Introduction to Special Section on Surgical Robotics

I. Introduction

"SURGERY is a side-effect of therapy." This statement implies that surgical trauma is largely the result of accessing the affected tissue, rather than the consequence of the therapeutic maneuver itself. This observation has led to the development of systems that approach the target using a minimally invasive access, and that employ images, acquired either intraoperatively, preoperatively, or a combination of both, for navigation and guidance. In some cases, the surgical instruments are inserted into the body cavity via one or more small ports, often accompanied by an endoscopic video camera and/or imaging probes such as ultrasound, with externally manipulated instruments performing the intervention. Often, to assist the interpretation of data that may not be visible by direct video, or even with intraoperative imaging, coregistered preoperative data may be used to augment intraoperative view.

Such image-guided minimally invasive interventions began with Stereotactic neurosurgery, where a target was defined in the brain, and located with respect to a coordinate system defined by a frame attached to the patient's skull with bone screws. Since then, minimally invasive procedures have moved from the placement of an instrument tip at the end of a rigid shaft, to highly complex manipulators performing sophisticated procedures on the target tissue. Surgical robotics was the obvious next step, enabling procedures to be performed under minimally invasive conditions, with similar or greater dexterity, as under open surgery.

The main motivation for implementing robotic surgery is clearly to improve the safety and consistency of procedures, as well as the ability to minimize traumatic and often disfiguring incisions to access the target organ. However, robotic surgery offers much more than these. If we examine the lineup in this special issue, we not only encounter papers dealing with conventional surgical robots, but also new approaches that use robotics-inspired principles toward enhancing the capabilities of conventional surgical approaches; articles that describe miniaturized devices that can be introduced into the vasculature or target organs; and descriptions of systems for training surgeons in the use of these new paradigms. This issue, therefore, provides a unique snapshot of the current research in a very active area that promises to revolutionize the way many surgical procedures are performed today. There is no doubt that robotic surgery is transforming the current surgical practice, and not necessarily only those for which robotic technology was originally developed. The daVinci robots from Intuitive Surgical (and Zeus from Computer Motion—until acquired by Intuitive), were originally envisaged for use in minimally invasive coronary artery bypass grafting procedures, but have since been adopted by a large number of disciplines including pediatric surgery, gynecology general surgery, urology, thoracic surgery, otorhinolaryngology, and head and neck Surgery. The potential impact on many of these areas is compelling but the current clinical practice has also raised many unmet clinical demands, for which the robotics community has just begun to address. From the ability to perform microsurgery on otherwise inaccessible organs, to untethered devices that can be introduced into blood vessels, and complex procedures performed within the abdominal cavity via a single a access port, robotically assisted surgery continues to improve the accuracy, consistency and overall efficacy of surgical procedures, while sparing the patient from unnecessary trauma.

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II. Overview of the Special Issue

The purpose of this Special Issue on *Surgical Robotics* is to report recent advances and clinical applications of surgical robotics. The special issue presents current and emerging trends; highlights many enabling technological advancements related to design, evaluation, and usability of surgical robots. It also identifies open research issues and further steps required for future clinical uptake.

A total of 110 manuscripts were submitted in response to our Call for Papers. After an initial screening for overall quality, relevance and contents, 78 submitted papers went through a peer-review procedure, and 22 papers were selected for inclusion in the Special Issue following peer review. Twelve of these papers present integrated medical robotic systems, novel mechatronic, and microrobot designs, and their clinical applications. Five papers present new surgical simulation and training techniques that use the robotics technology; five papers discuss surgical navigation, intraoperative imaging, and medical image computing techniques for robot-assisted interventions. The collection of papers in this issue covers a broad range of applications related to neurosurgery, image-guided catheterization procedures, needle steering and microrobots, cancer therapy, laparoscopic surgery, image fusion, cardiac intervention, and open platforms for surgical robotic research.

The first 12 papers present the design and integration of medical robotics systems and their clinical applications.

Motkoski *et al.* proposes to integrate a contact diode laser with neuroArm in neurological surgery. Preclinical evaluation on a range of procedures in a rat model, and four neurological cases in meningioma resection demonstrate the successful integration of contact laser technology into microsurgery, with and without robotic assistance. The use of laser improved microsurgical performance and reduced collateral thermal damage, while the neuroArm decreased intra- and inter-surgeon variability.

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Together, laser-powered tissue resection and robotic guidance offer a faster, more consistent and more precise tool for microsurgery.

Tavallaei *et al*. have developed a catheter navigation system that is compatible with magnetic resonance imaging, in order to facilitate real-time in-bore magnetic resonance image-guided catheterization procedures. Using a master–slave control mechanism, the motions of the interventionalist on an input catheter are measured by a pair of optical encoders, and position measurements are relayed to a pair of ultrasonic motors to drive the catheter within the scanner. The results show reduced system delay and accurate motion replication accuracy, with minimal effect on the image quality.

For increasing the curvature of bevel-steered needles, Swaney *et al*. propose a new flexure-based needle tip design that provides enhanced steerability, while simultaneously minimizing tissue damage due to axial rotation.

Also, related to robot-assisted needle steering, Baena and Ko present a miniaturized biologically inspired system, with which a programmable bevel is employed to control the tip angle as a function of the offset between interlocking needle segments. The bespoke trocar and insertion mechanism ensure that the segments do not come apart or buckle during the insertion. This prototype does not only steer around tight bends, but also offers superior obstacle avoidance owing to a noval path planner integrated in the system.

Simaan *et al*. present the design and evaluation of a telerobotic system for transurethral surveillance and surgical intervention. The system includes a dexterous continuum robot with access channels for the parallel deployment of multiple visualization and surgical instruments. The paper discusses the design considerations within the context of the clinical conditions imposed by transuretheral access, followed by design details. The integrated system demonstrates submillimetric positioning accuracy and intravesicular dexterity suitable for clinical translation to improve on transurethral surveillance and intervention.

For single-port surgery, we have included three papers in this special issue. Wortman *et al*. present experimental results with a multifunctional, dexterous, two-armed single-incision *in vivo* surgical robot. *In vivo* colectomy experiments comparing the robotic platform with traditional laparoscopic tools showed significant benefits from the robotic procedure including access to all quadrants in the peritoneal cavity and improved dexterity.

Gitlin *et al*. present a wireless miniature anchored robotic videoscope system for single-port procedures. The system includes multiple camera modules equipped with adjustable focus and multiwavelength illumination management, all wirelessly controlled to provide a full-hemisphere field of view inside the abdominal cavity. The system also includes a master control module that provides video wireless communications link with near-zero latency, as well as a wireless human–machine interface that provide the surgeon with full control over the intra-abdominal cameras.

Kwon *et al*. propose another kind of robot for single-port surgery, in this case employing a new joint mechanism that is suitable for surgical instruments with multiple degrees of freedom. Their design is to prevent hysteresis of the joint and achieve more accurate motion with a large force. An external arm with 2DOF is used to extend the workspace of the system during surgery.

Woods and Constandinou present a platform to achieve targeted drug delivery with wireless capsule endoscopy. The platform consists of a micropositioning mechanism, integrated with an extendible needle, which can deliver targeted medication and a holding mechanism that gives the functionality of resisting peristalsis. An in-depth analysis of the mechanics is presented and an overview of the requirements necessary to realize total system integration is discussed.

Gerber *et al*. propose a unique robot-assisted method of performing image to patient registration in image- guided microsurgery. Recognizing that such procedures require accuracies an order of magnitude higher than today's navigation systems can provide, they propose a method of reducing target registration error to a level that would facilitate the use of image-guided robotic microsurgery on the rigid anatomy of the head. To achieve their goals, they propose a semiautomatic - detection technique based on automatic force controlled localization of patient-mounted fiducials, using a robotically controlled tactile search of the head for surgical screws. They demonstrate that through the elimination of user variability, target registration errors can be reduced to approximately 0.1 mm.

Weber *et al*. propose a tool localization method during robot-guided minimally invasive mastoidectomy for cochlear implantation. The aim is to detect if the drill is advancing in the correct direction, by which injury of the facial nerve can be avoided. The method is based on the correlation of the observed axial drilling force and the heterogeneous bone density in the mastoid, extracted from 3-D image data and validated on human cadaver.

For research in surgical robotics, there is a pressing need for common standards and open platforms to boost collaboration and technical innovation. Hannaford *et al*. describe Raven-II, a platform based on open standards to facilitate collaborative research on advances in surgical robotics. The system has 2 DOF spherical positioning mechanisms capable of attaching interchangeable 4 DOF instruments. An electronic forum and an online software repository have been put in place to facilitate the interaction among the user community.

The next five papers present various methodologies and systems for surgical simulation and training.

Lin *et al*. propose a methodology for defining a processing model that objectively measures surgical movement performance during the course of routine laparoscopic training. Their approach is based on the analysis of kinematic data describing the movements of surgeon's upper limbs. An ultraminiaturized wearable motion capture system has been developed to measure and analyze these movements. Motion features of the subjects were used to train the data processing model, which was subsequently used to classify the expertise levels of the subjects. Experimental results show that, the proposed methodology can be efficiently used both for quantitative assessment of surgical movement performance, and for the discrimination between expert surgeons and novices.

De Momi *et al*. present an automatic multitrajectory planner for stereo electroencephalo Graphy (SEEG) procedures, where intracerebral electrodes are implanted in order to identify the epileptogenic zone in drug-resistant epilepsy patients. For a given entry and target region, the planner computes the best trajectory in terms of the distance from vessels and guiding screw angle, while sparing critical brain structures. Retrospective evaluation on 15 patients who had previously undergone SEEG investigation showed that the planner meet clinical requirements in planning safe trajectories, with clinically feasible temporal performance.

Folio *et al.* present a preoperative microrobotic surgical simulation and planning application to support minimally invasive surgical procedures that use an untethered microrobot navigated in the arterial networks. A microrobotic surgical planning framework is proposed to provide a pathway that is robust to navigation constraints. The framework is evaluated on a case study for the treatment of peripheral arterial diseases.

Goksel *et al.* present a virtual training system for prostate brachytherapy. The system integrates real-time ultrasound image synthesis and haptic transrectal ultrasound in a simulator that allows a trainee to maneuver the brachytherapy needle and the ultrasound transducer, to visualize the resulting patient-specific images and sense the interaction forces. It also allows simulations of seed unloading, fluoroscopy imaging, and switching between different ultrasound imaging planes, and also incorporates real-time dosimetry computation.

Boisvert *et al.* propose an approach to integrate blood circulation to computerized surgical simulation systems and allow for real-time processing of punctures, ruptures, and cauterization of blood vessels. It also incorporates real-time calculation of blood pressures and flows. The performance of the method is assessed on ten patients who underwent magnetic resonance angiograms.

The final five papers discuss various intraoperative imaging and surgical guidance techniques based on medical image computing.

Navkar *et al.* propose an approach for performing robot-assisted interventions with real-time magnetic resonance imaging guidance. Their framework comprises on-the-fly image processing, robot control, and information rendering on a visualization and force-feedback interface for enhanced perception of a dynamic area of procedure and for assisting the operator in the safe and accurate maneuvering of a robotic manipulator. The experimental results with a virtual robotic manipulator using a simulated transapical aortic valve implantation demonstrate reduced procedural duration by half. The results also demonstrate increased safety in the presence of cardiac and respiratory motion due to reduced duration or incidents the operator collides with the tissue.

Moore *et al.* describe the first porcine trials of an ultrasound-guided beating heart technique employed for repairing diseased mitral valves. The technique aims to attach neochordae to a mitral valve leaflet by augmenting ultrasound images with dynamic virtual geometric models. The results show much shorter distance errors of the tracked tool tip from the intended midline trajectory, navigation times, and total path lengths in the augmented ultrasound, compared to navigation with ultrasound alone. The results indicate substantial improvement in the safety and simplicity of the procedure.

Rosa *et al.* present visual servoing of robotically controlled motion from real-time endomicroscopy images. The system is used to alleviate the challenges associated with mosaicking real-time images of tissue when contacted by a small probe-based confocal laser endomicroscopy system that can be inserted *in vivo* through minimally invasive access. Experiments on two robotic platforms operating in different environments show that the quality of the visually servoed probe motion is sufficient to build mosaics with minimal distortion, in spite of intra-operative disturbances.

Allan *et al.* propose a probabilistic supervised classification method and a level set framework to detect and localize surgical instruments in laparoscopic images. Using simulated image data, they demonstrate that the proposed method is robust against noise. The method is quantitatively evaluated compared to ground truth obtained using an optical tracker. Moreover, practical application of the technique is demonstrated on *in vivo* data from minimally invasive traditional laparoscopic and robotic instruments.

Introducing cellular imaging into *in situ* surgical environment for detailed tissue characterization is an emerging trend in image-guided intervention. In this regard, the use of robotic assistance to control the fine movement and consistent tissue contact is important. Erden *et al.* attempt to assess the soft tissue behavior in surface contact with an imaging probe for confocal microlaparoscopy applications. The approach is inspired by finger slip studies and adapts the idea of load slip that explains the movement of the soft part of the finger when dragged on a hard surface. The concept of loading distance is proposed and a novel method is introduced to compensate the tissue movement during imaging.

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PURANG ABOLMAESUMI, *Guest Editor*
Department of Electrical and Computer Engineering,
The University of British Columbia
Vancouver BC V6T 1Z4, Canada
purang@ece.ubc.ca

GABOR FICHTINGER, *Guest Editor*
Queen's University, School of Computing, Canada
Departments of Computer Science and Radiology,
The Johns Hopkins University
Baltimore, MD 21218 USA
gabor@cs.queensu.ca

TERRY M. PETERS, *Guest Editor*
Robarts Research Institute,
Medical Imaging, Medical Biophysics,
Biomedical Engineering
Western University,
London, ON N6A 3K7, Canada
tpeters@robarts.ca

ICHIRO SAKUMA, *Guest Editor*
Department of Precision Engineering,
School of Engineering
The University of Tokyo
Tokyo 113-0033, Japan
sakuma@bmpe.t.u-tokyo.ac.jp

GUANG-ZHONG YANG, *Guest Editor*
The Hamlyn Centre for Robotic Surgery,
Imperial College London
London SW7 2AZ, U.K.
g.z.yang@imperial.ac.uk

Purang Abolmaesumi (SM'08) received the B.Sc. and M.Sc. degrees from the Sharif University of Technology, Tehran, Iran, in 1995 and 1997, respectively, and the Ph.D. degree from the University of British Columbia (UBC), Vancouver, BC, Canada, in 2002, all in electrical engineering.

He is a Canada Research Chair, Tier II, in Biomedical Engineering, and an Associate Professor at the Department of Electrical and Computer Engineering, UBC, with Associate Membership to the Department of Urologic Sciences. His research interest includes biomedical engineering with focus in the fields of computer-assisted surgery, image-guided therapy, and medical image analysis.

Dr. Abolmaesumi is internationally recognized and has received numerous awards for his pioneering developments in ultrasound image processing, image registration and image-guided interventions. He is an Associate Editor of the IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING, a Board Member of the International Society for Computer Aided Surgery, and serves on the Program Committees of the Medical Image Computing and Computing and Computer Assisted Intervention, International Society for Optics and Photonics Medical Imaging, and the International Conference on Information Processing in Computer Assisted Interventions. He served as Program Chair of IPCAI 2012 in Pisa and Workshop and Tutorial Chair of MICCAI 2011 in Toronto.

Gabor Fichtinger (M'04–SM'12) received the Ph.D. degree in computer science from the Technical University of Budapest, Budapest, Hungary, in 1990.

He is currently a Professor in the School of Computing, with cross appointments in the Departments of Mechanical and Material Engineering, Electrical and Computer Engineering, and Surgery, Queen's University, Kingston, ON, Canada, where he also directs the Percutaneous Surgery Laboratory. He is also an Adjunct Professor in Radiology and Computer Science at the Johns Hopkins University, Baltimore, MD, USA. His research interests include medical image computing and computer-assisted interventions, primarily for the diagnosis and therapy of cancer.

Prof. Fichtinger is a Distinguished Lecturer of IEEE EMBS, and a Fellow of the MICCAI Society. He holds a Level-1 Cancer Care Ontario Research Chair in Cancer Imaging.

Terry M. Peters received the Ph.D. in electrical engineering from the University of Canterbury, Christchurch, NZ, in 1974.

He is currently a Scientist at the Robarts Research Institute and Professor of Medical Imaging, Biomedical Engineering and Medical Biophysics at Western University, London, Canada, where his research focuses on image-guided Intervention. He has trained over 80 masters and Ph.D. students, and PDFs. He has authored more than 200 peer-reviewed papers and book chapters, and delivered more than 180 invited presentations.

Dr. Peters is a Fellow of the Canadian College of Physicists in Medicine, the American Association of Physicists in Medicine, the Australasian College of Physical Scientists and Engineers in Medicine, the MICCAI Society, and the Institute of Physics. He received the Erskine Travelling Fellowship by the University of Canterbury in 1996 and again in 2010, and the Hellmuth Prize for Research Excellence by Western University in 2012.

Ichiro Sakuma received the B.S., the M.S., and the Ph.D. degrees in precision machinery engineering from the University of Tokyo, Tokyo, Japan, in 1982, 1984, and 1989, respectively. He was Research Associate at the Department of Precision Machinery Engineering in Faculty of Engineering, the University of Tokyo from 1985 to 1987. He was an Associate Professor at the Department of Applied Electronic Engineering, Tokyo Denki University, Saitama, Japan, from 1991 to 1999. He was research instructor at the Department of Surgery, Baylor College of Medicine, Houston, Texas, from 1990 to 1991. He was an Associate Professor (1999–2001) and a Professor (2001–2006) at the Institute of Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo. He is currently a Professor at the Departments of Bioengineering and Precision Engineering, School of Engineering, The University of Tokyo. Since 2012, he is also serving as the inaugural director of the Medical Device Development and Regulation Research Center, School of Engineering, The University of Tokyo.

Guang-Zhong Yang (S'90–M'91–SM'08–F'11) received the B.Sc. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, and the Ph.D. degree in computer science from Imperial College, London, U.K.

He is the Director and cofounder of the Hamlyn Centre for Robotic Surgery, the Deputy Chairman of the Institute of Global Health Innovation, Imperial College London, London, U.K. He also holds a number of key academic positions at Imperial—he is Director and Founder of the Royal Society/Wolfson Medical Image Computing Laboratory, cofounder of the Wolfson Surgical Technology Laboratory, Chairman of the Centre for Pervasive Sensing. His research interests include medical imaging, sensing, and robotics. In imaging, he is credited for a number of novel MR phase contrast velocity imaging and computational modeling techniques that have transformed *in vivo* blood flow quantification and visualization. These include the development of locally focused imaging combined with real-time navigator echoes for resolving respiratory motion for high-resolution coronary angiography, as well as MR dynamic flow pressure mapping. He pioneered the concept of perceptual docking for robotic control, which represents a paradigm shift of learning and knowledge acquisition of motor and perceptual/cognitive behaviour for robotics, as well as the field of body sensor network (BSN) for providing personalized wireless monitoring platforms that are pervasive, intelligent, and context-aware.

Dr. Yang is a Fellow of the Royal Academy of Engineering, IET, and AIMBE. He received the ISMRM I. I Rabi Award.