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Micro-Telerobotic Applications for Microsurgery

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Abstract

MicroDexterity Systems Inc. and Sandia National Laboratories are collaborating on the design of a six degree-of-freedom surgeon-controlled micropositioner and a six degree-of-freedom surgeon-controlled master for use in microsurgery. A control system will provide the linkage between the force-reflecting master and micropositioner for force scaling, position scaling, and tremor filtering. The technologies developed by this project are expected to enhance the skills of surgeons, improve the success rates for existing microsurgical procedures, make new high-dexterity procedures possible, and ultimately reduce surgical costs by increasing the precision and speed of operations. This paper discusses the motivation, approach, and accomplishments to date.

1.0 Introduction

MicroDexterity Systems Inc. (MDS) approached Sandia National Laboratories (SNL) to negotiate a three year cooperative research and development agreement (CRADA) to develop a micro-telerobotic platform to perform microsurgery and microassembly. SNL was chosen for their experience in the fields of intelligent systems and robotics and additional experience in systems integration, control theory, robotics control, and mechanism design, while MDS is the market share leader for developing ophthalmic instruments and surgical tools. The concerted effort between SNL and MDS will result in the development of a 6 degree-of-freedom (DOF) surgeon-controlled micropositioner (SCMP) and a 6-DOF surgeon-controlled master (SCM). An SNL designed control system will provide the linkage between the master (SCM) and slave (SCMP) for force scaling, position scaling, and tremor filtering. SNL is focusing on the design of the SCMP/SCM, controls, kinematics, and user interfaces. MDS is concentrating on component specification, end effectors, enhanced feedback modes, and acceptance testing. The technologies developed by this project are expected to enhance the skills of surgeons, improve the success rates for existing microsurgical procedures, make new high-dexterity procedures possible, and ultimately reduce surgical costs by increasing the precision and speed of operations. It is also believed the technologies will be applicable to other forms of microsurgery and microassembly, but the focus is on ophthalmic surgery.

MDS has proposed applying a coarse-fine strategy in 6-DOF with translational resolutions of 10 to 20 microns and angular rotation resolutions of 0.056 to 0.06 degrees [1]. The teleoperated platform will be designed to enhance a surgeon's dexterity enabling surgical procedures on a scale measured in tens of microns as compared to present work in hundreds of microns. The development is also geared toward prolonging the careers of surgeons and increasing precision. In addition, the surgeon/operator will be able to experience, through bilateral teleoperation, scaled forces imposed upon the tool at the slave site – providing more intuitive control.

2.0 Discussion

One of the most important sensory modalities for a human is kinesthetic feedback or haptic sensation. These modalities are commonly referred to as tactile feedback or force feedback. Since the technology necessary to provide force feedback is still in its infancy, our primary objective is to design an appropriate force reflecting master and slave.

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2.1 Design Parameters for Force Feedback Hardware

In a force feedback system the flow of information forms a closed-loop feedback system that incorporates a human. A computer system tracks the surgeon's position using sensors. Software then calculates the forces the user should feel in the environment the slave device operates and the motions the user is making. The computer then sends commands to the force reflecting master's actuators to generate the desired forces and these forces are then transmitted to the user through a mechanical transmission. When the user feels these synthesized forces and reacts to them the cycle is complete.

The fidelity of a force feedback system depends on the accuracy of the sensors, the latency of the computer, the performance of the actuators, and the transparency of the mechanical transmission. The overall system's performance is usually characterized by its bandwidth, which is a measure of the highest frequency that can travel through the system with accurate reproduction. Haptic sensations that feel "crisp" require a high bandwidth, while those that are "mushy" require low bandwidth. Any component that adds lag into the system will reduce the system's bandwidth.

One of the most commonly used sensors is the digital position encoder. Unfortunately, the output of an encoder is quantized and can lead to limit cycles in digital control systems. In practice, the quadrature difference between samples are quite small and cause little problems unless the quantized signal is differentiated to obtain velocity. Because differentiation is known for amplifying high frequency noise, a better method for obtaining a velocity estimate is to sample more slowly. Unfortunately, this decreases the bandwidth of the system and therefore reduces stiffness. Another approach is to filter the signal digitally. But this approach introduces a delay into the sensor signal which also reduces the bandwidth of the system. A third approach is to use higher resolution encoders. While this approach does not eliminate limit cycles it reduces the amplitude. Also the higher the encoder's resolution the larger its physical size. A fourth approach is to use analog sensors for position and velocity (potentiometers, resolvers, and tachometers), although these suffer from noise problems as well.

After the surgeon's motions are detected by the sensors there are several sources of delay: the communication latency between sensor and computer, the computational delay, and the delay of sending the result to the actuators. Because serial communication often adds significant delay into a force reflecting system, one can resort to using parallel communication methods. The computation latency largely depends on the complexity of the calculations the computer must perform. To reduce latency, expensive high-speed computing hardware can be used or devices with simpler kinematics can be designed.

Ideally, the mechanical transmission should not introduce any significant dynamic effects. A low mass and therefore low inertia system will waste less effort in accelerating the mechanism leaving more force to be transmitted to the user. In addition, the transmission should be highly rigid or stiff with minimal compliance, since any compliance will reduce the system bandwidth. Furthermore, any transmission backlash or stiction will contribute to mechanical limit cycling and degrade the force feedback sensation.

The fundamental performance measure of a force feedback system is its ability to limit user input resistance to actual forces applied to the robot by its environment. In other words, the system must be completely backdriveable. The result will be a system where a user can apply delicate forces and be met with minimal opposition from the mechanism unless the computer commands a resistance force.

2.2 Mechanical Impedance and Scaling Effect

A force feedback device is required to generate different mechanical impedances. Impedance can be defined as a dynamic relationship between velocity and force. For example, for a "crisp" response, the device must exert a force proportional to acceleration, while a "mushy" feel demands a force proportional to displacement. The challenge of designing a force feedback system is to build master/slave devices which can sense and generate an extremely wide dynamic range of impedances.

Informal studies by MDS have shown that individuals vary widely in their accuracy and precision regarding position, velocity, and force. At one extreme there are surgeons who move slowly with tremor while at the other extreme there are surgeons who move quickly without tremor. Dexterity enhancement includes force upscaling, position downscaling, tremor filtering, gravity compensation, and other second-order issues such as confining the workspace, velocities, accelerations, or forces. The hand's positional performance is reduced when it actuates surgical tools, but remote actuation using scaling techniques can increase the hand's positioning capabilities. Rotary and telescopic functions are far more difficult than writing or engraving-like motions. Devices should be made with variable compliance so that they can function rigidly as a robot would or compliantly as a human would, depending on the setting of this parameter[2].

After observing numerous surgical procedures and discussions with many microsurgeons, it became clear that the tool tip forces experienced during eye surgery are so small that manipulation is guided mainly by vision (through a microscope) and not by kinesthetic feedback or haptic sensations. Because of this, computer assisted teleoperation can significantly enhance a surgeons performance both in speed and safety by providing increased kinesthetic feedback. Thus, by sensing forces exerted on a surgical tool tip and upscaling them to the surgeons hand, while at the same time scaling down the surgeons movements, teleoperation can greatly increase dexterity.

In teleoperation between different scales, a problem exists called the scaling effect [3][4]. Scaling effect is where the dominant physical phenomena is different between the two scales [3]. Thus, scaling effect is a problem of bilateral teleoperation between micro and macro worlds [4]. The force applied to the system can be decomposed into three terms [3]: an inertia term that is proportional to the fourth power of length, a viscous term, and stiffness term which are both proportional to the square of the length. Because of these properties, the viscous and stiffness terms become dominant compared to the inertia term as the scale of length goes down.

Two solutions proposed to overcome the scaling effect are impedance scaling [5] and power scaling [6]. Impedance scaling proposes to solve the scaling effect by independently changing the scale of each individual contributor [5]. The individual scaling is based on physical symmetry laws that indicate mass is proportional to volume, and viscous and friction forces are proportional to area. Power scaling is a method used to match the input and output impedances of the user and environment in multi-DOF systems [6].

2.3 Other Surgical Systems

Since this project began there have been several surgical robotic systems described in the literature. For instance, there is a system for use in orthopedic surgery performing precise bone machining procedures initially targeted at total hip replacement surgery [7]. There are developments in endoscopic surgery that deal with performing tasks such as grasping, positioning, dissection, preparation, suturing, clipping, and stapling of anatomical structures and tissues [8]. Also, there are developments in laparoscopic surgery primarily aimed at camera positioning [9]. A robot for neurosurgical operations has been tested as well [10]. In the discipline of ophthalmology several devices have been designed [11][12][13]. In each of these cases, the robots exhibit undesirable limitations for our particular surgical task. In most cases, the robot's size obstructs the microscope's view into the eye.

There has also been some force-reflecting hand controller work done recently. A micro object handling teleoperation system has been developed [14]. A telepresence laparoscopic surgery demonstration system which incorporates force reflecting loop handles from a pair of forceps [15]. EXOS Inc. has developed three systems that provide haptic feedback to the human hand and arm [16]. Again, while these devices do provide force-feedback, they have limitations in transparency of operation.

2.4 Requirements

Bilateral teleoperation demands a system that is backdriveable, light, fast, small, frictionless, backlash free, and capable of providing sufficient force and frequency response for smooth kinesthetic feedback or haptic sensations. Conventional robotic technology is inadequate for our surgical procedure. The ideal force reflecting teleoperation system would provide a completely transparent interface between user and robot. When there is no contact between the robot and environment, no forces should be felt by the user. Likewise, if there is contact the user should only feel the scaled forces of the tool tip. It is clear that such transparency is improved by reducing mass and friction while increasing the rigidity and backdriveability of the force feedback device. However these goals place conflicting requirements on sensors, actuators, and mechanical structures.

Below we have listed our design goals based on a preliminary investigation. The list is a working document that will change as our experience increases.

- 6-DOF force feedback.
- Range of motion (ROM): displacement: 3

inch diameter sphere, orientation: 55 degree cone angle.
- Translational resolution: 10 microns, angular resolution: 0.056 degrees.
- Range of Force (ROF): force-reflecting master 0-2 lbf, micropositioner 0-1 lbf.
- Minimize Mass: simple mechanism design, small actuators, compact size.
- Maximize encoder resolution.
- Maximize Stiffness.
- Smoothness: no motor cogging, reduce torque ripple, low inertia, low stiction.
- Backdriveability: minimize gear ratios.
- Backlash or stretch: minimize use of gears and cables.
- Minimize friction (especially static friction).
- High Bandwidth: minimize use of gears, maximize high frequency response: several in/sec.
- Ergonomics: work within the operating field with minimal obstruction to microscope & other surgeons.
- Variable compliance.
- Ability to incorporate different sensors easily.
- Use commercial-of-the-shelf (COTS) components when possible.
- Easy to assemble/disassemble (for sterilization, maintenance, or repair).
- Safety: no single mode failures, possible redundant joints, redundant encoders.
- Parallel communication interface boards and high throughput 68040 based computers for low latency

3.0 Progress and Future Direction

Last year's work included a preliminary investigation and resulted in the above goal list. We have also designed, fabricated, and partially tested a single-DOF testbed. This simple hardware platform has been used to resolve basic design issues concerning achievable dexterity, force sensitivity, effects of gearing, use of various types of motors, etc. The testbed is controlled by commercial-off-the-shelf computer hardware and interface cards. This year will bring about the completion of our testing on the single DOF device, and produce a multi-DOF master/slave system. Thus far, two potential designs have been modeled in a commercial robot simulation package. Both of the these 6-DOF robotic mechanisms have been analyzed for their range of motion (ROM) and potential singularities. We are currently designing and fabricating a 4-DOF master and 4-DOF slave. The designs have incorporated the lessons learned from the single-DOF platform and graphical simulations. They will be used to extend our lessons learned to multi-DOF platforms. MDS has determined what end-effectors are required for performing microsurgical tasks. The tools include actuated aspirators, shears, cutters, and forceps. MDS will either modify or design the end effectors for the SCMP.

In the coming months, SNL will be concentrating on testing the 4-DOF platforms and designing and fabricating a 6-DOF prototype pair. The 6-DOF system will allow a surgeon to move and rotate freely in all directions with full dexterity. It will be designed such that the moving mass and reflected motor inertia's are minimized while maximizing the system bandwidth. The final year of work will be devoted to the definition and refinement of the user interface, enhanced modes of operation, and acceptance testing. A graphical user interface (GUI) that will free the operator from typing in commands will be added first. The system will be accessed via touch screens or discrete analog controls. A passive stable support platform for the SCMP will be developed. The support is required because a patient may exhibit involuntary motion of the head even under general anesthesia. Thus, the base of the SCMP must use the head as a fixed reference frame to avoid inadvertent damage to the surgical tissues. At the same time, the device must be light and comfortable. The support mechanism will allow all standard operations, such as tool exchange, to be performed quickly.

A third task will be to set up and utilize a microsurgical testbed for experimental trials. Since none of the SNL personnel are trained in medicine, there is a substantial disconnect in what is desired by a microsurgeon and what the designers perceive as important. A test lab with simulated human eyes, microscope, and tooling will allow SNL to simulate surgical conditions, and will serve as a platform for evaluating the prototype SCMP/SCM system.

Fourth, software will be developed to filter surgeon tremor. Tremor is recognized as a significant problem in microsurgery. It should be possible to design special filters that will diminish the effects of tremor without hampering the dexterity of the surgeon.

Fifth, we will develop a system whereby the SCM/SCMP pair could be used for recording and back playing the forces and motions required in a microsurgical procedure. By simultaneously recording the video image and utilizing video image overlay, it will be possible for a student to repeat the same operation, follow the same motions, and feel the same forces the surgeon originally experienced. This will make it possible to teach students the techniques of experienced surgeons without risking any lives. Also, the dexterity of surgeons can be directly monitored and analytically quantified, helping to decide which medical students are potential microsurgeon candidates.

Finally, acceptance testing will be performed by MDS to determine if the technologies developed achieve the design goals and if the resulting system achieves the dexterity necessary for performing teleoperated microsurgery. MDS will conduct tests under simulated surgical conditions using the prototype hardware to determine to what extent the design goals have been met, and if any additional technology needs to be developed before commercialization.

4.0 Summary and Status

MDS and SNL are participating in a three year cooperative research and development agreement to develop a micro-telerobotic platform to perform microsurgery and microassembly. The effort will result in the development of a 6-DOF micropositioner, a 6-DOF surgeon-controlled master, and a control system that will provide position scaling, force scaling, and tremor filtering. The technologies developed by this project are expected to enhance the skills of surgeons, improve the success rates for existing microsurgical procedures, make new high-dexterity procedures possible, and ultimately reduce surgical costs by increasing the precision and speed of operations. The project team has completed a system goal list, partial testing of a single-DOF testbed, and modeling multi-DOF designs in a commercial robot simulation package. Currently, the project team is designing and fabricating a 4-DOF master and 4-DOF slave.

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