John Edwards

Touching Research: Haptics and Signal Processing

The science of haptics gets its name from the Greek word *haptikos*, which means the ability to grasp or touch.

Haptics researchers investigate ways of using tactile sensation and control to help people interact more intuitively with computers, robots, and various other types of electronic and electromechanical systems. Through the use of specially designed input/output devices, such as haptic joysticks, gloves, and surfaces, users receive feedback in the form of sensations that are felt in a finger, hand, or other part of the body. Haptic devices typically use resistance motors to supply force, vibration, or motion feedback.

When used in conjunction with a video display, haptics can help users perform complex tasks requiring precise hand–eye coordination, such as surgery, physical rehabilitation, flying a drone, or manipulating very large or very small objects, ranging from space vehicles to microscopic organisms. Haptics technology is also finding a home in consumer applications, such as computer games, enabling users to feel as well as see and hear play interactions.

"Haptics technology can provide the user with a representation of the sense of touch and corresponding force feedback in interacting with a virtual or a remote environment," says Robert Diraddo, medical devices' group leader for the National Research Council of Canada. "These (sensations) are most important in virtual reality and remote manipulation applications, where the interactive sense of touch is important."

Gabriel Robles-De-La-Torre, founder of the International Society for Haptics, notes that signal processing is crucial in haptic system design and operation. "[Applications] range from filtering signals coming from position and torque sensors in haptic interfaces to processing the signals coming from touch sensors intended for robot control," he says. "One can also use fast Fourier transform (FFT) and other techniques to analyze the results of measurements in human performance experiments."

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The most difficult task facing haptic system developers is creating accurate representations of real-world tactile sensations without consuming vast amounts of processor power or driving up costs excessively. "Ensuring suspension of multisensorial user disbelief while maintaining hardware affordability is the biggest challenge for haptics-driven virtual reality," Diraddo says. "If not addressed, user-adoption of the technology is limited."

VIRTUAL HANDS-ON TREATMENT

University of Texas (UT) at Dallas researchers are developing a haptics-based technology that promises to make it possible for physical therapists and other health-care professionals to work with patients located almost anywhere. The system utilizes multiple three-dimensional (3-D) cameras to create avatars of both the care provider and patient and then places them inside a virtual space where they can interact with each other in a realistic fashion.

"Our technology allows real-time capturing, transmission, and rendering of 3-D avatars of multiple human actors as well as force feedback," says Balakrishnan "Prabha" Prabhakaran, a professor of computer science at UT Dallas and the project's principal investigator (Figure 1).

With conventional telemedicine, a caregiver and patient can both appear on the same display, talk to each other, and even exchange medical data, yet still have no practical way of physically interacting. "Our project's goal is to facilitate high-quality multimodal 3-D teleimmersion incorporating a force-feedback experience in a 3-D virtual space using haptic devices," Prabhakaran says.

The researchers' current platform allows applied force to be sent from one user to the other. This way, a care provider could, for example, feel an accurate representation of the strength of a patient's muscle as it is being flexed. The platform uses force-feedback haptic devices manufactured by Geomagic of Morrisville, North Carolina. The units rely on built-in motors to create forces that push back on the user's hand to simulate touch and interaction with virtual objects. "We are focusing on upper-arm movement, because it's easier in terms of the off-the-shelf devices that already exist," Prabhakaran says.

Haptic devices come in different forms, and the one the researchers are currently using is not wearable. The device, which sits on a table, features a small, grabbable handle. "You can feel the force feedback when you are moving the handle," Prabhakaran says. The device can generate, or receive, force-feedback in three translational degrees of freedom as

Digital Object Identifier 10.1109/MSP.2013.2292433
Date of publication: 12 February 2014

[FIG1] **Balakrishnan "Prabha" Prabhakaran. (Photo courtesy of the University of Texas at Dallas.)**

well as torque feedback in three rotational degrees of freedom in yaw, pitch, and roll directions.

The current device isn't suitable for rehabilitation use, yet it is helping the researchers to coordinate haptic movements with the 3-D virtual space. More sophisticated haptic technologies are currently under development, Prabhakaran says. "What we are trying to do is to build our own haptic device using resistance motors and microcontrollers," he notes. Prabhakaran says the researchers are striving to achieve maximum realism and accuracy via force-feedback technology. "For instance, if I am moving my arm up, and the doctor is moving his or her arm down, then it would be like offering resistance in the opposite direction. That gives you a feel for how healthy the patient's muscles are."

In the years ahead, Prabhakaran sees care providers and patients using several different types of haptics devices, with each designed to mimic and communicate data about a specific body part. "We use our arms and legs in different ways," Prabhakaran says. "It's like when you go to the gym; you have different equipment for different muscle groups."

Transmitting large amounts of audio, video, and haptics data increases the likelihood of significant lag time and other types of transmission delays. The researchers are addressing this challenge by developing sophisticated algorithms and various types of software designed to speed data through the Internet in real time. "All the data that we are dealing with in realizing our goal of multimodal 3-D teleimmersion are digitized signals, representing time-varying and spatially varying physical quantities," Prabhakaran says. "These data need to be synchronously captured in real time, analyzed, compressed if needed, transmitted, and processed on the receiver's side before rendering them to the user. Hence, signal processing is an inherent component of our research."

[FIG2] **The Bristol Robotics Laboratory haptic robot palpitates artificial tissue samples. (Photo courtesy of Bristol Robotics Laboratory.)**

Prabhakaran notes that signal processing also plays key roles in other areas, including filtering, image processing, and pattern recognition, as well as in the development of different haptics devices. "Multidimensional and biomedical signal processing is also critical to the operation of the inertial body sensors," he adds.

Innovative algorithms will also help minimize the amount of data that needs to be exchanged. Xiaohu Guo, an associate professor of computer science at UT Dallas and a project coprincipal investigator, is an expert in computer graphics, animation, and modeling. Guo is refining techniques to allow data moving between haptic devices to be transmitted over a network more efficiently, as well as creating 3-D visual images of user movements in real time. Gao has also reported success in downsizing massive data sets with spectral transformation techniques. The technique relies on manifold harmonics to transform 3-D images into points that represent the surface of an object. The data is then compressed into a more compact form that can be transmitted more rapidly over networks.

Prabhakaran believes that the system will eventually provide benefits to users of both telerehabilitation and in-home rehabilitation services. "Current in-home rehabilitation relies on patients' word of mouth—or diary—for having done the prescribed exercises with the prescribed number of repetitions," he says. Limited oversight capabilities requires caregivers to trust that the patient has actually performed the exercises, and in the correct manner. "With 3-D teleimmersion incorporating haptics, the experts can have an exercise record ... that contains the trajectories of the body joint movements as the exercises were done, the number of repetitions and so on," Prabhakaran says.

Prabhakaran predicts a bright future for haptic medical and rehabilitation technologies. "Sense of touch is really important in areas such as physical medicine and rehabilitation, where the experts would like to have a 'feel' for the strength of muscles or the trajectory of body joint movement," he says. "It will be appreciated by both caregivers and patients."

ROBOTIC SURGERY WITH FEELING

Developing a haptics technology that can help a surgeon operate with great precision, even when using a robot as the primary surgical tool, is the goal of researchers at the Bristol Robotics Laboratory (BRL), a joint venture of the University of the West of England and the University of Bristol.

"At the moment, the da Vinci robot, which is the main robot used in surgery, doesn't actually provide any haptics feedback," explains Adam Spiers, a BRL research associate. "So surgeons need to make their diagnosis of tissue inside the body based purely on vision, which works but is also quite unnatural." Even with the assistance of the best video equipment, accidents still happen from time to time. "There have been examples of mistakes in operations because surgeons couldn't distinguish one type of tissue from another, or detect what is underlying a structure," Spiers notes.

The BRL researchers aim to give surgeons who operate with robots the ability to feel as well as see inside patients. The extra sensing ability, delivered from the robot to a surgeon's finger, promises to make surgical procedures more accurate and reduce the likelihood of potentially devastating errors.

"The area of surgery we've been looking at is keyhole—laparoscopic—surgery," Spiers says. "This type of surgery is very difficult to perform and has a lot of restrictions in terms of vision and touch feedback, which makes it quite easy to misidentify tissue structures."

Spiers notes that different types of organ tissues present various levels of stiffness, a characteristic that can be used to help robot-equipped surgeons operate more accurately and efficiently. "We work primarily with urologists, and the main thing they use their robot for is the removal of cancerous prostates," he says.

To find and remove a diseased prostate, a surgeon must slice through a great deal of tissue. "There's all these different types of tissue structures—fat, nerve tissue, and the prostate itself," Spiers says. "If you could find and detect those things by touch, you would potentially save errors where others have misidentified tissue and dissected it by accident."

Spirers says his team recently completed a study based on a prototype surgical system that demonstrated haptics ability in action (Figure 2). Project participants were asked to find hard tumors placed within opaque synthetic tissue samples located in a distant part of the lab (Figure 3). The system relayed the participants' finger movements to a robot that then precisely duplicated the motions and transmitted the corresponding sense information as it touched the tissue samples back to each participant. Using an Internet connection, there was a performance loss of under 1% compared to using one's own finger to detect the lumps, Spiers says. "If we can move this prototype system into a surgical scenario, the technology will have significant implications," he notes. "The main thing we're hoping for with the inclusion of haptics in surgical systems is a reduction of error—less error in surgery."

[FIG3] A user operates the Bristol Robotics Laboratory haptic robot. (Photo courtesy of Bristol Robotics Laboratory.)

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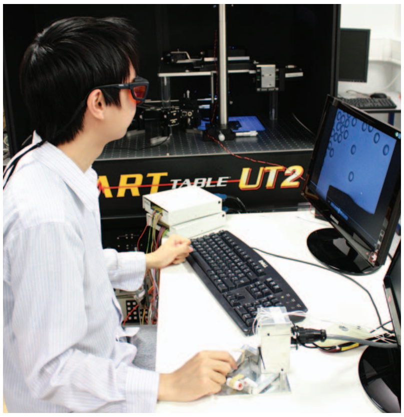
From a signal processing perspective, one of the biggest challenges facing the researchers is ensuring that the data moves from surgeon to robot and back again with as little delay as possible, Spiers says. "The whole idea is that we're trying to create the illusion to people that their finger is somewhere else, that they are feeling things on the other side of the room." Maintaining almost instantaneous feedback is essential to the technology's success. "As soon as things start slowing down, or getting jittery, or you feel something after you've finished touching it, then the illusion falls apart," Spiers explains.

System integration work consumes a great deal of the researchers' time. "We have quite a few different elements in our system—the part on their user's fingertip, the robot, and the robot's fingertip—and we have a lot of signals going between all of those components," Spiers says. "We spend quite a bit of time trying to make sure that all of our signal processing and networking algorithms work as fast as possible."

HAPTIC TWEEZERS

While scientists can turn to a microscope to view and study microscopic structures, touching and feeling extremely minute objects has always been a far more challenging task. But perhaps not for much longer. Researchers at France's Université Pierre et Marie Curie say that the new "haptic optical tweezers" they have developed (Figure 4) will enable microscope users to manipulate samples within worlds up to a million times smaller than humans.

The tool promises to help scientists explore microscopic worlds by sensing and exerting piconewton-scale forces, allowing improved micromanipulation and microassembly dexterity. "The initial results obtained are promising and demonstrate that optical tweezers have a significant potential for haptic exploration of the microworld," says Cecile Pacoret,



[FIG4] **The haptic optical tweezers. (Photo courtesy of Université Pierre et Marie Curie.)**

a postdoctoral research fellow at Université Pierre et Marie Curie, who also works in collaboration with the Nanorobotics Laboratory at Carnegie Mellon University. "Haptic optical tweezers will become an invaluable tool for force-feedback micromanipulation of biological samples and nano- and microassembly parts," she predicts.

Conventional optical tweezers, which manipulate tiny objects with highly focused laser light that generates an attractive or repulsive force, are already widely used for the study of single molecules and cells. Yet biological researchers exploring 3-D cells or molecular phenomena like DNA stretching would benefit greatly from having access to touch feedback as they go about their work. "Our system already provides great improvement in maneuverability and training requirements," Pacoret states.

The technology is also relatively easy to learn and use. Pacoret notes that guests visiting the lab are generally able to perform their first micromanipulations within just a few minutes. "Our system allows an operator to touch and explore microscaled shapes like microelectromechanical systems or single cells," she says. "Moreover, it is able to interact, apply stress, and give feedback."

One of the biggest challenges facing the researchers as they developed the technology was magnifying piconewton-scale forces high enough to allow human operators to perceive interactions never before physically sensed, such as adhesion phenomena, extremely low inertia, and the high-frequency dynamics of extremely small objects. Design requirements included very high sensitivity and dynamic stability. "Our system merges different techniques and is highly multidisciplinary, combining vision, signal processing, real-time programming, optics, robotics, automatics, [and] haptics," Pacoret says. "The classic optical tweezers have been modified to meet the human perception requirement: safety, stability, reliability, and responsiveness."

Signal processing is used to ensure the performance and reliability of the tool's haptic coupling and teleoperation functions. "Information is exchanged bilaterally between two robots: the slave robot—the micromanipulator in our case—and the master robot, the haptic interface," Pacoret says. The arrangement creates an automatic closed loop that must remain stable under all circumstances for the safety of both the samples and the robots. "The originality of our system is to have designed all the components to have the smallest need of filtering, so our coupling loop can be reduced to the most transparent type of coupling," Pacret says. "Our thesis is that a well-designed haptic system allows high performance."

> **MOST HAPTICS RESEARCHERS FEEL THAT THE TECHNOLOGY'S POTENTIAL IS ONLY BEGINNING TO BE FULLY UNDERSTOOD AND APPRECIATED.**

Pacoret predicts that the haptic optical tweezers will one day become an important tool for the exploration, diagnosis, and assembly of sensors, microsystems, and biomedical elements, including cells, bacteria, viruses, and proteins. Such objects tend to be extremely fragile and difficult to manipulate. "This tool will provide a new degree of freedom and accessibility to researchers, including, for example, new versatility in the study and micromanipulation of cells," she says.

THE FUTURE OF HAPTICS

Most haptics researchers feel that the technology's potential is only beginning to be fully understood and appreciated. "Applications in medicine already include the interactive design of surgical devices, surgical robotics, patient-specific (surgical) rehearsal, and rehabilitation," Diraddo says. "Outside of medicine, there are many potential applications, such as the handling of dangerous materials, maintenance training, interactive automotive design, aerospace telemanipulation, and serious gaming."

Robles-De-La-Torre believes that technology developers in a variety of fields are now acquiring a growing respect for haptics, coming to the realization that the sense of touch is as essential in many situations as vision and hearing. If this trend continues to build, as now appears likely, it should lead to haptics finding a place in a wider number of systems and applications.

"The importance of the scientific part of haptics is fundamental, but largely overlooked in general," Robles-De-La-Torre says. He points out that removing someone's haptic abilities would leave the individual unable to walk, chew food, or articulate speech normally. "Skilled tool use would be out of the question," he says. (Try, for example, using a pen or a pair of scissors after your arm has fallen asleep.) "Basically, our haptic capabilities enable us to interact with and change our environment," Robles-De-La-Torre says.

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