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Development of a StandAlone Surgical Haptic Arm

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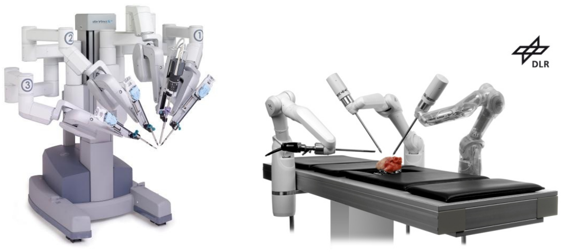
Abstract— **When performing telesurgery with current commercially available Minimally Invasive Robotic Surgery (MIRS) systems, a surgeon cannot feel the tool interactions that are inherent in traditional laparoscopy. It is proposed that haptic feedback in the control of MIRS systems could improve the speed, safety and learning curve of robotic surgery. To test this hypothesis, a standalone surgical haptic arm (SASHA) capable of manipulating da Vinci tools has been designed and fabricated with the additional ability of providing information for haptic feedback. This arm was developed as a research platform for developing and evaluating approaches to telesurgery, including various haptic mappings between master and slave and evaluating the effects of latency.**

I. INTRODUCTION

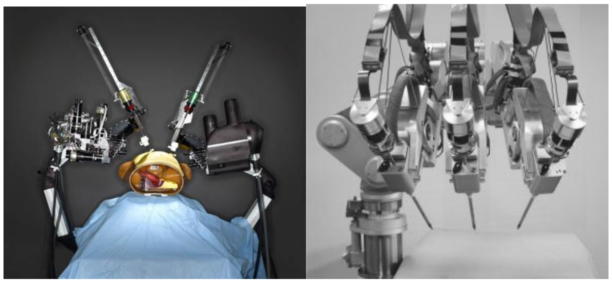
Minimally Invasive Robotic Surgery (MIRS) is currently dominated by Intuitive Surgical's da Vinci system. The first da Vinci system was introduced in 1999, and the most recent da Vinci SI system offers a 3D HD vision system, three robotic surgical arms and another robotic arm for controlling an endoscopic camera[1]. All of the arms attach to a common column that is wheeled to the operating table prior to surgery. A wide variety of interchangeable and disposable tools allows for a wide variety of surgical procedures that would be impossible to perform with traditional laparoscopy. Currently, haptic feedback is not an advertised feature of the da Vinci system.

Following the da Vinci's widespread success, there is a variety of research being performed to develop new MIRS systems. The German Aerospace Center (DLR) has developed its second generation robotic arm (MIRO) that is used in its MiroSurge robotic system[2]. The arms weigh less than 10kg each, and unlike the da Vinci system, can be attached directly to the operating table in order to optimize the workspace of each arm with respect to the others, much like the earlier Zeus system[3]. The MiroSurge system consists of three 7 Degree of Freedom (DoF) MIRO arms: two manipulating laparoscopic tools and another manipulating an endoscopic camera. Force and torque sensors located near the tips of the tools provide feedback that is represented haptically with Omega.7 haptic controllers (Force Dimension, Switzerland). Three translational degrees of haptic feedback are possible with the Omega.7 controller.

Teleoperation and telesurgery is the ability for surgeons to perform operations remotely, greatly reducing transportation costs as well as allowing a specialist to practice in almost any region of the world. The BioRobotics Lab at the University of Washington is in the process of developing and testing the RAVEN telerobotic system[4], which is specifically aimed at researching the effects of long distances on telesurgery. Although the RAVEN is currently teleoperated with Sensable's PHANTOM Omni controllers, haptic feedback has not yet been implemented.



(a) da Vinci, Intuitive Surgical [1] (b) DLR MiroSurge [2]



(c) RAVEN [4] (d) SOFIE [5]

Fig. 1: Existing research and commercially available minimally invasive robotic surgery systems

A large area of interest in robotic telesurgery is haptics: providing force feedback to the operator of a robot. One of the downsides to currently available forms of teleoperation is that the surgeon is unable to feel the forces applied to organs or a suture. When operating traditional laparoscopic tools, the surgeon is able to directly feel how much force is being applied. Researchers at the Technical University of Eindhoven have developed the SOFIE (Surgeon's Operating Force feedback Interface Eindhoven) robotic system as a means of improving upon the da Vinci system. SOFIE was designed with the following design requirements in mind: connection to the operating table for easier set-up, additional DoF at the instrument tip to improve organ approac, reduced system size, reduced costs, and force feedback for reduced operating time and increased patient safety[5].

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II. DESIGN REQUIREMENTS

The primary goal was not to develop an arm that would be superior to that of the da Vinci, rather to develop a research platform that allowed control of da Vinci tools while enabling open development and access to all low level controllers and sensor data. The arm was designed to be able to rapidly and continuously report information of the forces/torques generated from each of the actuators. This will enable research to be performed on haptic feedback as well as how the forces of the arm should be mapped onto the master controller. The internal and external communications for the haptic data were designed to be sufficiently fast to allow for an effective force feedback loop (at least 1kHz).

In teleoperation, there can potentially be a significant lag introduced between the surgeon and the arm and then back from the arm to the surgeon. The effects of this delay, especially when haptic feedback is incorporated, also needs to be investigated. The software for the arm was designed to allow for the arm to be easily operated over a network, as well as to allow for delays to be artificially introduced so that research on the acceptable delays could be performed.

Whether through mechanical or software means, maintaining a Remote Center of Motion (RCM) is necessary when performing any kind of laparoscopic surgery. Thus, the robot was designed to be able to maintain an RCM. Additionally, improvements upon the da Vinci and other systems were taken into consideration in the design of the StandAlone Surgical Haptic Arm (SASHA). At the head of these improvements was the ability to easily place place the robot and position its RCM in a surgical environment.

III. DESIGN OVERVIEW

A. Manipulator Design

The first iteration of SASHA, shown in Fig. 2, is a fully functional prototype. As such, it was designed to be highly tunable and easy to manufacture. The support structure is built with sheets of laser-cut acrylic held together with tapped blocks in the vertices. Ease of manufacturing and repeatability of parts was a major factor in designing the arm. There are several locations where the timing belt tensioners can be placed, which allows for a range of possible belt tensions. Additionally, the use of acrylic makes it easy and relatively inexpensive to replace single plates or entire components as part of an iterative design cycle. This will be particularly useful in experimenting with the optimal workspace and ergonomics of the robot.

It was decided that mechanically coupling opposite the links of the arm would be a reliable and simple solution for maintaining an RCM; as there is ostensibly no risk of software error in maintaining the remote center and it allows for the motions of a many-sectioned arm without requiring all of the joints be actively actuated. SASHA utilizes two sets of timing belts at the joint axles to keep opposite links parallel. In this configuration there need only be three actuated DoFs of the tool: two perpendicular rotations about the RCM and one linear translation/insertion through it. To minimize inertia, the rotational axes are actuated by motors located in the base. These large motors are geared to allow for back drivability when positioning the arm and enable force control. The larger motors have an integrated elctro-mechanical brake to keep the position of the arm in the unlikely case of loss of power. The linear actuation requires much less power compared to the other motions, thus these smaller motors are located on the same link as the tool manipulating carriage.

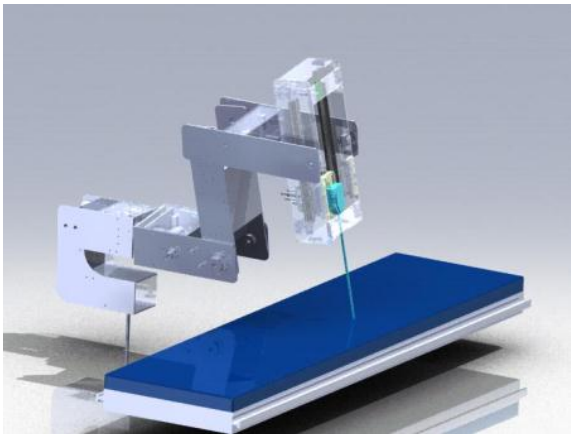

Fig. 2: Computer rendering of functional StandAlone Surgical Haptic Arm (SASHA) prototype. The arm maintains an RCM at the surgical point of entry and provides 3 tool positioning degrees of freedom in addition to 4 DoF for manipulating commercially available da Vinci tools.

The standard tool manipulating carriage interfaces directly with the standard da Vinci tool faceplate, which holds and interacts with the tool as shown in Fig. 3. As with the da Vinci system, each of the driving discs is individually spring-loaded; allowing for reliable, positive interaction with the tool interface. The levers on the sides of the tool allow for release from the interface. Custom torque sensors are placed between the motor and the tool in each spring-loaded module to enable measurement of the torque applied to each disc controlling the wrist. Measuring torque right at the interface plate provides the best possible measurement without customizing the tools themselves (an impracticality for modular, disposable tools). Although friction in the wrist will limit accuracy somewhat, it does not significantly affect the haptic experience – it is not necessary to precisely measure the specific force applied, rather to represent an appropriate experience to the surgeon.

The ability to easily position the robot is especially important with a robot with a mechanically fixed RCM, as it must be placed in the correct place and orientation. A set of laser line generators will be used to easily and clearly locate SASHA's remote center of motion on the patient during initial set-up. Positioning of the arm is currently passive in four axes: along the length of the operating table support rail, two rotations about the support rail mount and a linear translation through the mount. The rail mount is provided by Allen Medical Systems and supports a stainless steel rod that can be positioned and then easily secured. The next step in improving the positioning of the robot is implementing

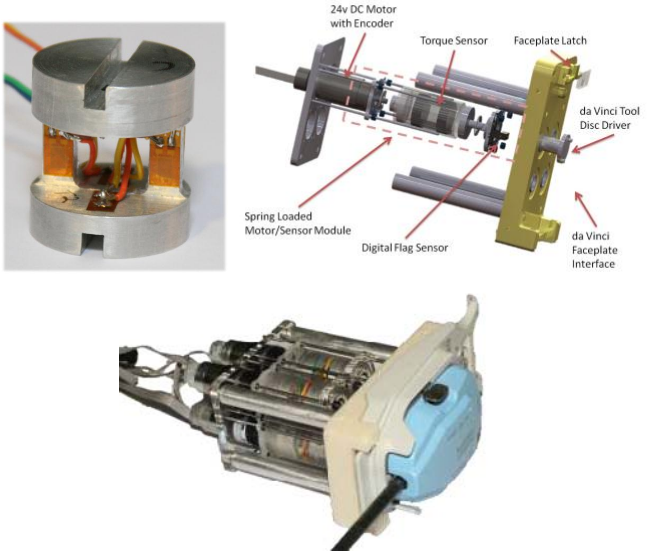

Fig. 3: Torque sensor and spring-loaded tool interface. The interface interacts directly with the standard da Vinci faceplate and is capable of manipulating the tool wrist while measuring the forces being applied to the tool tip.

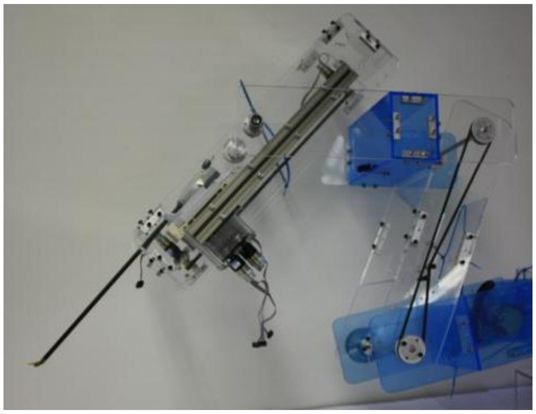

Fig. 4: First prototype of SASHA Research Platform.

the ability to position SASHA along an axis parallel to the operating table support rail. step in improving the positioning of the robot is using another link with 2 passive rotations.

B. Electrical Design

The electronics for this arm need to be able to provide precise control of each degree of freedom, and also provide force feedback to the user. The arm also needs to be able to operate over long distances or have the option to insert delays to facilitate research into teleoperation and haptics. This system is outlined in Fig. 5. The user interface is a PHANTOM desktop from Sensable, interfaced to a PC. This is connected to another program in the same or a different PC, which serves as the master for the other components. This controller talks to the remaining boards over RS485. Each motor is controlled by an individual motor controller which runs speed, position, and current control loop internally. A 24 Volt 40 Amp power supply is used to power the motor controllers and the force sensor interface. The use of RS485 and a single voltage supply means that only four wires total needed to be run to the motor controllers and the force decoder, greatly simplifying wiring.

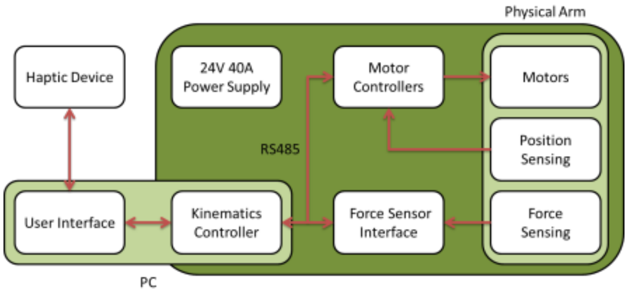

Fig. 5: System block diagram. In future experiments, articial time delays will be introduced between the User Interface and the Kinematics Controller.

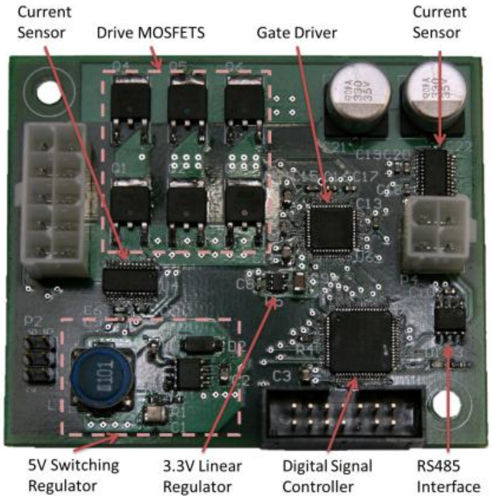

Fig. 6: High power 20 Amp motor control board for arm drive motors with current sensing and brake control

Brushed DC motors with integral encoders are used to drive the arm. These motors need to be controlled at precise speed and positions. It was also required that the motor controllers report forces back to the operator at rates sufficient for haptics. To this end, custom motor controllers were designed to communicate over a multidrop RS485 connection at 3 Mbaud, allowing them to report back their respective forces at greater than the 1kHz necessary for hard surface haptic rendering[6].

Two different types of motors were used, with two high power motors on the arm, two small motors on the linear slide, and four more of the small motors on the tool manipulator. The two high power motors also have electromagnetically released brakes, allowing for the gross positioning of the arm to be locked in place. The controller for the high power motors can be seen in Fig. 6 and the controller for the low power motors can be seen on the left in Fig. 7. Each of these motors has a quadrature encoder attached, and additional optical switches allow for homing. Each of the motor controllers has on board current sensing, allowing for motor torque at each joint to be estimated, controlled, and reported back over RS485.

Each of the motor controllers uses an H-bridge switched using pulse width modulation to allow for the motors to be controlled with variable speed. The low power motor controller uses an single IC with an internal H-bridge to drive the motors at up to 1 amp and 24 volts. The high power motor controllers use discrete MOSFETs in an H-bridge with a three phase gate driver. The high power board actually includes three half H-bridges, with two used to control the motor and one used to control the brake. This board is capable of driving a motor at 20 amps and 24 volts.

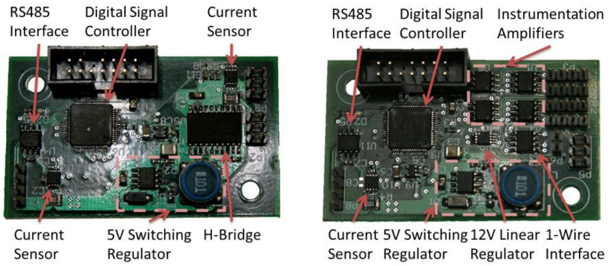

Fig. 7: Tool manipulation motor control board (left) and torque sensor interface board with 1-Wire da Vinci tool interface (right).

The torque sensors discussed earlier consist of four strain gages on a semi-deformable machined aluminum piece. The strain gages are placed in a full Wheatstone bridge configuration with an instrumentation amplifier to provide a signal that can be used in haptic rendering. In this configuration it should be possible to measure up to 0.6 Nm at each tool driving disc. It was decided to measure the tool torques in this manner because it does not require modifying the tool and does not rely on potentially variable motor characteristics. However, this method does not isolate the forces on the tool tip from such factors as stretch in the cables or deflection of the tool shaft. It is proposed that these intermediate forces will not interfere significantly or disproportionally enough to affect the haptic feedback.

A board was designed (Fig. 7), that can read the strain gages seen in Fig. 3 using instrumentation amplifiers and report the forces back over the RS485 connection. The da Vinci tools also have identifying information stored regarding their specific functionality, which is accessed using a 1-wire protocol from Maxim. The sensor board reports the identifying information via RS485 after retrieving it using a 1-wire interface circuit. The layout of the Faulhaber motor control boards and most of the components not specifically used to drive the motor were reused in creating this sensor board. This greatly cut down on the time taken to develop the sensor board and allowed for many of the same parts to be used on both boards.

C. *Software*

Each motor controller runs software written in C to handle the position and velocity control of the motors, as well as fault detection. These commands are received over the RS485 connection and feedback is sent over the same connection. Each of these motor controllers is running PID control loops on speed, position, and current.

A USB to RS485 converter was used to connect a PC to the motor controllers and the sensor board. A Java program running on the PC performs all of the kinematics calculations while also mapping the forces and movements to and from the haptic controller. A link over TCP/IP connects this to either a separate PC or another process on the same PC which interfaces to the haptic controller. A PHANTOM Desktop haptic controller from Sensable is used as the controller for the arm. The PHANTOM has 6 DoFs, which is sufficient to position and orient the tool tip, however not enough to inherently control the gripping action. A well defined API will allow for the arm to easily be interfaced to by other software. Decoupling the kinematics of the system is particularly easy: the position of the wrist is controlled by the major axes of the arm, and the orientation of the tool is controlled entirely by the motors on the carriage and represented by the orientation of the PHANTOM pen.

IV. DISCUSSION

This system will be used for research into the use of haptics in robotic surgery, evaluating latency and other issues associated with telesurgery, and can be used as a complement to the da Vinci in performing surgeries. The prototype arm has been developed and is currently being refined; when an appropriate size of the system has been determined, the prototype will be replaced with a more permanent and sturdy construction method. The arm has individual daisy chained motor controllers on each axis which enable position, velocity, and force control of the actuator through an internal closed loop controller or being updated at >1kHz through an RS485 bus. The software is designed to be open and modular - the primary interface is an API which enables control and measurement of all robot parameters from the PC which can then be integrated into the experimental software application. Commercially available haptic devices have been linked with SASHA, including the Novint Falcon and a Sensable PHANTOM Desktop. Specific areas of interest for research include: evaluating the most effective mappings of robot forces and torques to the user, determining the required accuracy of the force reflection provided, investigating force and motion scaling, evaluating differences between user performance and user preferences, and determining thresholds for control, force feedback, and visual time latency.

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