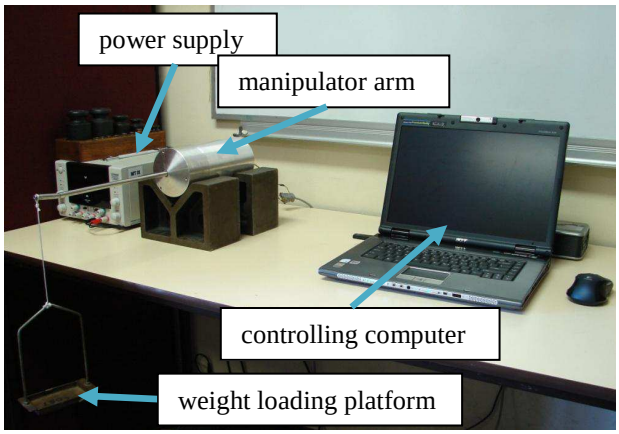


Figure 6: Experimental setup for strength test

The manipulator was held in a position where the revolute joint was deflected fully. A given load was on the loading platform after which the joint was moved to a 'less' deflected position – for example moving from position 55 (fully deflected at 55° relative to the PSM extension arm) to a position 10 (or 10°) – and the effects observed with varying loads. This was repeated for the starting position being 0 and moving towards a 'more' deflected position. In the experiment, the manipulator demonstrated that it was able to resist a 10 N opposing tip force. However, testing showed that the manipulator has a deflection error or positional error, as can be seen in figure 7. Figure 7 (left) shows the manipulator at a given position with a 200 g weight, while the image on the right shows the manipulator at the same motor position with a 1 kg weight. The resultant error is due to the increased torque from the weight at the pivoting axis of the wrist joint, which increases the tension in the cable, causing it to stretch more with an increase in weight. Due to there being no positional feedback from the manipulator wrist, the control electronics are unable to counter this. However, the surgeon is able to counter the positional error through visual feedback.

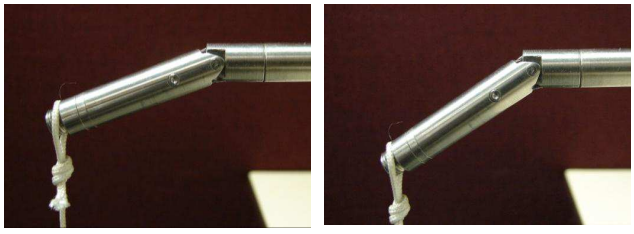


Figure 7: Manipulator deflection or position error due to weights (left: 200 g; right: 1 kg)

The gripping force could not be measured due to the nature of the gripper jaws used. However, the gripping force can be calculated using the maximum tensile force in the revolute joint's manipulation cables from the weights applied at the tip, and then using this force to determine what the theoretical gripping force would be according to Peeters *et al.*[26]. Figure 8 shows that the jaws rotate about point A and that point B moves within the slots in the jaws, causing the gripper jaws to close.

The gripper force can be calculated by finding the torque at point A as a result of the applied force (F_m) at point B, as shown in figure 9.

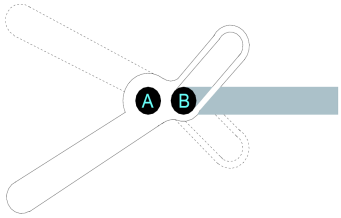


Figure 8: Drawing of the gripper jaws and the drive rod

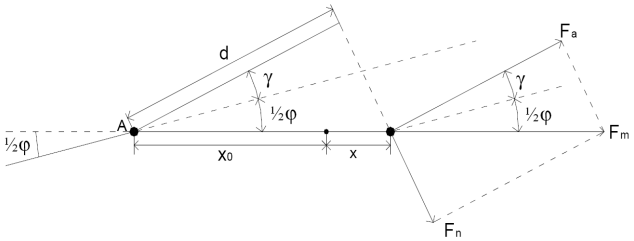


Figure 9: Force factorisation of the torque balance

Using a tensile force of approximately 115 N in the gripper actuation cable, and assuming x_{max} = 5 mm, x_0 = 2.25 mm, φ_{max} = 60° and γ = 30° for the equation:

$$T_g = \tfrac{1}{2} F_m (x_o + x) \sin(\varphi + 2\gamma) \quad (1)$$

the grasping torque (T_g) is then calculated to be an estimated 0.3 N.m, thereby giving a 15 N gripping force at the gripper jaw tip, taking the tip to be 20 mm from the pivoting pin (or point A).

4. Discussion and Conclusion

MIS benefits patients by giving surgeons the ability to work through only a few small incisions made in the patient's skin. However, conventional instrumentation is constrained due to their limited dexterity, the fulcrum effect and two-dimensional visualisation. Surgical robotics attempts to overcome these constraints through its increased manoeuvrability, eliminated fulcrum effect and three-dimensional visual feedback. Existing MIRS systems are hugely expensive, however, and sometimes require the employment of additional staff to continually calibrate and clean the system.

This paper therefore presents a new seven DOF primary slave manipulator for MIS applications. The manipulator is actuated by using five DC motors to wind up cables onto reels to ultimately manipulate the four DOF wrist. The further three DOF are made possible through a secondary

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slave manipulator. Figure 2 shows a schematic layout of the system.

Two experimental tests were performed to determine the feasibility of the manipulator with respect to the preset manipulator specifications and the literature. The experiments were the repeatability test and the strength test.

The repeatability study showed that the manipulator is able to find and return the same position (0.38° standard deviation or 0.53 mm positional accuracy), depending on the path followed to find the same position again. This hysteresis error caused by the manipulator's path dependency was found to be nearly seven degrees, which translates into a 9 mm positional error. The positional accuracy is a concern, but it must be remembered that this low-cost design will rely on visual feedback provided by a video camera. As part of the low-cost approach, the surgeon remains completely in control. Positional accuracy is considered to be within the limits of visual compensation.

The strength test experiment demonstrated that the manipulator is able to oppose a 10 N opposing tip force, although a positional error occurred due to the weight applied at the tip. This positional error could again be eliminated through the visual feedback to the surgeon, which allows the surgeon to correct the error by moving the manipulator a bit more. The gripping force was theoretically determined to be 15 N, which then, together with the 10 N opposing forces, proves that the manipulator should be able to meet the requirements to perform the basic tasks done in a typical minimally invasive procedure.

The cost of the prototype manipulator was determined to be about US$ 4500 for the manipulator, US$ 2500 for the five motors, and US$ 400 for the control electronics. This is still regarded as being relatively expensive for the PSM alone, but the cost can be reduced considerably in mass production.

5. Future Work

In the future, a newly designed manipulator should be developed to reduce friction on the cable, as well as to incorporate the ability of the manipulator to be sterilised. Physically smaller motors with smaller gear-reduction ratios that are capable of lower output torques should also be considered. These will allow for current sensing to be implemented, leading to auto-calibration and possibly even tactile feedback by the manipulator.

Furthermore, different tool tips should be designed for the manipulator to allow the surgeon to perform all the required tasks necessary in a typical MIS procedure. Lastly, the rest of the MIRS system should be developed and tested extensively before starting the animal and human trails.

6. Acknowledgments

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