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VerroTouch: High-Frequency Acceleration Feedback for Telerobotic Surgery

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Abstract

The Intuitive da Vinci system enables surgeons to see and manipulate structures deep within the body via tiny incisions. Though the robotic tools mimic one's hand motions, surgeons cannot feel what the tools are touching, a striking contrast to non-robotic techniques. We have developed a new method for partially restoring this lost sense of touch. Our VerroTouch system measures the vibrations caused by tool contact and immediately recreates them on the master handles for the surgeon to feel. This augmentation enables the surgeon to feel the texture of rough surfaces, the start and end of contact with manipulated objects, and other important tactile events. While it does not provide low frequency forces, we believe vibrotactile feedback will be highly useful for surgical task execution, a hypothesis we will test in future work.

Keywords

vibrotactile feedback, robot-assisted surgery

Comments

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VerroTouch: High-Frequency Acceleration Feedback for Telerobotic Surgery

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Abstract. The Intuitive da Vinci system enables surgeons to see and manipulate structures deep within the body via tiny incisions. Though the robotic tools mimic one’s hand motions, surgeons cannot feel what the tools are touching, a striking contrast to non-robotic techniques. We have developed a new method for partially restoring this lost sense of touch. Our VerroTouch system measures the vibrations caused by tool contact and immediately recreates them on the master handles for the surgeon to feel. This augmentation enables the surgeon to feel the texture of rough surfaces, the start and end of contact with manipulated objects, and other important tactile events. While it does not provide low frequency forces, we believe vibrotactile feedback will be highly useful for surgical task execution, a hypothesis we will test in future work.

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1 Introduction

The newest category of modern surgical practice is that of *robot-assisted minimally invasive surgery* (MIS) [17, 7]. Rather than holding laparoscopic tools directly, the surgeon uses a master console to control the motion of several slave robot arms that are positioned above the patient. One robotic arm holds a stereoscopic camera, and the others wield long, thin, interchangeable instruments that enter the patient’s body through tiny incisions. Unlike laparoscopy, the doctor can see a high-resolution stereoscopic image of the operating scene, and the surgical instruments are robotically controlled to precisely follow his or her hand motions. This innovative medical treatment approach (also known as telerobotic surgery) was pioneered at SRI International in the late 1980’s, and it was successfully commercialized in the 1990’s by Intuitive Surgical, Inc., in the form of the FDA-approved da Vinci Surgical System [1]. The da Vinci system is used to perform over 100,000 surgical procedures annually, primarily in prostatectomy, other deep pelvic surgeries, and various cardiac procedures [3].

Although robot-assisted MIS provides excellent visualization and a high level of tool dexterity, it suffers from a notable shortcoming: *the surgeon cannot feel the effects of contact between the teleoperated instruments and the surgical environment*. Understandably, surgeons regularly complain about the lack of touch feedback in the da Vinci system, especially individuals first learning to use the system, e.g., [2, 8]. Without appropriate haptic feedback, operators cannot feel simple tissue properties such as stiffness and texture, nor can they detect subtle changes in tool contact state. To compensate, surgeons must rely heavily upon visual feedback, which can increase cognitive load and error incidence [5].

As overviewed in the following section, researchers have investigated many approaches to adding haptic feedback to robotic MIS, but none has yet emerged as being both clinically useful and technically feasible. In light of this challenge, we have developed the VerroTouch system, a new approach to providing haptic feedback during telerobotic surgery. As described in Section 3, our fully functional prototype haptically recreates the high-frequency contact accelerations experienced by a teleoperated da Vinci tool for the surgeon to feel.

2 Prior Approaches

Many experts believe that high-quality haptic feedback (forces and/or tactile sensations) will help surgeons quickly learn and adeptly perform robot-assisted minimally invasive procedures, e.g., [4, 10, 15, 16]; however, the best method for providing this feedback remains unclear due to the wide variety of approaches being explored and the disparate requirements of the surgical tasks being studied. Furthermore, there are many technical challenges associated with adding haptic feedback to telerobotic MIS. For instance, the tool shaft must be very thin yet must also contain all of the mechanical cabling needed to drive the end-effector’s degrees of freedom (typically yaw, pitch, roll, and grip). The electrical wires for any sensors or distal actuators must also pass through this narrow channel, which is often just 5 to 8 mm in diameter. These constraints make it difficult to integrate force sensors into tools, as do the additional requirements for low cost, long life, consistent performance, and sterilizability.

The most straightforward method for creating a bilateral connection between the master and the slave is that of *position-position control*. The devices continually transmit their positions to one another, and each robot is controlled to track the other’s motion, yielding a spring-like connection between the two. One early effort found that position-based haptic feedback (which includes the effects of the slave’s friction and inertia) fatigued the operator during mock surgery and did not allow perception of soft tissue contact [9]. If parasitic forces are larger than contact forces, one can lower the gain of the position controller to reduce the slave’s detrimental effect on the user, but this action also softens the feel of all touched surfaces. Many more sophisticated controllers have been developed for teleoperation in surgery, e.g., [15], as well as the one used in the commercial da Vinci, but most of these are fundamentally built on position measurements.

If a dynamic model of the slave robot can be obtained, one can estimate the proportion of the slave’s actuator effort that is due only to contact with the environment and use this estimate as the haptic feedback command for the master. Mahvash and Okamura recently succeeded at using this model-based approach to cancel out a significant portion of the da Vinci slave tool forces that stem from friction [11] and inertia [10], thereby hiding the robot’s natural dynamics from the user. However, the dynamic modeling process is intensive and highly configuration dependent, so these techniques may not be parametrically tractable or sufficiently robust for commercial deployment.

Another approach is to use separate sensors that are dedicated to the purpose of haptic feedback. Strain gauges can be positioned on the outside of the tool shaft to measure lateral tip forces, as in [15, 16]. These sensors are small, but they are not sensitive to forces along the axis of the tool, and their placement and the associated wiring can interfere with insertion of the device into the trocar. A further option is to integrate a commercial force/torque sensor into the tool shaft, as in [18], but these are currently too bulky and expensive for clinical use. Others have developed novel, compact force sensors specifically for this purpose, e.g., [14], though these designs have not yet been commercialized. For all of these force sensor approaches, the data can be displayed to the surgeon haptically, through the motors on the master device, or through auditory or visual feedback. The loud environment of the operating room and the surgeon’s attention to the stereoscopic display make graphical overlays of simplified force information an excellent option, e.g., [16]. Lastly, other researchers have designed new types of surgical slave robots which are typically smaller than the da Vinci arms, e.g., [19], but these have not yet been transitioned to clinical practice, so it is difficult to speculate on their ability to provide the operator with good haptic feedback.

The final body of research that is relevant to this problem is that of high-fidelity vibration feedback for industrial telemanipulation. In 1995, Kontarinis and Howe used a voice coil actuator mounted near the user’s fingertips to superimpose acceleration waveforms measured at the slave’s end-effector with force feedback from strain gauges [6]. Although the vibration feedback was not carefully controlled, user tests indicated that this hybrid feedback strategy increased user performance in inspection, puncturing, and peg-in-slot tasks. We recently refined this approach for use with two Phantom Omni robots in position-position control, installing a voice coil actuator in a custom handle and characterizing the system’s dynamics to enable accurate acceleration matching between slave and master [12]. Tests with human subjects [13] showed that this high-frequency acceleration feedback significantly increases the realism of remote surfaces, and we believe it will have a similarly beneficial impact on telerobotic surgery.

3 System Design

We developed the VerroTouch system to enable surgeons to feel the structures they are touching during telerobotic surgery, specifically with the Intuitive da Vinci S surgical system. As diagrammed in Figure 1, VerroTouch continually

Fig. 1. VerroTouch installed on an Intuitive da Vinci S surgical system. The vibration sensors measure the high-frequency accelerations of the tool arms, and the central receiver drives the voice coil actuators on the master handles to let the surgeon feel these vibrations. The gain control knob adjusts the magnitude of the vibration feedback.

Fig. 2. The components of the VerroTouch system when not installed on a da Vinci surgical system. From left to right, one can see the gain control module, two vibration sensor clips, and two vibration actuator clips. The main receiver box is shown at the back.

measures the accelerations of the left and right teleoperated tools using small high-bandwidth accelerometers. These signals reflect the dynamic interaction that is instantaneously occurring between each tool and its environment, whether it is probing, cutting, sticking, or slipping. The system's main receiver filters and amplifies the two measured accelerations and uses a pair of vibration actuators (affixed to the sides of the master handles) to re-create these acceleration profiles at the fingertips of the surgeon. Like the tactile grasping system of [4], VerroTouch attaches to a fully functional da Vinci surgical system. Figure 2 provides a photograph of the VerroTouch components when they are not installed on a da Vinci, and the subsections below explain their functionality.

Vibration Sensors. VerroTouch uses acceleration sensors to detect the vibrations occurring in the da Vinci tools. After considering many possible mounting locations, we chose to attach the sensors to the da Vinci S patient-side manip-

ulators just below the interchangeable tool mounting point. This location does not interfere with tool or arm motion, and it allows measurement of significant vibrations along the long axis of the clip (perpendicular to the tool axis). Furthermore, this location is inside the da Vinci’s plastic drapes, so the sensors would not need to be sterilized if used for actual surgery, thus reducing cost. Each clip contains an Analog Devices ADXL322 MEMS-based accelerometer, which is firmly held against the surface of the tool arm. This accelerometer has a range of $\pm 20 \text{ m/s}^2$, and we configure it with an on-board first-order low-pass filter set at 1000 Hz. The clips are 3D printed in ABS plastic, and the sensors are attached to the main controller via flexible shielded wire.

Vibration Actuators. VerroTouch’s two actuator modules mount onto the da Vinci master handles on top of the platform wrist joints, as pictured in Figure 1. Early versions of our system placed the actuator on the rounded portion closer to the user’s fingers, but we found that the weight of the actuator then constantly pulls down on the user’s fingers, which is uncomfortable and fatiguing. Integration with the da Vinci controller would allow software gravity compensation, but we sought to create an independent system. Several other mounting positions were considered, and the current location was found to permit excellent signal transmission while minimizing interference with the user. The weight of the actuator does still create a moment around the elbow of the master arm; we alleviate this problem by adding a calibrated counterweight to the motor controlling this axis, which balances out the actuator’s weight. Each actuator module is 3D printed from ABS plastic and contains an NCC04-10-005-1X voice coil actuator from H2W Industries. These actuators have a stroke of 10.4 mm with a maximum continuous force of 2.2 N and a peak force of 6.6 N; their force output is directly proportional to the applied current. The coil is rigidly attached to the plastic housing, and the magnet rides on a linear bearing and is centered in its workspace by a pair of compression springs. The actuators are connected to the main receiver using flexible shielded wire.

Main Receiver. The main receiver takes the measured acceleration signals from the sensor clips and drives the corresponding voice coil actuators to replicate these vibrations for the surgeon to feel. Figure 3 provides a flow chart for the analog circuit inside the receiver. A DC blocking capacitor removes the mean of the accelerometer’s output, and a voltage amplification stage increases the magnitude of this signal according to the setting of the gain control knob. The signal is then band-pass filtered to remove low frequencies (not reproducible by our actuation method) and very high frequencies (beyond the bandwidth of hu-

Fig. 3. The signal flow diagram for each channel of the VerroTouch system.

man perception). The resulting signal is applied to the voice coil actuator as a current command.

4 Testing and Results

To benchmark its performance, we installed VerroTouch on a da Vinci S surgical system. Each actuator module was instrumented with an ADXL320 ± 50 m/s² accelerometer to allow us to record the system’s output. The acceleration feedback gain was set to a comfortable level, and several tasks were performed by the operator, as shown in Figure 4. The interaction was videotaped, and a National Instruments USB-6216 16-Bit analog input device was used to record tool accelerations, actuator currents, and actuator accelerations.

Figure 5 shows time-domain and frequency-domain views of ten seconds of data recorded during this session. The shape of the master acceleration waveform is seen to generally match the shape of the slave tool acceleration, scaled up by a factor of 15. The continuous vibrations of dragging and the sharp vibrations of contact events are all transmitted for the operator to feel. Comparing the power spectrograms of the two signals reveals the ways in which the signals differ. The slave tool acceleration contains significant power at very low frequency, which was not being recreated on the master due to the settings of the adjustable bandpass filter. The master acceleration spectrogram is also seen to consistently contain significant power at 200 Hz and a moderate amount of power near 600 Hz and above 800 Hz; we believe these additional vibrations stem from either parasitic vibrations of the master or electrical noise. After correcting for the circuit’s 1.75 ms time delay, the correlation between the depicted time-domain master and slave acceleration signals has a moderate R^2 value of 0.34, demonstrating a reasonable temporal match despite the addition of high-frequency noise and the presence of uncharacterized system dynamics. The correlation between the Fourier transforms of these master and slave accelerations has an R^2 value of 0.77, showing that frequencies are largely being preserved. Throughout the testing, the operator was able to easily feel these vibrations at their fingertips, including the texture of rough surfaces, the start and end of contact with manipulated objects, and other important tactile events. We were also pleased to find that the voice coil actuators produce collocated sounds that match the feel of these vibrations.

Fig. 4. The manipulation environment chosen for testing. The operator used a large da Vinci needle driver to interact with the practice suture pads, suture needles, small objects, rubber tubes, soft strings, and the hard plastic structure of the task board.

Fig. 5. Sample acceleration data recorded during VerroTouch testing with the setup shown in Figure 4. During these ten seconds, the operator stroked the practice suture pad, picked up the needle, and pricked the suture pad with the needle four times. This data was sampled at 20 kHz, and the spectrograms were calculated using a Blackman-Harris window of length 2048 in order to emphasize temporal events.

5 Conclusion

VerroTouch is the first work to add naturalistic high-frequency acceleration feedback to a commercial robot-assisted surgical system. Experimental analysis demonstrated that the accelerations VerroTouch creates at the da Vinci handles strongly resemble those measured at the tools. While VerroTouch does not provide low-frequency forces, we believe that its high-frequency acceleration feedback will be useful for surgical task execution. We plan to test this hypothesis with human subjects in future work.

While most previous approaches to haptic feedback require significant modification to the robotic system, VerroTouch is a simple augmentation that can easily be added to an existing teleoperator. Additionally, VerroTouch uses inexpensive off-the-shelf components, with the only custom hardware being the plastic mounts for the sensors and actuators. We believe these attributes are important in making VerroTouch practical as an addition to a clinical robot-assisted surgical system, such as the da Vinci S.

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