CISST-Retrospective_TG-CL-RT

ERC on Surgical Systems and Technology Has Pioneered Robotic Surgery

Over its ten-year lifetime as an NSF-funded Engineering Research Center (ERC), the Center for Computer Integrated Surgical Systems and Technology (CISST), based at John Hopkins University (JHU) in Baltimore, Maryland, made major advances in robotic surgery. These include new technologies that steady the hands of surgeons while they perform microscopically precise eye surgeries; tiny robotic “snakes” that can travel through the esophagus to remove hard-to-reach tumors that normally require very invasive surgery to reach; and visualization and mapping tools that give surgeons greater confidence and accuracy in performing biopsies, delivering radiation seeds, and other delicate operations.

The vision that drove and still drives the Center’s research is to integrate cutting-edge technologies into systems that are able both to greatly improve physicians’ ability to plan and perform existing surgical interventions and to enable new procedures that would not otherwise be possible. This vision has led the Center to explore all aspects of computer-integrated interventional medicine. The advances pursued will eventually touch upon virtually every aspect of care delivery: more accurate procedures; more consistent, predictable results from one patient to the next; improved clinical outcomes; greater patient safety; more cost-effective methods for treatment of care; better methods for physician training; and creation of an information infrastructure that will facilitate experience-based methods for assessing treatment alternatives and improving procedures.

Although the Center’s central focus has been on “medical robotics,” its interdisciplinary research has accordingly been very broad, encompassing medical imaging, modeling of patient anatomy and surgical procedures, novel sensors and mechanisms, human-machine interactions, and systems science.

CISST’s technology development effort has also generated a web of collaborations that extends throughout the engineering and medical campuses at JHU and unites several major universities and companies. The founding partner institutions included Johns Hopkins, The Massachusetts Institute of Technology, Carnegie-Mellon University, and Brigham and Women’s Hospital, all of which have contributed broadly to the Center’s research. Morgan State University joined the Center in 2001 and has been doing work on imaging technology and on informatics methods for organizing and retrieving scientific data. The University of Pennsylvania helped to develop minimally invasive surgical techniques with human-machine systems, as well as medical image processing methods for prostate biopsy and other clinical applications. Columbia University is a partner for the development of high dexterity “snake” robots for minimally-invasive surgery in confined spaces. Harvard University has been involved in helping to develop systems that relay a sense of touch from a mechanical device to the hands of a surgeon. The Center has also begun to work with two international partners: Queens University of Canada and the Technical University of Munich, in Germany. Partnerships with industry, including Burdette Medical Systems, Siemens Inc., and Intuitive Surgical, have led to several patents and a variety of collaborative research and development projects.

Computer-integrated surgery curricula emerging from CISST have augmented degrees in several engineering departments, along with unique courses such as Surgery for Engineers, which brings engineering students into the operating room, where they perform basic surgical operations on a variety of “phantoms” and then on live animals. In addition, for several years the Center has conducted a summer robotics camp for middle school students, as well as pioneering NSF’s Research Experiences for Teachers program.

Surgery for Engineers is an innovative CISST course developed at Johns Hopkins University that brings engineering students into the operating room to gain hands-on training in surgical technique.

One significant application of CISST’s technology has been in retinal microsurgery, in which surgeons must perform tasks at the boundaries of human sensing and manipulation capabilities. The Center developed two microsurgical manipulation devices that enhance physical precision—the Johns Hopkins “steady-hand” robot and the MICRON system—which are being integrated into a complete micro-surgical assistant workstation.

CISST has been a research leader in developing effective methods for human-machine cooperation in surgical applications, including “virtual fixtures” for improving the safety and precision of interventions, methods for registration and virtual reality overlay of surgical plan and image information onto a surgeon’s view of patient anatomy, and methods for improving a surgeon’s sense of the forces exerted by his or her tools on tissue. The Center has also developed methods for accurately locating tumors and other clinical targets in computed tomography (CT), magnetic resonance imaging (MRI), or ultrasound images and then using robotic devices to place a needle or other therapy device onto the target.

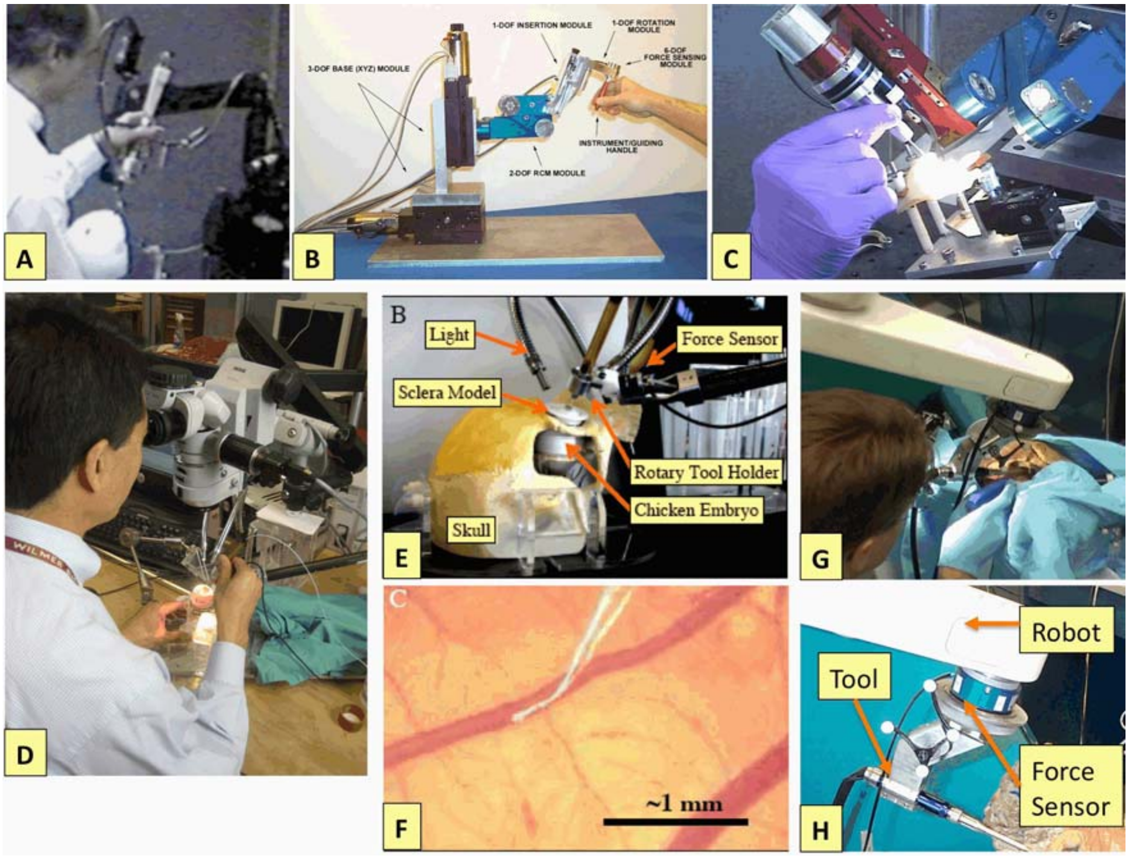
In partnership with Burdette Medical, the predecessor of Acoustic MedSystems, CISST developed ultrasound-guided robotic systems to more accurately deliver radioactive seeds to prostate tumors. In response to an early NSF site visit suggestion, the Center initiated research toward similar technologies for breast and liver cancers. Today these projects are funded from external resources combining clinical trial grants, industry contributions, NIH research grants, and fellowship grants.

CISST’s research in this area generally followed a consistent sequence: define the architecture of the technology, provide documented and tested components, and establish the development process and tools. The architectural design included the creation of standard interfaces for all of the systems’ major components. For example, there are many technologies (e.g., optical, magnetic, mechanical) that can be used to track the position of a surgical instrument; but they all provide the same fundamental capabilities. Defining a generic interface to these devices leads to a modular architecture that enables “plug and play” medical devices.

Although a formal software development process is generally not necessary for a specific research project, it is appropriate when the goal is to create a core development platform that can support many research projects and can ultimately be used in clinical trials. For example, NSF funded a “translational research” project at CISST in partnership with Intuitive Surgical Systems to develop software platforms to extend the use of the existing da Vinci surgical robot and to facilitate medical robotics research generally. This open-source "Surgical Assistant Workstation (SAW)" software provides a compatible software environment for linking advanced research and functions to the da Vinci and to research robots developed in academic laboratories. It is based in significant part on open-source software libraries developed over 10 years by the CISST ERC and released to the public. Currently, a "beta" version of the SAW is widely used inside JHU for multiple medical robotics projects and is also used in advanced research activities inside Intuitive. In addition, this "beta" SAW is beginning to be used by other selected academic institutions. As the software becomes stable, it will be widely released.

Some Sample Devices

The Center has established world leadership in the development of medical robots for a wide spectrum of applications including microsurgery, minimally invasive surgery and therapies, and a variety of non-medical biological applications.

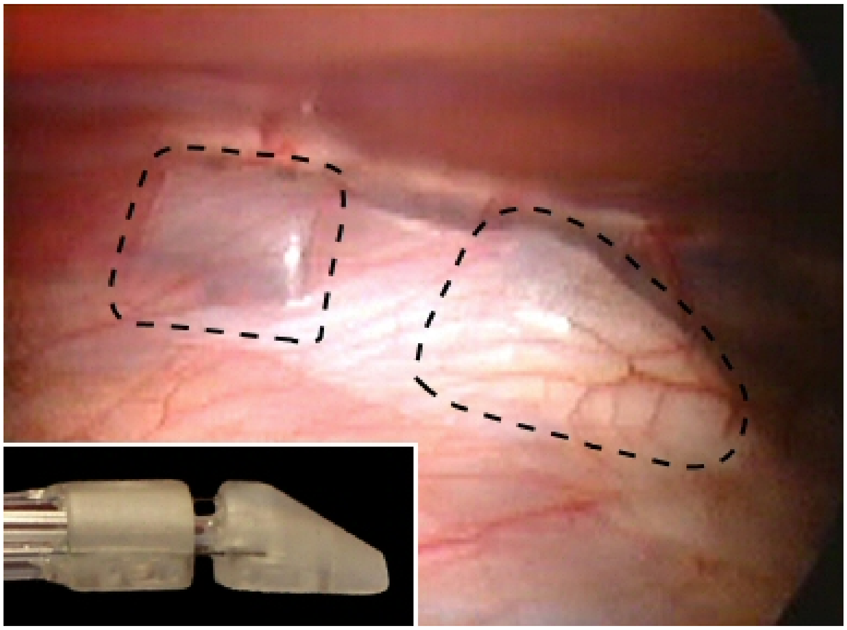


JHU Steady Hand Robots: A) Early experiments with steady-hand evacuation of hematoma model with the IBM/JHU LARS robot, using a 5-bar linkage remote-center-of-motion (RCM) mechanism; B) Next generation Steady Hand Robot incorporating high dexterity chain drive RCM; C) Steady hand otology microsurgery experiments using the robot in B; D) Retinal surgeon James Handa using our current generation steady hand "Eye Robot" to cannulate 100 µm vessels in chick embryo; E) Detail of the robot and experimental setup for the Eye Robot; F) close up of the micro-pipette and blood vessels from the cannulation experiments; G, H) Steady-hand skull base surgery using a modified Neuromate™ neurosurgical robot. The systems shown in A-C have mechanically constrained remote-centers-of-motion, while the systems in D-G use software to enforce RCM constraints.

In the late 1990s, Drs. Russell Taylor, Louis Whitcomb, and Daniel Stoianovici developed the first generation of the Johns Hopkins *Steady-Hand Robot*, extending earlier work at IBM and JHU by Dr. Taylor. The system proved effective at reducing hand tremor and increasing motion precision for manipulation tasks at the microscopic level. This has particular relevance to retinal microsurgery, where manipulations at the boundaries of human capabilities are common. The latest generation of this system is now part of a recent NIH Bioengineering Research Partnership (BRP) project to develop a complete eye surgery workstation, as is Carnegie-Mellon's hand-held MICRON robot (discussed below).

The latest MICRON and its associated optical motion tracking system, the Apparatus for Sensing Accuracy of Position, or ASAP, with visual tracking.

A key related technology was developed by Dr. Cameron Riviere at Carnegie-Mellon.. The *MICRON* system also seeks to eliminate hand tremor for microscopic manipulation tasks. The instrument handle incorporates an inertial motion-sensing module. Using these sensors, the velocity of the instrument tip is computed and integrated to obtain tip displacement. The tremulous component of this motion is then estimated, and a micromanipulator built into the instrument tip then deflects the tool tip with an equal but opposite motion, compensating for the tremor. As with the steady-hand robot, several generations of the instrument have been designed. The most recent provides a range of motion of more than 1 mm in each of the three coordinate directions, more than enough for canceling of physiological tremor during microsurgery.

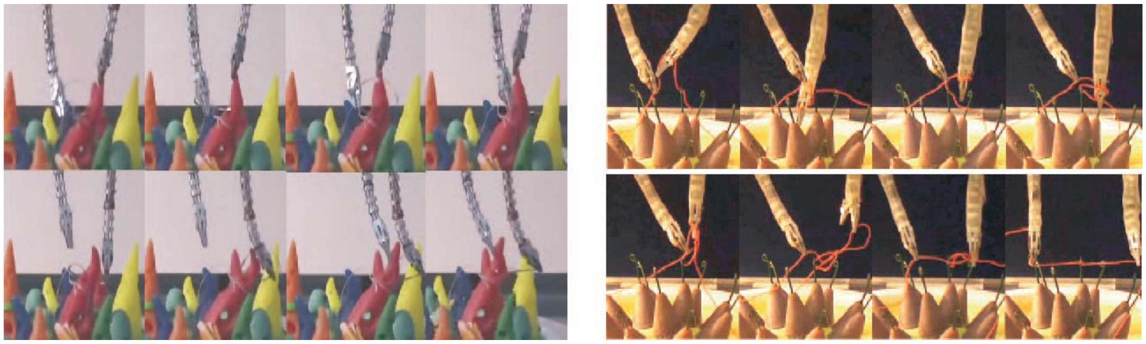


The HeartLander Robot prototype being tested in vivo on the beating heart of a pig.

Most robot systems are “grounded,” meaning they are physically attached to a stable base that is independent of the patient. However, systems attached to the patient can have great benefit when the organ of interest is highly mobile. For example, Dr. Riviere and his colleagues at Carnegie-Mellon developed *HeartLander,* a minimally invasive robotic device for heart surgery that can adhere to the heart surface and navigate to any desired work site under the control of a surgeon. It uses suction to fasten itself to the heart and crawls like an inchworm across the surface. The device incorporates a videoscope to provide visual feedback to the surgeon, who controls it with a joystick. The device has a small working channel through which various tools can be introduced for surgical procedures such as electrode placement or drug injection. It can crawl or “walk” to reach any point on the heart surface. The device can be inserted through an incision below the ribcage and does not require general anesthesia. Since it is compatible with local or regional anesthesia, it could enable ambulatory outpatient heart surgery for the first time.

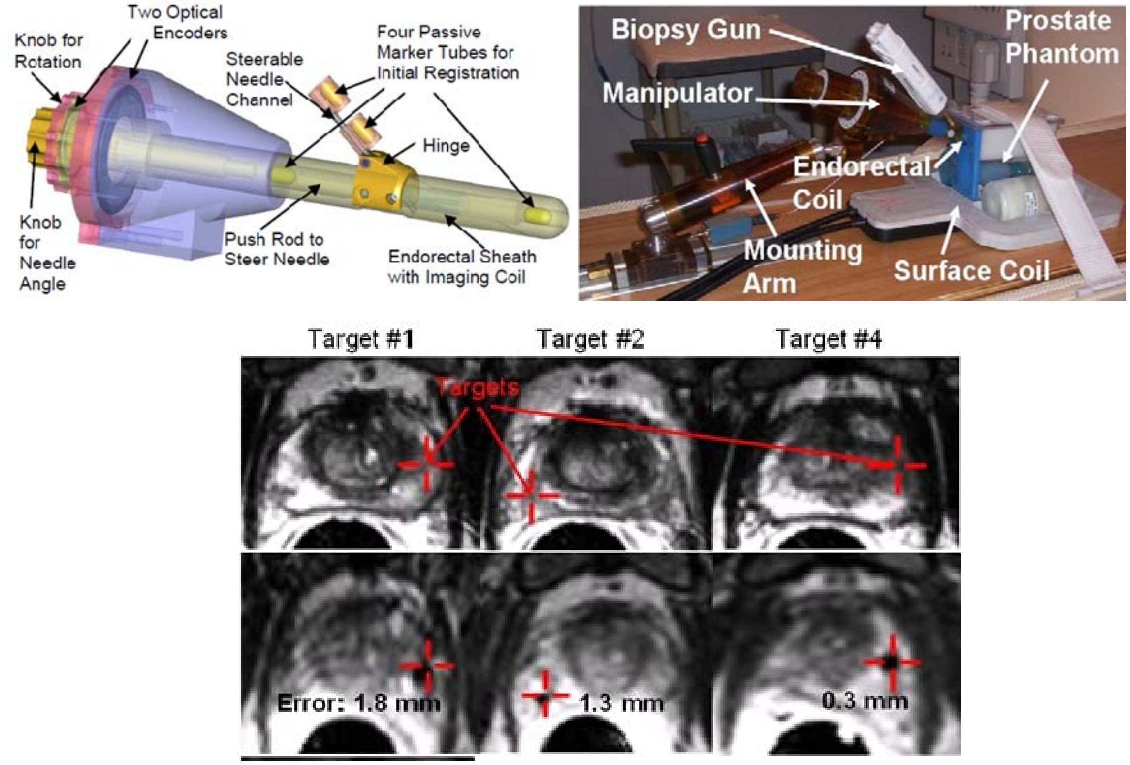
The prototype has been tested on the beating heart of 28 live pigs, where it has demonstrated access to all parts of the epicardial surface, treatment targeting accuracy of 1.7 mm, and stable station-keeping on the beating heart surface (0.7 mm drift). A patent has been filed for the device and Carnegie Mellon has established a start-up company (now called HeartLander Surgical) to commercialize the technology.

Dr. Nabil Simaan (Columbia University),Russell Taylor, and students Ankur Kapoor, Kai Xu, and Wei Wei, in collaboration with Dr. Paul Flint at Hopkins, developed a *Snake-like Robot* system for minimally invasive surgeries. Such devices are particularly useful in procedures such as laryngeal surgery that require high dexterity in a constrained workspace. Current manual instrumentation is awkward, hard to manipulate precisely, and lacks sufficient dexterity to permit common surgical subtasks such as suturing vocal fold tissue. Size limitations require a small-diameter robot (less than 5 mm) for suturing purposes inside the throat. This robot is based on a new design concept for snake-like robots using flexible members and redundant actuation. Its innovative design makes it possible to build extremely small robots that can apply the forces necessary for surgical instrument manipulation. The basic technology has been licensed to Intuitive Surgical, Inc.



Prototype of a snake-like robot for laryngeal surgery.(left) throwing a circular suture; (right) tying a knot.

One of CISST's first clinically successful medical robotics projects is an MRI-guided robotic device—called the "*APT-MRI*," for performing precision image-guided intervention in the prostate—that was developed by CISST faculty Fichtinger and Whitcomb, along with their students and collaborators. Initial CISST support enabled the team to develop a prototype and preliminary data to obtain subsequent NIH support for development of a clinical APT-MRI. This system has been employed in clinical trials at the National Institutes of Health (Bethesda, MD) and the University of Toronto, Canada, to perform over 45 human subject trials of MRI-guided biopsies, fiducial marker placements, and injections. JHU has filed for patents on the APT MRI and has licensed the system for commercial development by a leading MRI-guided medical instrument company. FDA approval of the commercial APT MRI is pending. CISST graduated from NSF ERC program funding in late 2009. Although its administrative structure and financial processes have changed, CISST has continued to function as a multidisciplinary research center at Johns Hopkins. Most of the research is currently funded by NIH grants or through industry partnerships.



(Top left) *The APT-MRI-2 scanner-independent IG prostate robot CAD Model.* ***(Top right)*** *APT-MRI-2 phantom trials.* ***(Bottom)*** *Prostate biopsy and fiducial marker insertion in human subjects with manual APT-MRI-2.*

In addition to CISST's traditional focus on medical robotics and interventional imaging, there is also increasing interest in broader initiatives emphasizing statistical learning methods and large-scale databases and "informatics" techniques to improve both treatment processes and physician training.

CISST's fundamental mode of operation remains one in which clinical end users and engineers work together in teams to develop novel solutions to clinically important problems. During the NSF-funded ERC phase, most of these teams were led by engineering faculty, with significant participation from clinicians. Engineer-led projects motivated by clinical needs continue to be created. However, as the technology has matured, there are beginning to be more clinician-led projects and proposals exploiting the new capabilities developed during the NSF-funded phase. Thus, the future of CISST will increasingly see the application of its innovations to health care needs in clinical practice.