this is an EXAMPLE comment

NOTES to self:
be sure to indicate the country of all referenced agencies, labs, companies, etc.
add websites for products, agencies, labs, companies and workshop participants in the references

Forward

Takeo should write

Definitions and acronyms

pre-operative	before a surgical procedure
intra-operative (or peri-operative)	during a surgical procedure
post-operative	after a surgical procedure

ADL	activity of daily living
CABG	coronary artery bypass graft
CAS	computer assisted surgery
CT	computerized tomography
DOF	degree of freedom
IGT	image guided therapy
MRI	magnetic resonance imaging
PAVA	Palo Alto Veterans Administration
PET	positron emission tomography
US	ultrasound
VAR	vocational assistant robot

Executive Summary

The International Advanced Robotics Program held a workshop on medical robotics at Hidden Valley Pennsylvania (USA) May 19-22, 2004. The primary goals of the workshop were to 1) assess the current states of art and practice of medical robotics, 2) identify technological and other problems that must be solved in order advance those states, and 3) forecast the future of medical robotics in the 10- and 25-year timeframes. The workshop was led by Takeo Kanade of Carnegie Mellon University and organized with the help of Branislav Jaramaz, Yoky Matsuoka, Jim Osborn and Cameron Riviere, also of Carnegie Mellon. The National Science Foundation (USA) provided major financial support. Workshop participants were selected primarily on the basis of recognition in and contributions to medical robotics and to achieve a balance of international perspectives. Several physicians and representatives of industry and government agencies also participated.

The main theme of the workshop was technologies that are used for patient interventions; though robotic technologies are applied in other areas of medicine such as diagnosis, medical informatics, drug discovery and pharmaceuticals, they were not included in our consideration. The workshop was organized along four topical areas with approximately equal numbers of participants in each:

- Interventional Devices – robots and instruments that are used by surgeons and other interventionalists intraoperatively
- Image-Guided Therapy and Interventional Systems – robotic technologies used to plan, simulate, guide and otherwise assist clinicians before and during interventions
- Rehabilitation Robotics – robotic technologies for physical and occupational therapy during recovery from injury
- Assistive Technologies – robotic technologies that enable persons with chronic physical or cognitive impairments to conduct activities of daily living

All participants were asked to complete a questionnaire in advance to elucidate their perspectives and their responses were used to draft a working report that served as a platform for workshop discussions. At the beginning of the workshop, all participants were given the opportunity to describe their most recent research, development and application efforts through short briefings. Each topical area was then introduced by a keynote address summarizing its current state followed by a digest of the questionnaire responses. The majority of the workshop was devoted to discussions within the topical groups.

Major Findings

Robotics has been applied to several areas of medicine, in some cases with notable success. Orthopaedic surgery has adopted robots and image guidance for total joint replacement, and to a lesser extent, spinal interventions. A number of medical robotics products for those procedures are now sold by major medical device companies (as well as several smaller firms). Teleoperated robots are also commercially available for several procedures in cardiothoracic and abdominal surgery as an alternative to laparoscopy. There is general trend toward minimally invasive surgery and medical robotics is viewed as an important enabling technology.

Several problems have to be solved, however, before medical robotics can be broadly applied to a wide spectrum of surgeries. Dealing with deformable soft tissue – sensing, modeling, simulating, segmenting, and registration – remains the most significant and formidable challenge facing interventional devices and systems. In addition, much improved haptic interfaces are needed to recover the sense of touch that is lost when a robotic device is interposed between surgeon and patient.

There are has been far less attention to (and funding available for) the application of robotics for rehabilitation and assistive technologies and there are no noteworthy success stories to date. The major technological barriers are associated with interfaces to the patient and include better haptics, physiological and human movement sensors, speech and natural language interpretation, and direct connections between computers and neurons. Fundamental biomedical research is needed to achieve a full understanding of the human neuromuscular system as well as the physiology of rehabilitation.

For all forms of medical robotics, systemic issues of safety, reliability, form factor and complexity require much more attention.

Medical robotics suffers from a “chicken and egg” phenomenon in the sense that systems need to be developed before they can be tested clinically, but only through the latter will their true effectiveness and utility be proven. Compelling clinical benefit is crucial, but for the majority of applications, medical robotics offers an alternative to a conventional procedure, not a capability that otherwise does not exist. Medical robotics is virtually unknown to regulatory bodies and very few precedent technologies upon which to base evaluations. Lack of performance guidelines – indeed, lack of techniques to rigorously quantify most interventions, whether robotic or manual and relate measurable interventional parameters to clinical outcomes – makes it difficult to measure effectiveness. Engineering specifications alone are accepted neither by the clinical nor regulatory communities.

To date, much of medical robotics research has been performed on a “technology push” rather than a “market demand” basis. If the potential of medical robotics is to be realized in a timely manner, it must become more responsive to the needs of clinicians and patients, and this will only occur if research teams are expanded to include them. Similarly, medical robotics teams need to become more interdisciplinary by including biomedical expertise to a much greater extent.

Strategic investment in research and development is needed: we estimate several $US billion are required over the next decade. Because medical robotics has yet to show its ultimate value, it is unlikely that industry will provide much of the needed funding, hence government will have to be the main source. Unfortunately, the agencies that fund biomedical research, e.g., the US National Institutes of Health, are currently dedicating only very small fractions of their budgets to medical robotics and the funds that are available are hotly competed for. Future funding will have to come by increasing the medical robotics portfolio of these agencies as well as finding “non-traditional” sources like the military and space agencies..

Several non-technological drivers should increase adoption of medical robotics. Aging of the world’s population coupled with increasing life expectancy point to greater prevalence of medical conditions associated with old age and greater demand for therapies. Demand by the elderly to maintain the quality of life they are accustomed to will motivate less invasive palliative and curative care, assisted living technologies and rehabilitation robots. The economics of modern medicine and a dwindling clinical workforce are forcing increased patient treatment throughput and more efficient use of clinicians’ time, both of which will eventually be facilitated by robotics. Though perhaps counterintuitive, medical robotics may be even more valuable to developing countries than developed countries since they can afford capability for intervention with simpler medical infrastructure and less medical expertise. Improvements in teleradiology and telesurgery will enable the more challenging cases to be addressed by specialists from a distance. Finally, there are many emerging therapies such as tissue engineering and cell transplantation that will be enabled by robotics.

Report Outline

Each of the four classes of medical robotics is discussed in the same format. In “Summary & Conclusions,” we present needs, technological and otherwise, and prospects for adoption of that class. The “Current Technology & Research Issues” section begins with explanations, definitions, examples and applications; it then presents technological needs and concludes with non-technological barriers. In the “Future Directions” section we first present our expectations for the next decade: applications of medical robotics applications that will emerge and the technical solutions and innovations that will enable them. We also provide a more speculative forecast for the 25-year horizon. Recommendations, including funding needs, other needs and potential pitfalls are then presented.

Interventional Devices

pictures of examples from participants

Davies	Neurobot
deMathelin	laparascopic robot
Dombre	compensation for cardiac motion
Fichtinger	MR compatible device for prostate biopsy
Fujie	micro manipulator
Ikuta	micro forceps
Krobreif	biosy robot
Kwon	laparascopic robot
Morel	laparascopic robot
Riviere	Micron
Troccaz	endocscopic robot
Zenati	heartlander

Summary & Conclusions

Technology Needs

Surgical robots must be proven cost effective: genuine clinical benefits must be proven in order to justify their capital and operating costs, complexity of use, and the time their use adds to surgical procedures, all of which must also be reduced. Specific desirable targets include:
The operating room environment and surgical workflow present system integration challenges that must be addressed before surgical robots will be adopted on a widespread basis.

- labor savings: obviating the need for a technical team in the operating room and reducing current manpower requirements
- time savings: robotic procedures have to be at least as fast as conventional, and should be faster
- robustness: surgical robots should introduce no additional safety concerns and should be as reliable as other components used in surgery

Further research is needed in modeling and tracking of soft tissue deformation, human-machine interfaces, and end effectors including unconventional cutting tools.

Other Needs

Beyond support of these technology developments, funding is also needed to transition robotics research from laboratory to clinic, particularly for applied systems integration. Such studies are expensive: it is estimated that working in the operating room setting is an order of magnitude more costly and difficult than research laboratory studies. These studies will also have to (and will help define) regulatory issues. In order to conduct them, the research community will need to be more tightly coupled to the clinical community.

Future Prospects

It is likely that “hands-on” surgical robots have the brightest future, because they keep the surgeon in control but add robotic functionalities of constrained motion and higher than manual accuracy to ensure the pre-operative plan is achieved.

Current Technology & Research Issues

Explanations, Definitions, Applications and Examples

There are several classes of surgical robots, generally distinguished by their level of autonomy:

- Passive, in which the robot serves as a guide to the surgeon's hands. Examples include the Remote Center-of-Motion (RCM) robots of Johns Hopkins and the Neuromate that locate guides through which a surgeon drives an instrument.
- Hands-on, in which the surgeon operates the device in the surgical field. An example is Micron, a hand-held instrument for vitroretinal surgery that senses and actively cancels hand tremor; another is ACROBOT, a special purpose manipulator for knee surgery.
- Teleoperated, in which the robot is in the surgical field but controlled by a surgeon some distance (usually a few feet, i.e., within the operating room) away. Examples include Zeus (Computer Motion, Inc.) and da Vinci (Intuitive Surgical Systems) that are used for a variety of abdominal and thoracic procedures, often as an alternative to laparoscopic surgery. The da Vinci is currently used for cardiac procedures (mitral valve repair and pacemaker epicardial lead placement), gastroenterological procedures (Nissen fundoplication, gastric bypass and esophageal surgery) and other procedures including radical prostatectomy and thymectomy.
- Active or autonomous, in which the robot acts on its own. Examples include RoboDoc, which is used to ream the channel to accept the femoral component in a total hip replacement, and Caspar, which is to machine bone surfaces to accept prosthetics in total knee replacement.

It is worth noting that 1) a class of robotic tools is emerging that have features of both passive and hands-on robots, and 2) autonomous surgical robots are actually pre-programmed, i.e., they do not sense and reason on their environment nor do they plan their own actions and reactions. In all but the autonomous class, the surgeon is an integral part of the overall system, providing both the sensing (visual, and to a lesser extent, haptic) and the signal processing to close the control loop. Many surgical robots, including Neuromate and RoboDoc, are based on or strongly resemble industrial manipulators.

photo of Neuromate, photo of ACROBOT, photo of RoboDoc, photo of daVinci

There is a general consensus that robot-assisted interventions in general have been adopted at a very slow rate in the past decade. Surgical robots are widely used only for endoscopic sensor positioning, though systems for total hip and knee replacement (e.g., Robodoc and Acrobot) and heart and prostate surgery (e.g., daVinci) are slowly becoming more common.

The major technical barriers to widespread adoption of robotic interventional devices include cost, time added to the overall duration of the surgical procedure, and safety. Unlike their counterparts in manufacturing, surgical robots have not reduced labor costs of surgery, in fact they have increased them due to the general need for a technical team to support the medical team. There are also no methods for relating improvements in engineering performance, e.g., accuracy and speed, to improvements in patient outcomes. Indeed, many surgeons are dubious about the clinical advantages of surgical robots over the current gold standard (for minimal invasiveness) of endoscopy. Many feel that the set up time for a surgical robot is unwarranted particularly since the robot is only useful in selected parts of the intervention. Finally, the learning curve for using surgical robots remains steep.

In order to meet accuracy, stiffness, safety, range of motion and dexterity requirements, contemporary surgical robots have multiple degrees of freedom, hence are generally bulky and costly. Surgical robots are also too complex for medical teams to install and use reliably without the assistance of dedicated technical teams in the operating room, which adds to their cost of use. Thus, systemic issues such as miniaturization, robustness and sterilization must be solved. In addition, control systems that promote ease of use, are stable, yet versatile, and allow self-diagnosis, must be developed. Though solvable, these problems are not receiving sufficient attention. From a regulatory standpoint, patient safety is universally accepted as being paramount, however, there are no safety guidelines for surgical robots at present.

A major unsolved problem with autonomous surgical robots is the ability to sense and react to intraoperative soft tissue motion. As a consequence they are used predominantly in orthopaedics working to a fixed pre-operative plan to modify rigid tissue (bone). An important area of needed fundamental research is methods to accurately model and/or track deformation of soft tissue in real time.

Teleoperated surgical robots are generally used for procedures that are often done laparoscopically, but have the advantage of wrists with more degrees of freedom (usually 2 rotations plus jaw open/close) than laparoscopic instruments. They share many features with their non-surgical counterparts. For example, motion scaling allows the surgeon to move the input device (sometimes referred to as the “master”) one centimeter while the output (“output”) moves one millimeter. The input can also be clutched, allowing the surgeon to halt motion of the slave while he re-positions the master, e.g., to obtain a more comfortable position. These systems are supported by endoscopic viewing systems, either stereoscopic or high-resolution monoscopic, but lack good tactile feedback. Indeed, providing good haptic interfaces for teleoperated surgical robots is an area in which considerable research is needed.

Technological Barriers

Surgical robots are still viewed as large, cumbersome and complex, requiring substantial physical and personnel infrastructure in operating rooms (indeed, there is often a technical support team present during surgery). There is some work underway to develop robots to perform some functions of operating room support personnel, e.g., the Penelope robot intended to replace scrub nurses.

Accuracy and safety are both expensive to achieve, requiring redundant precision motion control components. Paradoxically, there is an open clinical research question of how accurate surgical robots need to be, though this fundamentally speaks to the lack of models of the surgical process.

The potential of surgical robots has similarities to that of robots used in other fields: greater accuracy and lower tremor than human hands; the ability to move repetitively without tiring; constraint of motions to be inside a prescribed workspace; and motion consistency (and the ability to record actual movements made). For these reasons, surgical robots have the potential to make many procedures less invasive than conventional surgery and could also lead to few revision surgeries.

Technology Needs

We identify several key technological needs in interventional devices:

- Better means of intra-operative monitoring, including real-time 3D imaging and sensors for measurement of non-geometric parameters such as temperature, stiffness and chemistry

- End effectors that allow non-reactive tissue destruction and non-invasive tissue removal
- Techniques to model and track soft tissue deformation
- Haptic interfaces for both training/pre-operative and intra-operative robot control
- Other improvements in user interfaces that make control by the surgeon natural, intuitive and transparent
- General improvements such as device miniaturization, safety and reliability
- Much tighter integration of robots with the operating room and surgical workflow
- Implantable sensors that can be interrogated periodically

Some specific examples of needed technologies include:

- Sterilizable 6dof end effector with force-torque sensors
- Intra-operative 3D ultrasound sensors
- Small hand-held cutters with no reactive cutting forces
- Small navigation systems, accurate to tenths of millimeters over a field of 1 meter cube
- Small sensors of all type that could be used inside the body (and resist septic treatments)
- Small (e.g., 5 x 0.5 x 0.5 cm), high-bandwidth actuators with 1 cm range of motion

Non-technological Barriers

There are several non-technical reasons why robots have not yet been widely adopted for surgery. Hospitals have genuine concerns over safety and want to minimize the need for revision surgeries. Ironically, while surgical robots are supposed to facilitate minimally invasive procedures (which reduce tissue trauma relative to conventional surgeries), there is a fear among both surgeons and patients that robots present greater potential for collateral damage to soft tissue. A related concern is how blame would be placed if something goes wrong: is the doctor or robot developer at fault? Another important reason is that robotic procedures require greater operating room time than conventional procedures; at present, robots for surgery do not provide analogous savings of time to their counterparts in manufacturing. Perhaps the most overriding consideration is proof of efficacy or the lack thereof. Because robotic surgery is only a tiny minority of all procedures and has only been in practice for a few years, there is still insufficient evidence that it offers statistically significant long-term patient outcomes. Healthcare economics are based on relatively short-term events, i.e., reimbursable services, so there are no compelling financial reasons to adopt robotic surgery over the conventional alternatives. Many of the same factors explain why there have few examples of successful surgical robot companies: fear of litigation, the need for external capitalization while efficacy of a robot product is demonstrated, and the need to provide technical support in the operating room.

Future Directions

10-Year Expectations & Targets

In addition to the orthopaedic and laparoscopic procedures they are currently used for, surgical robots will also be adopted for other minimally invasive procedures in cardiac surgery as well interventions on the prostate and brain that involve needle placement. The former will be motivated by considerable need and the difficulty of accomplishing them with conventional approaches, and will be enabled by new control techniques will allow cardiac interventions without the need to fixate the beating heart. The latter have similar increasing demand and are relatively easy goals because of low dexterity requirements. Also in response to a growing patient population, and following current trends in orthopaedic surgery, robots will also enable minimally invasive total joint replacement, particularly knees and hips.

End effectors for non-reactive tissue dissection and destruction will emerge, as will the use of robots to precisely deliver micro-scale modules or capsules at targeted locations within the patient's anatomy. In addition to surgical robots, other interventional devices such as intelligent dexterous catheters for various applications and temporarily implantable robotic devices to detect and treat diseased tissue in very localized areas will be developed.

A number of technological innovations in the next ten years will support increased use of surgical robots. Robots that can work within radiological environments (x-ray fluoroscopy, CT and MR) will be perfected, and when complemented with augmented reality techniques and intra-operative tracking of tissue deformation, will allow use of real-time 3D imaging for robot control. Faster and higher fidelity surgical simulators will all pre-operative planning and rehearsal of soft tissue interventions. Improvements in component technologies such as computers, actuators, controllers and sensors will also contribute by reducing costs, increasing reliability and allowing miniaturization. Increased use of MEMS technology will be an important contributor. Improvements in human-machine interfaces, especially haptics, and tighter integration with surgical navigation systems will make surgical robots more usable.

25-Year Horizon

We speculate that twenty-five years from now, the following will be true.

- Miniature robots will be used for delivery of tissue engineering, cell replacement and other regenerative medicine therapies that are only in their infancy at present.
- Advances in general robotics science will enable natural human-machine interfaces for robot control and truly autonomous robots.
- Teams of tiny free-roaming *in vivo* robots will work cooperatively for diagnosis and treatment
- Robots will perform interventions on individual cells.
- Intervention will be tightly coupled to diagnosis in fast, iterative loops.

Diagnosis and surgery themselves will have changed through development of new devices that sense biochemical, biophysical and other parameters *in vivo*. These will usher in classes of micro-robots and surgical end effectors that adapt their behavior in response to local biological phenomena. There will be new answers to basic technical questions of robots, many advances in biotechnology and perhaps most notably, genuine convergence and synergy of robotics and biomedicine. Robots will become an enabling technology that supports trends toward early screening and intervention of disease and toward biological therapies.

Recommendations

Funding Needs and Sources

Development of those solutions will almost have to be supported almost entirely by government agencies (particularly NIH in the US). Traditional suppliers of robots are less likely to engage in medical robotics than new specialty companies. New designs that are inexpensive to manufacture (so that the device can be marketed as disposable) or facilitate sterilization are needed. The former is preferable as a business proposition.

Other Needs

Despite its sophistication, current surgical practice is highly variable and only semi-quantitative. Relatively few quantitative studies of existing surgical procedure have been done and it is difficult for surgeons to articulate their intentions quantitatively. There is therefore a need to study and quantify current surgical performance, its variability and relationships between surgical actions and patient outcomes. This will help answer the questions about necessary robot accuracy and what variables need to be monitored intra-operatively. Development of large anatomical atlases that statistically represent variability in performance will also aid in this effort.

There is a pervasive trend in medicine toward early detection and intervention, which adds impetus to the need for tighter coupling of diagnostic imaging and interventional devices. In addition to fast, highly effective screening processes, there will be increased demand for very low-morbidity interventions that can be performed at the time of diagnosis rather than days or weeks later. Interventional devices that are compatible with imaging systems will be particularly valuable.

Potential Pitfalls

?

Image-Guided Therapy & Interventional Systems

pictures of examples from participants

Baur	EasyTrack
Cleary	CT fluoroscopy guided robot
Jaramaz	HipNav
Kanade	ultrasound-to-CT registration
Magee	robotic scrub nurse
Masamune	MRI compatible robot
Philips	fluoroscope guided guidewire placement
Sakuma	laser guidance system

Summary & Conclusions

Technology Needs

There are several unsolved problems that hinder the use of image-guided therapy. Despite considerable attention, algorithms to automatically segment medical images with the same accuracy as manual techniques have failed to emerge. Related to that is lack of techniques for real-time intra-operative registration of high-fidelity pre-operative medical images to patient anatomy, except for a few successful approaches in orthopaedics where the anatomical structures of interest are rigid and neurology, because brain deforms much less during surgery than does other soft tissue. In both cases, technologists' limited medical knowledge and the general difficulty of the problem are the main reasons why solutions have yet to be obtained. Some notable procedures that one might expected to be enabled by image-guided approaches, surgery on beating hearts and pre-natal interventions *in utero*, remain largely unattainable at present, again because their technical difficulty has been underestimated.

The most important technological needs are associated with modeling, imaging and tracking of soft tissue. Related are the needs for surgical simulators, so that procedures can be rehearsed on a patient specific basis, for in-situ measurements (position, shape, physics, bio, etc.) so that surgical plans can be updated in real time. Additional research in image analysis and deformable registration is also needed.

Other Needs

Interdisciplinary approaches, especially closer collaborations of technologists and clinicians, are crucial.

Future Prospects

The trend toward minimally invasive interventions is pervasive in medicine as evidenced by both the dramatic increase of laparascopic/endoscopic techniques in abdominal, cardiac and thoracic surgery, as well as more widespread use of catheter based therapies in cardiovascular medicine in lieu of surgery. Following this trend, the future will see both increased prevalence of minimally invasive surgery (MIS) and movement beyond it to non-invasive therapy (NIT). Current interventional systems are essentially computer-based, electromechanical systems. In the future, they will also have biological and chemical aspects.

Current Technology & Research Issues

Explanations, Definitions, Applications and Examples

Interventional systems include:

- computer-aided endoscopy
- instrument and patient localization and tracking
- pre-operative planning
- surgical simulation and training

For the purposes of this workshop, they are distinguished from interventional devices by the absence of physical interaction with the patient, i.e., they provide assistance the interventionalist (hence the term computer-assisted surgery). The principal motivation for IGT/IS is to extend the surgeon's sensori-motor capabilities by, for example, motion scaling, improving access, enhancing interpretation of 3D geometry and allowing action at a distance (the latter is relevant in military combat).

An interventional system is used to identify, localize, access, remove and/or interact with a region of interest within the patient. The latter is determined in a pre-operative phase that begins with diagnosis using techniques as simple as palpating to non-invasive imaging techniques such as PET, CT, MRI, US and x-ray. Image acquisition is followed by one or more stages of image enhancement, particularly segmentation to define anatomical structures of interest. The result is a computerized model, usually 3D, that the clinician can use to visualize the patient's anatomy. Often the clinician can interact with the model through simulation to pre-plan the intervention.

insert Baur's or Taylor's block diagram

Even in orthopaedics, which deals with tissues that are for all intents and purposes rigid, one cannot rely solely on pre-operative data for surgical navigation. Computer assisted surgery (CAS) is an alternative to surgical robots that requires less operating room infrastructure. A CAS system generally includes some form of surgical navigation, in which the positions of surgical instruments and sometimes the patient's anatomy are measured with high precision and in real time by a tracking system. Optical tracking systems, the most popular, use multiple cameras to determine the location of targets affixed to the instruments and the patient. They have working volumes of a few cubic meters, require line-of-sight between the camera and can have sub-millimeter accuracy. Electromagnetic systems, which are less accurate and have smaller work volumes but alleviate the requirement for line-of-sight, are beginning to be used. One drawback of these systems is interference caused by the presence of metal objects that distort the electromagnetic field. CAS systems are less expensive that surgical robots, but are generally less accurate, and can neither control nor constrain actions of the surgeon.

photos of OptoTrak, Polaris, easyTrack, Aurora

A key technology is registration, the process of merging and reconciling pre-operative and intra-operative data, especially geometry.

Brian's presentation has several slides on pre-operative planning and intra-operative registration

Examples of interventional systems include

- CALT (Computer Aided Laser Treatment)
- Biopsy Navigator
- Liver transplant on living donor

A key user interface technology is haptics, which can provide both qualitative feedback of actual forces to the surgeon as well as artificial kinesthetic cues for guidance of instrument location and trajectory. Augmented reality technology, which can blend computer graphics and the surgeon's natural vision, is just beginning to be applied to interventions, particularly for visualization of pre-operative medical images and surgical trajectories.

photos Image Overlay

Image-guided approaches are currently most popular in orthopaedic surgery (joint repair and replacement, spine procedures and maxillo-facial reconstruction), stereotactic neurosurgery, some intravascular interventions and some cancer interventions including biopsies and prostate brachytherapy and cryosurgery.

Technological Barriers

Intrinsic (of the object) and extrinsic (of the environment and the imaging system) influence the quality, resolution, completeness and accuracy of the information. Examples of the former include patient-specific factors such as thicknesses and densities of tissue layers and the possible presence of metallic implants. An illustrative example of the latter is volumetric imaging: even the fastest CT systems do not image an entire volume instantaneously meaning that the individual slices are captured at slightly different times. Cardiac, respiratory and other patient motion therefore introduces artifacts in the 3D volumetric model that is computed from those individual slices. Pre-operative models have associated uncertainty. At present, they are generally restricted to 3D and the dimension of time is not accounted for. An important need is to update the model during the intervention – accurately, reliably and quickly. In addition, the models are generally incomplete, meaning that important data might be missing.

Other important user interface technologies are needed to facilitate the surgeon's control over various components in the operating room. A few early examples include Hermes and Aesop (Computer Motion, Inc., where USA) which afford the surgeon voice control over operating room equipment and an endoscopic viewing camera, respectively, and M/ORIS, or Medical/Operating Room Interaction System (Ecole Polytechnique Federale de Lausanne, Switzerland), which includes a stereo camera system that tracks the surgeon's hand so he can use a virtual computer mouse.

The major technological problems confronting IGT are in imaging, tissue modeling and user interaction. At present, there is no single imaging modality that can produce a complete and accurate geometric model of the entire body. The problem of cross-modality registration is largely unsolved which confounds both pre-operative modeling and registration of intra-operative images to pre-operative models. Further, there are no inexpensive solutions for high-fidelity intra-operative 3D imaging, though some are on the horizon, including 3D ultrasound and 3D fluoroscopy. Image segmentation remains as much an art as it is a science, and there are no automatic techniques that rival manual segmentation by a trained radiologist. Part of the difficulty is in the subtle yet important anatomical differences across patients. Biomechanical modeling algorithms are far too slow to be useful for real-time simulation, let alone intra-operatively. And even if speed was a solved problem, we currently lack biomechanical property data for most human tissue types and techniques to measure them *in vivo*. For all but the simplest and most homogeneous of tissues, it is not yet possible to build realistic models that allow topological changes like cutting and suturing. Existing haptic interfaces to surgical simulators (for example the popular Phantom manipulator) have insufficient bandwidth for adequate force feedback; further, they are morphologically too different from surgical instruments to provide an intuitive user interface to surgical simulatoirs.

photo of Phantom

The amount of useful information to be presented to the surgeon is so large, that it cannot be presented in its full extent. Accordingly, data are presented selectively according to the design of the system developer, not the surgeon. In general, the process of surgery is not well modeled and regardless each surgeon's workflow is individualized. The best of augmented reality systems are still too cumbersome and complicated for use in the operating room. All of these problems are very hard to solve and none, with the possible exception of deformable modeling techniques for registration and segmentation, are being adequately addressed at present.

Technology Needs

To summarize, we identify several key technological needs in IGT and other interventional systems.

- Automatic segmentation of medical images
- Non-line-of-sight surgical navigation systems with sub-millimeter accuracy and immunity to environmental effects
- High fidelity, near real-time 3D intra-operative imaging
- Real-time, minimally invasive anatomical registration techniques
- Sensing techniques to measure relevant tissue parameters pre-operatively, allowing rehearsal prior to surgery
- Sensing techniques to measure relevant tissue parameters intra-operatively, allowing force control of surgical instruments
- High fidelity biomechanical simulations of soft tissue of all types
- Techniques to quantitatively assess surgical actions
- Surgical simulators that predict the functional consequences (patient outcomes) of interventions
- Clinically feasible procedures for the adaptation of pre-operative diagnostic images to intra-operative situation
- Systems that can self-diagnose both accuracy and faults

Non-technological Barriers

Physicians who use IGT point to more thorough pre-surgical planning and intra-operative restoration of perceptual information that would otherwise be lost as key benefits. Those who resist using IGT cite one or more reasons including additional cost (capital as well as extra operating room time and often additional pre-operative CT or MR imaging), obtrusiveness and weak integration with the operating room environment, steep learning curves and the need to modify their customary surgical workflow. Some lack understanding and appreciation of the technology itself and are concerned about relying on a computer rather than their own judgment. Because clinical benefits have not been rigorously quantified, it is difficult to make the case that IGT benefits outweigh costs. It is difficult to perform randomized clinical trials, such as those are typically required by the FDA, as funding for these must typically come for industry and not from government agencies. There are also concerns for patient safety, though less so than with surgical robots because the surgeon executes all interactions with the patient. Patients themselves are concerned that IGT too experimental and feel safer with “classic” established procedures. They are generally unwilling to be IGT patients if they have to pay for it personally.

Future Directions

10-Year Expectations & Targets

There will be evolutionary improvements to procedures that are currently performed with IGT today and increased adoption for transplant surgery, liver surgery, coronary bypass, head and neck surgery, otolaryngological procedures, and various forms of microsurgery including endovascular interventions and vitroretinal surgery. It will be used to support minimally invasive therapies such as radiofrequency ablation, cyrotherapy, and focused ultrasound, as well as laparoscopic interventions. A base of new technologies, and extensions of and improvements on existing technologies and lessons learned from applied research (clinical trials) will enable these procedures. In addition to these "mainstream" applications, IGT will be used for a number of procedures that are virtually impossible at present, such as prenatal cardiac interventions, *in vivo* tissue engineering. The applications themselves will be motivated by their socio-economic importance as well as increasing demand for minimally invasive approaches and localized therapy. A decade from now image guidance systems will be sold as options for CT, MR and other imagers.

A key technological development in the next decade will be the surgical simulator that affords real-time, high fidelity interactions with deformable tissue through a haptic interface. Basic simulators will allow surgical trainees to acquire and hone their perceptual and motor skills outside the operating room, greatly reducing needs for animal and cadaver training. Through better and more automatic image enhancement, segmentation and modeling techniques, patient-specific simulations will be readily attainable. Similarly, there will be increased use of augmented reality displays in the operating room to take advantage of improved modeling and pre-surgical planning capabilities.

Some specific examples of needed technologies include:

- Easier intraoperative 3D imaging
- In vivo determination of physiological tissue properties
- High bandwidth haptic feedback device
- Augmented reality device of excellent optical quality with intuitive handling and ergonomics that would not affect the surgeon at all
- Accurate and robust non-line-of-sight tracking. Electromagnetic tracking is getting close but is not quite there yet.
- A device telling me what is in front of my tool tip and what is the next efficient move to do based on both pre- and peri-operative local and global measurements and models.

To transition IGT is to internal organs such as the liver, pancreas, and lung the major challenges are dealing with soft tissue and non-line-of-sight tracking. Quantitative performance assessment is necessary for monitoring the learning curve in novel educational tools, like simulators.

25-Year Horizon

We speculate that in 25 years there will be unified platforms for surgical skill training and pre-surgical planning that make it possible to simulate almost all general surgical procedures and to rehearse patient-specific operations. Such systems will be made possible by dramatic performance improvements in haptic feedback devices, development of real-time forward and inverse biomechanical modeling techniques, establishing the biomechanical properties for most tissue types, multi-modal immersive virtual reality environments and quantum performance increases in computation. Patient models will capture 4D (3D plus time) geometry as well as temperature, chemistry, mechanical, electrical and other parameters and techniques to modify/update patient-specific models in real time will be available and enabled by unprecedented sensors and modeling techniques. Using these models and new simulators, surgeons will be able to rehearse surgeries and to re-plan them if necessary on the fly. Importantly, since patient-specific modeling will also be predictive, both simulators and the recordings of actual surgical actions will be able to predict surgical outcome. The interfaces to these capabilities will be natural for the physician and s/he will not require technical support to use them.

Recommendations

Funding Needs

Several $100M's are needed to solve the technical problems facing IGT. This will mostly have to be provided by government agencies, which should include the military since interventional systems are highly relevant to combat casualty care. If manned spaceflight is re-emphasized in space exploration, e.g., a mission to Mars, there will be additional impetus for space agencies to fund as well. Industry will become more inclined to support IGT R&D as the technology becomes more mainstream and industry sees new revenues from IGT add-on's to imaging devices.

Other Needs

We stress that adoption of interventional systems will be accelerated only if clinicians participate in their development. Further, the development teams of the future must be even more interdisciplinary and include experts in other basic fields such as biology and chemistry as well as other forms of interdisciplinary research such as tissue engineering. However, a balance must be struck: even though roboticists need to embrace other science, a potential pitfall is over-aggressive adoption of new technologies And instead of relying on serendipity, mechanisms that proactively stimulate formation of these new collaborations need to be put in place.

Potential Pitfalls

Finally, the research community needs to become increasingly conscious of the ultimate costs of interventional systems: acquisition, training, installation and use.

Rehabilitation Robotics

pictures of examples from participants

Edgerton	walking trainer
Gradetsky	massage robot
Harwin	virtual reality for rehabilitation
Matsuoka	virtual reality for rehabilitation
Patton	force trainer

Summary & Conclusions

Technology Needs

The most important needs in rehabilitation robotics are better human-robot interfaces. At the physical level, haptics need to be improved; at higher levels, there need to be more robust techniques to interpret a patient's intentions. Substantial engineering is needed to ensure reliability and safety and to reduce costs of rehabilitation robots.

Other Needs

At present, there are few techniques to quantitatively measure human parameters during traditional rehabilitation. While robots offer the possibility of simultaneously performing and measuring the effects of physical therapy, little is known about exactly what parameters should be measured. Rehabilitation robots are in a dilemma similar as surgical robots: it is difficult to prove their effectiveness since there are no established methods to relate conventional (non-robotic) techniques that would serve as benchmarks.

Future Prospects

Despite relatively little attention (and funding) to date, large markets for both clinical and home rehabilitation robots seem inevitable.

Current Technology & Research Issues

Explanations, Definitions, Applications & examples:

We define a rehabilitation robot as a therapeutic tool to help retrain voluntary movement control for individuals who have sustained a local or central nervous system injury. They are distinguished from assistive technologies, e.g., wheelchairs and prosthetics, in that they are used temporarily for rehabilitation, not chronically post-injury.

Rehabilitation robots are generally used to exercise limbs of patients who have experienced a stroke, sustained a spinal cord injury or have some other condition such as cerebral palsy that has reduced their ability to move and/or control them. Most have only a few degrees of freedom; many are single DOF exercise devices. For example, the InMotion robots (Interactive Motion Technologies, Inc., Cambridge, Massachusetts USA) are human-scale manipulators that can be controlled to guide a patient through an exercise while presenting a set amount of resistance. Barrett Technology's (Cambridge, Massachusetts USA) Whole Arm Manipulator or WAM is similar though has 6 DOF's; SensAble Technologies, Inc. (Woburn, Massachusetts USA) makes a family of smaller manipulators called Phantoms that have up to 6 DOF's but offer lower total resistance. A key requirement for use as an exerciser is that the manipulator be highly back-drivable. It is worth noting that both the WAM and Phantom are currently used more for neuromuscular research than for rehabilitation; the Phantom is also very popular as a haptic interface for simulations. The Rehabilitation Institute of Chicago (USA) has an experimental exerciser called the ARM Guide.

photos of InMotion WAM, Phantom, ARM Guide

Robots used for lower limb rehabilitation include the Lokomat (Hocoma AG, Volketswil, Switzerland), the AutoAmbulator (HealthSouth, Birmingham, Alabama USA), and a variety of experimental devices such as those at the University of Tsukuba (Japan) and the University of California at Los Angeles (USA). Though slightly different in design, all share common elements: exoskeletons with robotic linkages that attach to the patient's legs, a treadmill and a mechanism that provides weight and balance support.

photos of Lokomat, AutoAmbulator, Gaitmaster, diagram from Edgerton's talk

By the standards of robots in more mature application domains, they are relatively crude and there are very few commercial devices.

Robotic exercisers can be used in a variety of modes. In passive mode it functions much like a coordinate measuring machine as the patient back-drives the mechanism and all movements are recorded. In active mode, the robot guides the patient through a pre-programmed path. A hybrid of the two is for the robot to provide an amount of resistance that has some prescribed relationship to position that encourages the patient to follow a particular trajectory. These control modes are used in a number of therapy regimens such as repetitive movement, imitation of a movement demonstrated by the robot and movement against a resistance provided by the robot. In all cases, it is possible to measure patient's movements and generate a record of progress from one session to the next. Measurement of motion also allows exercises to be modified on the fly, e.g., in response to fatigue. In a relatively new paradigm, virtual reality techniques are being employed to provide a visual feedback channel to the patient. Since it is a computer graphic, virtual reality feedback can be distorted so that the patient is encouraged to exercise harder, reach farther, etc., than he/she might do otherwise.

Technological Barriers

User interfaces, especially between robot and patient, represent the most significant challenges in rehabilitation robotics. Techniques that can readily and reliably measure and interpret the patient's intentions do not yet exist. Electromyography (sensing electrical activity generated by muscle contraction) has been recently shown to be a useful, though crude interface technique between human physiology and electro-mechanisms, one who's value is largely attributable to the user's ability to be trained and learn how to control the external device with patterns of peripheral neuromuscular signals. There has also been some research in direct interfaces of the central nervous system to robots, though the only successes thus far have been in non-human primates (reference Schwartz).

Technology Needs

Current rehabilitation robots, being predominantly research prototypes, are too generally too cumbersome, technical and unreliable for home-use. Engineering development is needed to make them safer, portable, fool-proof and easy to don and doff. For them to be truly practical, they must anthropometrically scaled to a large segment of the population, or be available in a range of sizes. Substantial miniaturization and cost reduction of components is needed, particularly for actuators and sensors. Versatile controllers need to be developed that individualize and adapt therapy on the basis of the patient, which limb is being exercised, and its health. Likewise, simpler and easier to use data acquisition and display technologies need to be incorporated to take advantage of the robot's ability to measure the patient's movements and strength and present that information to clinicians. These include computer vision technologies to do motion capture easily and inexpensively (high fidelity systems such as those used in cinema are available but are too costly and technical to be clinically viable) and accurate wearable motion sensors. Most of these problems are several years from being solved.

Non-Technological Barriers

The domain of rehabilitation robotics is embryonic and poorly understood by the clinical community. As such, it is open to – and needs – fresh ideas from clinicians as to how to effectively use robots in physical and occupational therapy. For example, use of virtual reality appears to be very promising, but little is known about how to use it most effectively. Part of the problem is incomplete understanding of the human neuromuscular system; as medical knowledge in that area increases, so will our insights as to how to design better therapeutic regimens and the roles that robots can play in them. Likewise, a great deal of clinical research is needed to understand and evaluate the potential clinical benefits of rehabilitation robotics. Evidence of both clinical efficacy and cost effectiveness is also needed to convince clinicians to use them, to prompt payors to reimburse their use, and to stimulate commercial proliferation. We note that at present, the Netherlands is the only country in which use of a rehabilitation robot is covered by health insurance. Safety will also have to be proven to all of these parties plus regulatory bodies and patients; there is a dilemma in that there are as yet no safety standards. Market studies will have to be performed to determine if rehabilitation robots are viable for home use, institutional use, or both.

A clinical barrier related to user interfaces is measuring and understanding the user’s effort level. Even if techniques to do that existed, the physical and occupational therapy communities do not yet know how to optimally adjust exercise regimens according to the patient’s ability and desired goals. It would appear that motion and force encoders built into rehabilitation robots at least create the opportunity to tune therapy on a patient-specific basis. It is suspected that such on-line monitoring of a patient’s movements and strength could dramatically change the practice of rehabilitation since a complete and quantitative record of progress could be generated and replace the subjective assessments of therapists. However, because such data have never before been available, it is unclear what to do with that information.

Use of robots will theoretically reduce the workload on therapists. For example, they would not need to conduct separate tests in order to assess a patient’s progress since an automatic record would be created automatically. Further, instead of the one-on-one paradigm of present, a therapist could tend to several patients simultaneously. Such a shift is resisted by many in the clinical community who are concerned about losing the “human touch” of therapy. And like other medical robots, rehabilitation robots present a steep learning curve to clinicians, the great majority of whom currently lack the skills and training to use them.

Future Directions

10-Year Expectations & Targets

In 2014, rehabilitation robotics will allow individuals to re-learn how to stand, step, and manipulate objects with their arms & hands. Via a user-friendly interface, physical therapists will be able to design customized exercise programs by drawing upon a library of therapy routines. Rehabilitation robots will automatically tailor those designs to the dimensions and capabilities of particular patients. They will prepare reports with therapist-selectable level of detail on patients’ individual sessions and trends across multiple sessions. Positive outcomes will have been shown in clinical trials in institutional settings; there will also have been some less definitive trials of home-based physical therapy using robots. There will be some insurance reimbursement for rehabilitation robots. Relative to the present, there will be increased demand for rehabilitation robots, in large part due to an much larger population of older adults. The advent of rehabilitation robots will parallel improved knowledge of human neuromuscular control, i.e., the clinical community will have a better understanding of how to make use of them.

Technological advances in the next decade will include better haptic and virtual reality interfaces, wearable and vision-based motion capture capabilities, and improved components for the actuation, sensing, and interconnection needs of robotic electro-mechanisms. Other advances only being contemplated at present, such as micro-actuators, implantable *in vivo* sensors and “smart” shape-changing materials, will yield entirely new forms of rehabilitation robots. Control software that is robust and adaptable to the needs of both therapist and patient will be realized.

25-Year Horizon

In 2029 Rehabilitation Robotics will allow highly personalized effective therapy of all limbs. A rehabilitation system will include full immersion virtual reality, a variety of robot mechanisms for exercising different parts of the body, on-line monitoring of and adaptation to the patient’s needs and current condition, and technologies that directly assess improvements at the neurological level. Therapists will still manage the overall recovery process and make the crucial clinical decisions, but the system will devise and adjust the exercise regimen based on directives from the clinician and its own assessment of the patient’s abilities and motivation level. The rehabilitation process will include both institutional and home-based devices, the latter being wearable. Telemedicine technologies, including remote supervision and automatic reporting of patient data, will keep the clinician informed about the patient’s progress. Clinically, we will have full understanding of human motor control and quantitative functional outcomes tests will have replaced qualitative assessments.

Recommendations

Funding Needs

Substantial investments ($100M’s) in research and development are needed if these futures are to be realized. Finding those resources is a bigger challenge for rehabilitation robotics than interventional devices and systems because 1) there are fewer sources and 2) those sources have relatively small budgets. Indeed, it was noted that the US government currently provides a total of about $150M annually for all rehabilitation research, of which robotics is a tiny fraction. The main source in the US at present is the National Institute for Disabilities and Rehabilitation Research, which is part of the Department of Education. The Veterans Administration, the National Science Foundation, the National Institutes of Health and private foundations provide much lesser amounts. Funding, particular philanthropy, may increase as wealth in America shifts toward the older population. Consumer demand might also be stimulated if rehabilitation robots can be shown to preserve, not just recover, health and fitness.

Other Needs

As with the other forms of medical robotics, it is imperative to increase awareness of rehabilitation robotics within the clinical community, for instance through sessions and symposia at therapist-centric conferences. To gain consumer acceptance, cost effective home therapy robots need to be developed and therapies based on them have to be engaging, motivating and above all flexible. The systems have to be marketed as therapies, not as robots (which still have negative connotations for most people).

Rehabilitation research and development will have to achieve a much more interdisciplinary character and educational programs that create therapists with an engineering background and engineers with therapy background need to be developed and encouraged.

Potential Pitfalls

To gain acceptance by clinicians, it may be more advisable to pursue clinical trials of currently available promising techniques and devices than to work on advancing the technology itself. The robotics community will have to pay more attention to demonstrating genuine clinical evidence of effect than it has been willing to thus far. This includes development of quantitative functional assessment tools in collaboration with the clinical community. Until they have more resources to disburse, funding agencies need to focus on a smaller number of problems and avoid spreading those resources too thin.

Assistive Technologies

pictures of examples from participants

Dario	Cyberhand
Dario	MOVaid
Ding	Smart Power Assist Module
Helal	Smart Room
Van der Loos	ProVAR
Wang	Companion

Summary & Conclusions

Technology Needs

As with rehabilitation robots, the most crucial aspects of assistive robots (i.e., robot prosthetics and other robots that replace lost or damaged limb function) are human-machine interfaces. However, because they are permanent surrogates, interfaces to these devices are more sophisticated. Breakthroughs are needed to create viable direct connections between robots and the human nervous system. Advances in component technologies, particularly reduction of size, weight and power consumption, are also needed. More natural ways of communicating, including speech recognition and natural language interpretation are needed to enable use of assistive technologies such as personal robot assistants, smart appliances and smart living spaces.

Other Needs

Like rehabilitation robotics, research and development for assistive robots is woefully under-funded. Substantial biomedical and cognitive psychology research is needed to understand the human neuromuscular system.

Future Prospects

Though perhaps a decade away, direct neuron-silicon interfaces will eventually be realized, creating opportunities to dramatically improve quality of life for persons with disabilities. Driven by a technology-hungry consumer market, home robots and smart products with embedded intelligence will serve as a platform for creating assistive technologies.

Current Technology & Research Issues

Explanations, Definitions, Applications and Examples

Assistive technologies are intended to improve quality of life for persons with chronic physical and/or cognitive disabilities, including those associated with old age. There are two broad classes of assistive technologies. The first is assistive robots: devices that perform tasks associated with activities of daily living (ADL) for and under the control of a person with a disability that would otherwise be performed by an attendant. Assistive robots are classified as:

- Fixed base, e.g., vocational and ADL workstations
- Mobile, which includes autonomously navigating wheelchairs and wheelchair-mounted manipulators; robots that provide other mobility support; and robots that perform fetch and carry functions

Examples of contemporary workstation robots are the Palo Alto Veterans Administration Desktop Vocational Assistant Robot (DeVAR) and its successor, ProVAR.

photo of DeVAR

Since human-robot interfaces are more important to the overall success of a VAR they are currently receiving greater attention than the robots themselves. A number of research groups are creating computer assisted design tools, especially simulators, to aid in development of assistive robots.

illustrations of Cricket & Jiminey
screen shot of ProVAR interface

Examples of wheelchair-mounted manipulators are the MANUS (Exact Dynamics, The Netherlands) and Raptor (Applied Resources Corporation, where?). Both are multi-DOF (5 and 4, respectively) and are commercially available.

photo of MANUS, Raptor

In contrast, there are no commercial navigation systems for wheelchairs, though there are numerous prototypes in research labs, including Hephaestus (University of Pittsburgh), SmartChair (University of Pennsylvania) and Wheelesley (Massachusetts Institute of Technology). These systems are not unlike those employed in indoor mobile robots: they are a combination of sonar, infrared and laser proximity sensors, as well as cameras and tactile sensors, all mounted on an electric wheelchair. A laptop PC reads these sensors plus the wheelchair user’s input commands to effect collision avoidance. Several research labs, including Carnegie Mellon, are developing smart walkers that provide physical (weight) support, sense user steering commands and map the path in front a walking person to help the user avoid obstacles. One known commercial example of such a robot is Guido (Haptica, Dublin Ireland).

photo of Hephaestus, SmartChair, Wheelesley, Guido

There are several examples of free-roaming mobile robots aimed at assisting persons with disabilities, including Helpmate (Pyxis, Inc., where), Movaid (SSSA, Pisa Italy), Care-O-Bot (Fraunhofer Institute, Stuttgart Germany) and Nursebot (Carnegie Mellon, Stanford, University of Michigan and University of Pittsburgh, USA. In addition, several Japanese and Korean companies and research institutes are developing humanoid robots intended to operate as personal assistants. Numerous technological problems, most notably robust indoor navigation and natural language interfaces, must be solved to make these devices practical for home use. However, some commercial examples are on the market for institutional use, where the environment is somewhat more predictable, including the HelpMate (Pixus, USA) and Companion (InTouch Health, USA).

photos of HelpMate and Companion

Artificial robotic limbs are currently in their infancy. There are a few commercially available examples lower limb prosthetics that respond to sensed forces and measures of gait; the remaining examples are currently research prototypes of replacement limbs and wearable exoskeletons. An example of the former is the Cyberhand (Scuola Superiore Sant’Anna, Italy); an example of the latter is the Power Assist Suit of Kanagawa Institute of Technology (Japan). Numerous technological problems need to be solved, particularly sensor and control interfaces to the nervous system and miniaturization of actuators and batteries, before practical devices can be realized.

photos of Otto Bock Healthcare C-Leg, Cyberhand, Power Assist Suit

The second emerging class of assistive technologies is sometimes referred to as ubiquitous robotics: intelligence built into appliances and living spaces, the purpose of which is to simplify or otherwise support a person's ability to perform activities of daily living. This class includes "smart living space" technologies that infer what a person is doing based on data from a number of sensors embedded in the environment or worn by the person. Such information is vital for control systems to understand (or anticipate) the person's needs and intentions; it is also useful for monitoring and diagnosis by off-site medical personnel, caregivers and friends/family members. Several research groups are developing or have developed smart spaces, including Carnegie Mellon (Pittsburgh, USA), Georgia Institute of Technology (Atlanta, USA), Intel Corporation (where was that lab?), Massachusetts Institute of Technology (Boston, USA), National Rehabilitation Hospital (Washington, DC, USA), Scuola Superiore Sant'Anna (Pisa, Italy), Stanford University (USA), University of Florida (Gainesville) and University of Virginia (Charlottesville USA).

Many smart spaces infer the behavior of their occupants from combinations of motion detectors, microphones, switches that signal door opening/closing and other sensors; alternatively, computer vision techniques are used to track human occupants, measure their movements and interpret what actions they are performing. The former has the advantages of low-cost sensing and the disadvantages of networking them together, while the latter requires fewer sensors but relies on sophisticated video analysis. Video-based schemes also raise ethical questions about privacy.

Though not directly interventional, we recognize that sensors and software to monitor health and well-being will be integral components of smart spaces of the future. These will include miniature implantable and wearable devices that directly measure physiological parameters, techniques to infer gross levels of function (e.g., mobility, dexterity and strength) and algorithms that analyze those data over long periods of time to identify subtle changes that might not be detectable by caregivers.

photos/diagrams of some above cited facilities

Technological Barriers

The most crucial technological hurdles to be overcome are associated with human-machine interfaces. It is suspected that users will not be able to effectively control assistive robots until they can be directly interfaced to the human nervous system thus allowing the user's brain functions to become part of the overall system control loop. Such interfaces pose numerous technical challenges, especially in issues of biocompatibility. For example, attempts to place electrodes in cortical neurons, while successful for a few days, have ultimately failed because the body eventually rejects the electrodes for reasons that are not well understood. A second challenge, also medically related, is our lack of knowledge about which neurons to interface to. At present, we have only sketchy knowledge about which regions of the brain are responsible for different functions; successful control of external devices and reception of data from external sensors is part science, part serendipity and most certainly facilitated by the human brain's remarkable adaptability.

Besides direct neural connections, there are alternative approaches to interfacing to human biology, including implantable or wearable micro-sensors and micro-actuators. Interface schemes based on such devices rely on more integrative levels of processing in the human nervous system. For example, a technique called "sensory transfer" uses an array of miniature pressure sensors as surrogates for the body's natural proprioceptors and presents the measured force distribution with an array of actuators at an unaffected part of the body. There are strong indications that the brain can learn to re-associate sensations displayed at one part of the body with those being "felt" by synthetic sensors. Achieving spatial resolution similar to that of a human requires large numbers of very small sensors such as those based on MEMS technology. While the sensors themselves are fairly mature, interconnection techniques for large distributed arrays are lacking.

The more conventional approaches to human-machine interfaces, such as those described above, tend to be brittle, and usually require user-specific customization that is difficult and/or expensive to implement. As with rehabilitation robots, the key challenge is to determine the user's intentions based on readings from sensors that themselves are probably suboptimal interfaces.

In general, reliability and robustness of all aspects of assistive technologies (not just user interfaces) need to dramatically improve. Likewise cost effectiveness must increase before they can become true products. For example, the IBOT stair-climbing wheelchair (Independence Technology, USA) is priced well beyond what insurance companies are willing to reimburse for a wheelchair. Assistive technologies have to date failed to exploit mature technologies from other domains (including other applications of robotics) and industries. This partially explains why there are only a few research prototypes of navigation systems for wheelchairs though many viable systems on commercial mobile robots.

Ubiquitous robotics/smart space technology is still virtually inaccessible to non-technologists, mainly because of highly technical interfaces that are difficult to learn and use. Social interaction of computers with humans, particularly speech understanding, natural language interpretation, facial expression analysis and interpretation of other gestures are major unsolved problems. Human movement/behavior interpretation is hampered by many of the same reliability issues as other applications of computer vision. As smart space technologies proliferate, interoperability of components manufactured by different vendors will almost certainly become an issue; as yet there are no standards.

As do their counterparts in many other domains, assistive robots and space spaces require smaller, cheaper and more robust components, particularly sensors, processors and buses, as well as better real-time operating systems and control software. Improvements in wireless technology will ease system integration and end-use.

Technology Needs

To summarize, we identify the following needed technologies:

- direct interfaces to the human nervous system
- mechatronic components,
- much better understanding of the human neuromuscular system
- solutions to biocompatibility problems associated with chronic implants
- control algorithms that are robust to uncertainties in sensor data and inferred user intentions
- robust speech understanding
- natural language understanding

- real-time interpretation of human movement and behavior from video
- standards for interconnection (hardware and software) of smart space components

Non-technological Barriers

The principal barrier to assistive technologies is paucity of research funding, which has the side effects of limiting the size of the research community to small number of experienced and talented investigators and hindering the pace at which research results are translated into viable products. For assistive robots, FDA approval is needed, itself a very expensive process. At present, assistive technology solutions aren't cost-effective for users nor do the represent profitable business opportunities. As a consumer group, the end-user community is weak relative to insurance companies and major government payors (Medicare, Medicaid and the Veterans Administration in the USA).

The primary concern of assistive robot end-users is safety; otherwise, they are generally open to using technologies that will improve their quality of life (assuming that costs are borne by third parties). Overcoming the inherently conservative disposition of rehabilitation clinicians remains a challenge as they tend to prefer "natural" healing and like their counterparts in other domains of medicine, are technologically unsophisticated and faced with time pressures that make learning new technologies very difficult.

Future Directions

10-Year Expectations & Targets

The demographics of disability are changing. Society is aging, and better general healthcare is increasing life expectancies. Both factors indicate rising demand for rehabilitation and assistive technologies. A diminishing caregiver workforce and consumer demand for quality of life that is better and sustained throughout one's life will drive these technologies more toward the home and less toward the clinical environment. The costs of assistive robots will drop as other robotics technologies, especially sensors, actuators and intelligence embedded in traditional household products become part of the mainstream consumer market. Some changes in social and cultural attitudes, as well as economic pressure to allow elderly to live independently for longer periods of time, will stimulate the commercial market for assistive technologies.

Continued R&D on functional electrical stimulation, silicon-neuron interfaces, bio-inspired control and machine learning will usher in a new generation of advanced prosthetics that have closed-loop control of limb function. Advances in MEMS technology and solutions to biocompatibility problems will make chronically implantable biosensors for health monitoring possible. There will be a variety of devices to assist with activities of daily living, including affordable personal robot assistants. Smart living space technologies will have begun to proliferate, particularly in new construction.

25-Year Horizon

At some time in the future, there will be major government-led efforts to maximize the independence of persons with disabilities. One such initiative will assure that the mean time to nursing home entry rises in proportion to increasing life expectancy. Though an increased portion of the population will have a functional impairment (many due simply to old age), there will be a commensurately larger workforce addressing assistive technologies: more engineers who desire to make humanistic contributions and a new generation of clinicians with much greater appreciation for and grasp of technology.

In 25 years the technological and biomedical problems associated with chronic interfaces for recording and stimulating brain activity will have been solved, enabling direct connection of robots and the human nervous system. Miniaturization and standardization of sensors, electronics and processing components will have made ubiquitous computing and robotics realities, and most living spaces (at least in developed countries) will be highly interactive.

Recommendations

Funding Needs

Because they have received so little attention, there are major assistive technology problems to be solved. Many will take at least a decade; in total a very large investment – on order of $1B – is needed. Government agencies that are currently not funding assistive technology R&D will have to become involved. Some funding from industry can be expected once the commercial market for assistive technology is firmly established.

The market is there: in the USA alone, there is an estimated user population of over 150,000 assistive robot users, a number that includes people with spinal cord injuries, cerebral palsy and rheumatoid arthritis (Note: the user population is about 5% of the total number of persons with those conditions). QUESTION: why not the other 95%? Additional potential users include the frail elderly, patients with amyotrophic lateral sclerosis (ALS or Lou Gehrig's disease), muscular dystrophy, or multiple sclerosis, stroke victims and those with temporary impairments. Reimbursement issues aside, the capital costs of assistive robots do not appear to be prohibitive: a $50k robot amortized over three years pays for itself if it replaces an attendant working eight hours per day for $6/hour. Therefore, costs of customization, installation, training, maintenance and repair, as well as the costs of traditional care, will ultimately be determinants in widespread adoption of assistive robots.

Other Needs

Development of assistive technologies needs to become a more user-driven process. For example, because normal subjects do not faithfully represent the end-users, many efforts to develop assistive robots have been hindered by lack of persons with disabilities on the development team. Similarly, the research community often overestimates the technical abilities of end-users, particularly the elderly population. A highly iterative process with rapidly alternating development and evaluation by real end-users is much more likely to succeed than one with prolonged engineering.

Similarly, early involvement of clinical (medical, physical therapy and occupational therapy) personnel – in addition to end-users – can reduce system development time. This also promotes "buy-in" by and instills a sense of ownership in the clinical community. Since it is imperative that assistive technology R&D be performed in a socially responsible manner, it is important to involve expertise such as sociologists and anthropologists for field and clinical assessments.

To date, very little attention has been given to the assistive technology needs in developing countries. This can and should change. However, efforts should strive to create technology that is locally sustainable.

Potential Pitfalls

Until funding levels increase, the research community should concentrate on a small number of problems and solve them well. It is better to focus on achievable goals and in so doing build trust and confidence in assistive technologies, then progress to higher levels of socio-technical complexity and cost. Similarly, it is advisable to develop solutions around commercially available technology and to embed assistive functionality and utility in products conceived and marketed for other primary purposes.

Appendix A – Workshop Participants

Charles Baur, Ecole Polytechnique Federale de Lausanne, Switzerland
Kevin Cleary, Georgetown University Medical Center, USA
Francois Conti, Swiss Federal Institute of Technology, Switzerland
Paolo Dario, Scuola Superiore Sant'Anna, Italy
Brian Davies, Imperial College of Science, Technology and Medicine, UK
Michel de Mathelin, Ecole Nationale Supérieure de Physique de Strasbourg, France
Gil Devey, National Science Foundation, USA
Dan Ding, University of Pittsburgh, USA
Etienne Dombre, Le Laboratoire d'Informatique, France
Reggie Edgerton, University of California at Los Angeles, USA
Gabor Fichtinger, Johns Hopkins University, USA
Masakatsu Fujie, Waseda University, Japan
Valery Gradetsky, Russian Academy of Sciences, Russia
William Harwin, University of Reading, UK
William Heetderks, National Institute of Biomedical Imaging and Bioengineering, USA
Abdelsalam Helal, University of Florida, USA
Koji Ikuta, Nagoya University, Japan
Branko Jaramaz, Carnegie Mellon University, USA
Takeo Kanade, Carnegie Mellon University, USA
Robert Kirsch, Case Western Reserve University, USA
Gernot Kronreif, ARC Seibersdorf Research, Austria
Dong-Soo Kwon, Korea Advanced Institute of Science & Technology, Korea
Christian Lange, Agence Spatiale Canadienne, Canada
Larry Leifer, Stanford University, USA
Harvey Magee, Telemedicine and Advanced Technology Research, USA
Ken Masamune, Tokyo Denko University, Japan
Yoky Matsuoka, Carnegie Mellon University, USA
Robert Michler, Ohio State University, USA
Guillaume Morel, University of Paris, France
Jim Osborn, Carnegie Mellon University, USA
James Patton, Rehabilitation Institute of Chicago, USA
Geoff Pegman, RTS Advanced Robotics Ltd, UK
Roger Phillips, University of Hull, UK
Cam Riviere, Carnegie Mellon University, USA
Icbhiro Sakuma, University of Tokyo, Japan
Tobias Salb, Universitat Karlsruhe, Germany
Russell Taylor, Johns Hopkins University, USA
Jocelyne Troccaz, CNRS, Grenoble, France
Machiel Van der Loos, Veterans Administration, Palo Alto, USA
Yulun Wang, InTouch Health, USA
Marco Zenati, UPMC Presbyterian Hospital, USA

Appendix B – Questionnaire Summary: Image-Guided Therapy & Interventional Systems

Appendix C – Questionnaire Summary: Interventional Devices

Appendix D – Questionnaire Summary: Rehabilitation Robotics

Appendix E – Questionnaire Summary: Assistive Technologies

Appendix F – Keynote Presentations

Appendix G – Bibliography