5th Summer University in Surgical Robotics, Montpellier, September 7-14, 2011

Abstracts of the lectures

Introduction to surgical robotics
Etienne Dombre (LIRMM, Université Montpellier 2 - CNRS, France)

The talk is intended to give an overview of surgical robotics and introduce the lectures of the Summer School. I will analyze some classical surgical functions ("machining", constrained manipulation, constrained targeting, surface tracking, micro-manipulation), from the viewpoint of the engineer, in order to illustrate the limitations of the manual procedures. This analysis will serve to justify the introduction of robotics in surgery. The added-values and limitations of computer- & robot-aided surgery will be discussed. A state of the art will present the main prototypes and commercial systems. Finally, I will list some future directions of R&D and technical challenges.

Interaction control in medical robotics
Philippe Poignet (LIRMM, Université Montpellier 2 - CNRS, France)

Medical robots require high performance and robustness for achieving accurate task in interaction with patient such as knee surgery, resection of brain tumors, skin harvesting, MIS… The capability to handle interaction between manipulator and patient or surgeon is one of the fundamental requirements of medical robots. High performance or interaction are ensured by specific controllers. In the lecture, we will first introduce the basic schemes for free space control (joint space and output space). Then we will focus on interaction control. We will present the classical concepts developed for force control. Finally we will exhibit the hybrid external force/position control scheme and a more advanced controller based on an active observer. The advantages and the efficiency of these schemes will be illustrated on applications in reconstructive surgery performed with the SCALPP robot and in teleoperation with force feedback for MIS developed at the LIRMM lab.

Robot registration
Jocelyne Troccaz (TIMC-IMAG, Université J. Fourier - CNRS, Grenoble, France)

The general problem of registration consists in determining the geometrical relationship between different reference frames where some information is represented. In the context of computer-assisted surgery, this term is most often used when fusing imaging data coming from multi-modality sensors and acquired in different places or at different times. When a robot is introduced, this device also needs to be registered to the data. Indeed, in order to enable the robot to execute a pre-defined plan, or to assist the surgeon in this execution, the relationship between patient data where the planning is defined and the robot reference frame has to be determined. In this talk we present this general context and describe how this problem has been solved for different categories of systems. We distinguish four main intra-operative situations: robot alone, robot plus tracking device, robot plus imaging sensor, robot plus imaging sensor plus tracking device. Several examples are detailed and discussed.

Vision-based control of robots and applications in medical robotics

Florent Nageotte (LSIIT, Université de Strasbourg - CNRS, France)

Vision-based control of robots consists in using an imaging device as an external sensor for controlling robots. It is attractive because of its similarity with the way human-beings control their own arms and hands for reaching and moving objects. The interest for this kind of control has begun in the 1980's and a uniform framework has been given at the end of the 1980's and during the 90's by researchers like F. Chaumette and P. Corke. Since then visual servoing has become an important field of robotics and has generated thousands of papers with the goal to improve trajectories, stability, robustness of vision-based control. Vision-based control has also been used in medical robotics and it has probably an important role to play in medical applications where vision sensors are often the only available sensors.

In this lecture I will first present the standard ways to control robots with visual sensors: Position-based visual servoing and Image-based visual servoing. I will try to emphasize practical limitations and problems for standard cameras as well as for slice imaging devices used in medical applications. Then I will give an overview of some of the existing improvements on different interesting aspects, such as hybrid visual servoing or the use of general and even unknown targets. Finally, we will look at some of the existing applications in the field of medical robotics and discuss current limitations.

Design and applications of robotic devices for endoluminal surgery

Paolo Dario, Arianna Menciassi, Edoardo Sinibaldi, Cesare Stefanini (The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy)

Surgical and diagnostic procedures of the future will evolve from today’s minimally invasive approach to extremely targeted, localized and high precision endoluminal techniques. This will require a new generation of surgical tools, capable of entering the human body through natural orifices (by insertion, ingestion or inhalation), very small incisions (injection), or even through skin absorption, and maybe configuring themselves in complex kinematic structures at the specific site of intervention. Large robots for minimally invasive surgery (MIS) are well established in clinical applications (e.g. da Vinci system by Intuitive Surgical Inc., Sunnyvale CA). These machines are designed to operate in small workspaces and on delicate tissues by ensuring high accuracy, reducing the operator fatigue, and leveling the surgeons’ performance. Merging the accuracy and controllability typical of robotic medical tools, with the potentials offered by miniaturization technologies and nanotechnologies is one of the major challenges of current research for developing truly non invasive – yet extremely effective - surgical and diagnostic devices.

The lecture will introduce advanced concepts and demonstrators that go beyond existing commercial systems in terms of invasiveness and miniaturization. The case of a single port robotic system will be described, integrating the advantages of traditional open surgery, laparoscopic surgery (MIS), and robotics surgery into an innovative platform for bi-manual, ambulatory, tethered, visible scarless surgery. The design of a prototype master/slave robot with two arms, having partial distal actuation of 7 degrees of freedom per arm will be analyzed and key technological challenges for industrialization will be addressed. This system represents an innovative platform *per se,* but also a starting point for developing novel surgical tools, with reconfiguration abilities in different kinematic chains, and with a complete distal actuation. In these “totally inside” surgical systems, the *redundancy* of many different articulated components plays a more important role than *dexterity* in the case of a single surgical arm.
Miniaturized robotic capsules for advanced diagnostics and therapy in the human digestive tract will be then presented, focusing on the results of an ongoing research project on the diagnosis and treatment of digestive cancers and their precursors through novel intelligent endoscopic capsules using innovations in micro- and nanotechnology.
Devices for endoluminal sites that are more delicate and critical than the gastrointestinal or the abdominal ones will be also analyzed, as in the case of an interventional neuro-endoscope for navigation, diagnosis and therapy within the subarachnoid space surrounding the spinal cord. A prototype, in-vivo validated, will be described encompassing an interesting set of design and fabrication solutions. Additional investigations for treating the brain by releasing drugs or miniaturized therapeutic patches will be also presented as one of the most challenging objectives in the field.
Still concerning difficult environments and lumina of the human body where safety issues and active forces are demanding, a novel robotic approach for treating vascular pathologies will be introduced: it merges magnetic navigation and dragging, ultrasound tracking and a combination of mechanical, chemical, US-based therapeutic tools for vascular obstructions removal.
Steps towards further miniaturization of interventional devices will be outlined, down to nano-, nonviral vectors for safe and efficient gene delivery and local, non invasive therapy. The potential of carbon and boron nanotube technology in this field will be briefly discussed, as well as the one of magnetic nanoparticles and nanosheets as drug carriers.
Finally ultra-precision microfabrication technologies potentially enabling mass production of hybrid (in terms of blending between different bio-materials), complex and customized 3D microparts will be presented. These technologies may open new perspectives and insights onto future scenarios with wider design boundaries and weaker manufacturing constraints.

Human Machine Interfaces in Surgical Robotics

Jacob Rosen (Bionics Lab, University of California, Santa Cruz, California, USA)

The introduction of surgical robotics into the operating room (OR) created two new interfaces including the surgeon /robot (S-R) interface and the robot / patient (R-P) interface. These two new interfaces redefined the dynamics between the surgeon, the patients, as well as the supporting staff in the OR. The S-R interface may dictate the level of automation provided to the system during the operation whereas the R-P interface defines the level of invasiveness. As part of the talk, the field of surgical robotics will be introduced and classified based on these two interfaces. This introduction will be followed by a detailed description of the design procedure of a minimally invasive surgical robotic system (Raven) starting with the system specification, kinematic analysis, mechanism optimization, system design, software architecture, approach to safety, along with the experiments conducted with the system. Selected topics addressing key topics associated with the two interfaces will be reviewed including tissue biomechanics and tissue damage (R-P interface) , objective assessment of surgical skills (S-R interface), and the effect of time delay on surgical robotics performance (S-R interface). The talk will be concluded by extrapolating on existing trends in surgical robotics that may provide visions for future studies and systems development.

Medical imaging (Basic)

Guang-Zhong Yang (Hamlyn Centre for Robotic Surgery, Imperial College, London, UK)

In this lecture, we will discuss the basic principles of key medical imaging modalities including ultrasound, CT, MRI and PET/SPECT and outline the current trend of imaging being increasingly moving from a primarily diagnostic modality towards a therapeutic and interventional aid, facilitated by advances in minimal access and robotic assisted surgery, along with the emergence of novel drugs and other forms of treatment.

Medical imaging (Advanced)

Guang-Zhong Yang (Hamlyn Centre for Robotic Surgery, Imperial College, London, UK)

This lecture will focus on the latest development of real-time adaptive imaging techniques for in situ, in vivo surgical guidance. We will use intra-operative MRI and biophotonics as examples to demonstrate how such modalities can be integrated with the current surgical workflow, particularly robotic assisted MIS. Issues related to multi-scale integration, image guided navigation and augmented reality (particularly the concept of inverse realism) will be discussed.

Medical robotics and computer-integrated interventional medicine

Russell H. Taylor, (CISST ERC, The John Hopkins University, Baltimore, USA)

This talk will discuss ongoing research at the JHU Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) to develop systems that combine innovative algorithms, robotic devices, imaging systems, sensors, and human-machine interfaces to work cooperatively with surgeons in the planning and execution of surgery and other interventional procedures. This talk will describe past and emerging research themes and illustrate them with examples drawn from our current research activities in medical robotics and computer-integrated interventional systems.

Surgical simulation with physics-based deformations and interactions
Christian Duriez (INRIA, Villeneuve d'Ascq, France)

We believe that the simulation of surgical procedures, whether targeted at education, training, planning of interventions, or even guidance during procedures, will be a major element of the Medicine of the twenty-first century. However, some key scientific problems remain to be addressed. Among them, one important issue concerns the accuracy of the biomechanics within the real-time constraint: in a very short computation time, many physical phenomenons like the deformations of the soft-tissue, the interactions between surgical tools and organs or the haptic feedback need to be simulated. This lecture will introduce the scientific issues and some recent results: algorithms and models to simulate the deformations of the anatomical structures with finite element method, models for the simulation of the tool-tissue interactions, and the approaches dedicated to haptic rendering of surgical simulation. Finally, the open-source SOFA framework (www.sofa-framework.org) dedicated to interactive medical simulations will be presented.

Design and haptics - Experimental measurements for specification of surgical mechanisms and understanding of surgical skill
Blake Hannaford (BioRobotics Lab., University of Washington, Seattle, USA)

This lecture will cover a "bottom up" approach to surgical robot mechanism design. In this approach, we begin by extensive physical measurements of the mechanics of surgery. From this large database, we analyze signal measurements and synthesize requirements. We then repeat the process with candidate robot mechanism designs.
Outline:
I. Surgical Variables and Sensors
  Mechanical Variables
  Force Sensing
II. Instrumented Instruments
  Grasper
  Motorized Grasper
  "Blue Dragon" motion tracker
III. Data Analysis
  Tissue Properties
  Surgical Processes (Hidden Markov Models)
  Motion Range and Kinematics
  Norms and Histograms
IV. Synthesis and Testing of a next generation surgical manipulator
  Port Locations
  Mockup-Testing
  Mechanism Optimization and CAD Visualization
  Design Goals
  Status
  Future Visions

Ultrasound-guided medical interventions

Tim Salcudean (University of British Columbia, Vancouver, Canada)

Ultrasound is the most commonly used medical imaging method because it is real-time, inexpensive, accessible and safe. We will provide some background to ultrasound imaging and discuss in more detail approaches to the ultrasound-based measurement of tissue elasticity, or ultrasound "elastography".
We will discuss the use of ultrasound guidance for prostate cancer diagnosis and treatment and for kidney surgery. Our approaches include a "pick-up" ultrasound - a small transducer that can be left in the abdomen and used as needed - and a remotely operated endorectal ultrasound system for prostate surgery.
We will discuss issues of design, calibration and use of these systems, as well as advanced elastography imaging techniques. Elastography has many applications, from the detection of cancer to the simulation of medical procedures. We will present some of these applications.

Ultrasound guidance for cardiac procedures

Robert Howe (BioRobotics Lab., Harvard School of Engineering and Applied Sciences, Cambridge, USA)

To treat defects within the heart, surgeons currently use stopped-heart techniques. These procedures are highly invasive and incur a significant risk of neurological impairment. This presentation will describe methods for performing surgery within the heart while it is beating. New real-time 3-D ultrasound imaging allows visualization through the opaque blood pool, but this imaging modality poses difficult image processing challenges, including poor resolution, acoustic artifacts, and data rates of 30 to 40 million voxels per second. To track instruments and tissue structures within the heart we have developed algorithms which are implemented in real-time on graphics processor units. For manipulation of rapidly moving cardiac tissue we have created fast robotic devices that can follow the tissue based on ultrasound image features. This allows the surgeon to interact with the heart as if it was stationary. To integrate ultrasound imaging with the robotic device we have developed a predictive controller that compensates for the 50-100 ms imaging and image processing delays to ensure good tracking performance. In vivo studies show that this approach enhances dexterity and lowers applied forces. Clinical applications of this technology include atrial septal defect closure and mitral valve annuloplasty.

Computer-aided surgery, biomedical measurement, and surgical robotics

Ichiro Sakuma (Biomedical Precision Engineering Laboratory, The University of Tokyo, Japan)

In conventional Image guided surgical, information obtained with pre/intra operative three dimensional imaging devices (CT, MRI, US etc.) are used to localize pathological area and to navigate surgical operation such as tumor resection. In principle, the three dimensional volumetric image should be registered to patient coordinates using three dimensional position tracking system such as optical tracking system and electromagnetic tracking system. This information can be used to control

surgical robotics. Because of errors originated from three dimensional position tracking, image registration, and spatial resolution, in particular limitation of slice thickness, resultant accuracy of surgical navigation is at most as large as a few mm. In addition, living organs deforms due to various reasons. Preoperative image based surgical navigation system has accuracy limitation in principle. Additional intra-operative information can be used to overcome the limitation. For example, electrocortical and subcortical stimulation are conducted to identifying important functional areas such as motor and speech center while registering the three dimensional location of the stimulating points are registered to the conventional navigation system to understand functional localization. This information can be also used for surgical navigation. Various physiological information such as oxygen saturation, spectroscopic property, tissue pH, tissue perfusion, concentration of a specific chemicals, and local temperature can be measured using advanced biomedical instrumentation techniques. These kinds of physiological information at local area can be mapped to the anatomical information used for surgical navigation to help surgeon's intra-operative determination of pathological/healthy area in surgical field. This enables target therapy of the pathological area that can keep the healthy tissue intact. It leads to realization of minimally invasive therapy.
In this lecture, I will briefly introduce biomedical instrumentation technologies that can be used intra-operatively, fusion with surgical navigation system, and use of the integrated information to control surgical robot. Recent works in the field of surgical robotics and computer-aided surgery will be discussed.

Image-guided hybrid minimally invasive surgery

Luc Soler, Jacques Marescaux (IRCAD, Strasbourg, France)

Computer-assisted surgery led to a major improvement in medicine which can be summarized in four major steps. The first one consists in automated 3D modelling of patients from their medical images. The second one consists in using this modelling in surgical planning and simulation software offering then the opportunity to train the surgical gesture before carrying it out. The third step consists in intraoperatively superimposing preoperative data onto the real view of patients. This Augmented Reality provides surgeons a view in transparency of their patient allowing to track instruments and improve pathology targeting. The last one consists in robotizing the procedure by replacing human gesture by a robotic gesture that can be automated.
Essentially developed for open and Minimally Invasive surgery, these techniques lead to the development of a new surgical specialty: Image-Guided Hybrid Minimally Invasive Surgery. It consists in combining technologies of conventional minimally invasive surgery using rigid endoscopes, gastroenterology using flexible endoscopes and interventional radiology using intraoperative medical imaging. Development of computer-assisted surgery is here mandatory to obtain efficient clinical results demonstrating benefits for the patient, reducing pain and post-operative complications. Natural Orifice Transluminal Endoscopic Surgery (NOTES), the new generation of High Intensity Focalized Ultrasound (HIFU) and Image-guided robotized drug delivery treatment are examples of such future generations of surgery. We will present here the concept and existing applications of Image-Guided Hybrid Minimally Invasive Surgery, and future perspectives in this domain.

Robotic applications in ear surgery

Yann Nguyen, Oliviers Sterkers (Department of Otorhinolaryngology, Baujon Hospital & INSERM-University Paris 7, France)

Great improvements of the surgical techniques are expected by the medical community with the development of robotic tools. Computer assisted surgery is routinely used in operating rooms. Accurate positioning, sub-millimetric displacements, tremor filtration, and preservation of the microscope vision field are the primary requirements for a robotic assistance in Ear Surgery. Applications are mainly represented by middle ear surgery and cochlear implantation. These two fields are under investigation in our research laboratory. First of all, a new teleoperated robotic device dedicated to middle ear surgery called RobOtol will be presented. Preliminary evaluation results on temporal bone will be presented. Then, minimally invasive computer assisted approach to cochlea through the facial recess will be presented. At last, methods for real time cochlear insertion forces measurements will be described. All these technologies will be combined in the future in order to perform a minimally invasive approach and a controlled force insertion during cochlear implantation.

Head and neck robotic surgery: clinical applications of the da Vinci system

Benjamin Lallemant (Department of Otorhinolaryngology and Maxillo-Facial Surgery, University Hospital of Nîmes, France)

Clinical applications of the da Vinci ® robotic system have recently emerged in the field of head and neck surgery. Transaxillary robotic thyroidectomy was developed to avoid a scar in the neck and to decrease the incidence of postoperative complications such as hyporathyroidism and inferior laryngeal nerve palsy. Transoral robotic surgery was developed to carry out less invasive surgery for cancer of the upper aero-digestive tracts in order to improve postoperative functional results (eg: voice, swallowing and breathing). The preliminary experience of a French surgical team will be presented. Results, clinical implications and technical limitations will be discussed as well as future developments.

Computer assisted orthopaedics surgery

Eric Stindel (LATIM, ENST Bretagne - INSERM - CHU Brest, France)

Information technologies are now almost everywhere in the medical field. Among several stories, Computer Assisted Orthopedic Surgery is one of the most successful one. Several thousands of patients have been operated thanks to these innovative techniques in the last 10 years and a true new industry is born.

In this lecture, after a brief history, we will present the basic knowledge required to understand the clinical challenges and how bricks of technology and software can be mixed together to answer to these challenges. We will address three very different issues: conservative surgery (High tibial osteotomy), joint replacement (Hip and Knee) and ligament repair (Anterior cruciate ligament).

Based on our experience, both as a developer and an orthopedic surgeon we will discuss the pros and cons of such new approaches. A critical review of the literature will also be presented 10 years after the introduction of computer assisted total knee replacement as a routine technique.
In conclusion, future directions and remaining challenges will be underlined.

Collaborative robots for assistance to gesture

Guillaume Morel (ISIR, Université Pierre et Marie Curie - CNRS, Paris, France)

This talk will focus on the concept of comanipulation and its applications to medical robotics. A comanipulation system is a robotic device that does not perform tasks autonomously but is rather aimed at assisting a human operator to perform a task. Potential assistive functions cover a very wide range that includes:

- Guidance, which can be provided by applying geometrical constraints to a tool.
- Tremor cancelling, which can be obtained by appropriately filtering the user motion.
- Force scaling, which may be brought by dual port force control.
- Augmented tactile perception, which consists of imposing extra force to the interface in the aim of coding information.
- Augmented dexterity, which covers the fields of handheld dexterous instruments.

A common feature of these applications is that a human operator is definitely part of the loop. For these reasons, a key issue in this field is to study the properties of human motion and motor control characteristics.
The talk will emphasize some of the theoretical questions that are raised by this growing field, as well as applications for surgery (handheld instruments for eye surgery, for laparoscopic surgery, assistive devices for orthopedic surgery, for neurosurgery, assistance to ultrasound examination, etc.) and for neuromotor rehabilitation.

Applications of robotics and computer-aided surgery in urology

P. Mozer (ISIR, Université Pierre et Marie Curie - CNRS & Service d'Urologie, Groupe Hospitalier Pitié-Salpétrière, Paris, France)

Urology is the medical and surgical specialty that focuses on the urinary tracts (kidneys, uretere, bladder) of males and females, and on the reproductive system of males (prostate and testicle). Urology is probably the most advanced surgical field of « soft tissue » for computer-aided surgery and robotics.
In this presentation after a historical introduction, we will focus mainly on prostate and kidney applications from a clinical point of view with a technical perspective. We will introduce the advantages and drawbacks of Direct Image Guided Interventions versus navigation systems and teleoperative system as for example the da Vinci system (Intuitive Inc). To conclude, we will describe our experience of the process from « bench to bedside » to develop devices CE marked and FDA approved.