Breakout Report: BR3.3 - Medical Robotics

Lead: Peter Kazanzides (Johns Hopkins), Co-Leads: Hawkeye King (University of Washington), Tho Nguyen (NSF)

Introduction

Medical robotics represents the ultimate merger of cyber- and physical- systems. Sensors and data create a health-care model for the patient, algorithms and human-computer interaction create a therapeutic course of treatment, and mechatronic arms and effectors physically treat the patient. Ultimately the machine affects a person's life on a profound level.

The most successful and widely recognized among medical robotics are telesurgical robots exemplified by the daVinci robot by Intuitive Surgical. Surgical robots are leading a revolution in surgical care. At the same time, however, medical robotics includes other applications like rehabilitation, prosthetics and exoskeletons, interventional radiology, robotic catheters, colonoscopy, and home health care.

This report outlines important research directions in the field of CPS Medical Robotics.

What do we know and do well today?

The most mature CPS medical robotic systems are **local master-slave teleoperation** robots where the surgeon and patient are in the same operating room. FDA approved systems from companies like Intuitive Surgical (Sunnyvale, CA) and Hansen Medical (Mountain View, CA) use this paradigm. Other systems use a cooperative control paradigm, where the surgeon and robot share control of the instrument, as in the FDA approved system from Mako Surgical (Ft. Lauderdale, FL).

Autonomous and human-machine collaborative surgical robotics has been demonstrated in **static surgical environments**, e.g., orthopaedics and neurosurgery applications. These have the advantage of operating in well-known environments, where the anatomy does not deform significantly.

Medical imaging techniques are highly mature and provide excellent sensing and environment mapping that can be used with robotics.

Non-medical robotics have many proven technologies that could be highly beneficial in the medical realm. For example, precise repetitive motion, miniaturization, and neural interfaces are all available robotics techniques that could be brought to bear.

What are the research challenges and approaches?

Modeling is important for planning and executing safe effective therapy. Soft-tissue modeling for surgery. Human behavior and therapy modeling for rehabilitation. Modeling whole procedures for stateful robot action and human-machine ergonomics.

Sensing and adaptation: real-time environment sensing is limited by needs for sterilizability, miniaturization. More sensing of the robots actions and environment will lead to more effective procedures. Miniaturized, sterilizable force, blood oxygenation, 3D imaging, and robot-guided ultrasound sensors would improve MIS robotic surgery.

Novel actuation will enable, for example, miniaturized surgical manipulators, intrinsically safe home health-care systems, or in-body robotics.

We need better **validation platforms** to develop and compare systems. One example is realistic phantoms that are standard and sharable, such as a realistic CPS beating heart. Shared ground-truth / reference data sets provide the raw material for new data-driven research. Access to shared, powerful simulation platforms (e.g., computation-intensive cloud based physical models) could help validate new methods in simulation providing new training platforms and shortening the hardware development cycle.

Common benchmarks for medical robotics, both surgeon and robot performance, is key to validating new technologies.

Human-robot interaction technologies with rich haptic, visual, verbal, and neural interfaces will improve our control of existing teleoperation systems. Non-surgical patients will benefit from richer feedback, e.g., haptic/neural interface prosthetics.

Human-machine collaborative control of teleoperation systems will combine human capabilities (intelligent, dextrous, safe) and robotic ones (precise, abundant). Augmented reality (haptic, visual) telepresence will improve human perception of and action in the treatment space.

Presently there are no **robot interaction paradigms** that dictate interaction between the care team, the robot, and the patient. How can information flow to all the caregivers in the robotic OR when the room itself is acting autonomously? How will a home healthcare robot inform the patient about their cooperative rehabilitation activities?

Educational Needs

First and foremost **cross-disciplinary training and collaboration** among clinicians and engineers is critical. This focuses engineering programs on positive therapeutic outcomes, and enlightens medical providers with new possibilities in delivering care.

Open platforms for training and experimentation will quickly bring neophytes up to the state of the art. This includes open simulators, open-access hardware such as Raven and the daVinci Research Kit, and possibly remote-access platforms- high-performance centralized simulation sandboxes that are open to use.

More **courses in medical device development** will train clinicians and engineers about cutting edge practices.

Hardware Needs

In CPS Surgical Robotics the primary hardware needs are for **miniaturized, biocompatible, sterilizable sensing and actuation**. Three elements together would provide a new level of immersive robotic telesurgery: rich force and tactile sensing at the end-effector, highly dextrous multi-dof end-effectors, and advanced haptic human-machine interfaces.

Roboticized miniature sensors like ultrasound, Optical Coherence Tomography and 3D imaging will help surgeons see and feel the surface and internal structures they operate on.

Non-invasive sensing and actuation such as HIFU, OCT, Gamma Knife™ could make a tremendous impact on medical care. Robotic control of these systems will be absolutely necessary for targeting treatment sights.

System Needs: Interoperability

Robotics is unique in its system-level **integration of many varied components**. Incorporating heterogeneous sensors, actuators, and devices with distributed computation and human-interaction requires a wide variety of technologies to work together.

Future medical robotics research should **use and contribute open source software** to minimize redundant development, and leverage existing work. Robot Operating System (ROS) is a popular and useful open-source software framework. Surgical Assistant Workstation (SAW) is also open-source purposefully designed for surgical robotics.

Non proprietary **data exchange standards** should be more widely adopted to ensure compatibility of developed robots. Several ad-hoc research standards for robotic systems integration are likely candidates, OpenIGTLink is a data interface designed for image guided therapy. Interoperable Teleoperation Protocol (ITP) was specifically designed for master-slave teleoperation and telesurgery robots.

Furthermore, devices entering the clinical setting should make efforts towards a **standardized user interface** to simplify training and reduce the cognitive load required to operate many machines.

Safety

CPS Medical Robotics presents a unique safety challenge. A robot has a direct effect on a patient's physical state, and **compromise of a robot can do immediate harm**.

At the same time, **physical properties** of the system give a convenient method for validation of robot behavior. Pure teleoperation systems' output should not exceed the performance envelope of the human operator, providing validation of intended movement commands. Similarly, a rehabilitation system should not apply more force to a patient than the patient can withstand. As a result, **physical models of system behavior** will provide safety checks (in addition to other potential benefits mentioned above).

Methods for validating CPS medical robotics might include **formal methods** such as model checking and deductive verification techniques, or through extensive **testing**.

Safety vulnerability in the **network and networked control loop** must be addressed. Unique, CPS robotics specific **attacks on the network and network based control loop** such as delaying, dropping or spoofing feedback messages need to be addressed. Addressing these attacks will rely on security mechanisms proposed for networked control, while other mechanisms will be based on the knowledge about physical constraints and dynamics of the system. For example, knowing the allowed operating region of the remote manipulator will allow for quick detection of spoofed feedback messages.

Roadmap

Medical robotics development in the future will have the following themes: **increased access** with **decreased invasiveness**, continued **merging of human and machine control**, **richer feedback and dexterity**.

5 Years

Surgery: medical imaging augments surgeon's view of the patient. Novel, miniaturized robotic systems provide fully-insertable manipulation and visualization platforms. Miniaturized articulated arms provide dextrous single-port surgery capabilities.

Rehabilitation: first robots in the home help patients comply with rehab, monitor progress to help with figure diagnosis, receive updates from physician.

Prostheses: prosthetic devices will move towards closed loop control. Not only will better control algorithms be implemented (both EMG and neural - EEG, BCI, spinal), but sensory feedback via haptics and targeted muscle reinnervation will also provide an important component in control.

10 Years

Surgery: immersive telepresence surgery with 360 degree visualization of anatomy. Augmented reality overlays merge medical imaging with vision to automatically identify anatomical structures. Surgical workflow heuristics and pre-operative plans guide surgeons through procedures and minimize mistakes. Partial automation helps with precise dissection, suturing, manipulation. Tissue interaction modeling estimates and minimizes unnecessary tissue damage.

Prostheses: Progress towards osteointegrated prosthetic implants.

General medical: Robotic devices take over many manual tasks, like blood pressure, blood draws, immunizations.

Home healthcare: In home telepresence robots provide doctor housecall consultation, assistance with healthy behaviors and lifestyle choices, first-responder capabilities, and act as rehabilitation partner.

Security: new network security features for robotics use operator or task behavior signatures to identify intended/erroneous action.

Imaging: swallowable, steerable cameras.

(20 years)

Surgery: high degree of automation in a mostly robotic OR. Imaging, planning, and actuation are all highly integrated and robot assisted.

Prostheses: cyborgs. direct interface of neurons to microcontrollers. Growing neurons on chips embedded in some biocompatible material/prosthetic limb.

Attendees:

Gian-Luca Mariottini	UT Arlington	gianluca@uta.edu
Andy Won	Temple	cwon@temple.edu
Susan Trolier-Mckinstry	Penn State	stmckinstry@psu.edu
Julian Goldman	MGH	jmgoldman@MGH.harvard.edu
Paolo Masci	QMUL	paolo.masci@eecs.qmul.ac.uk
Yanni Kouskoulas	Johns Hopkins/APL	yanni.kouskoulas@jhuapl.edu