New Technologies Supporting Surgical Interventions and Training of Surgical Skills

A Look at Projects in Europe Supporting Minimally Invasive Techniques

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With the introduction of new technology for surgical and interventional procedures, more complex operations can be performed. The goals are to increase the accuracy and safety of interventions and to reduce their invasiveness and discomfort to patients. If properly engineered, technology can reduce human limitations in dexterity and stability, while still leaving clinical decisions and high-level control to the medical doctor [1]. The technology supporting surgery can be roughly divided into 1) technology for the improvement of manipulation, directly performed by the surgeon himself focusing on minimally invasive procedures, including teleoperated surgical robots, surgical assistants, and other augmented devices and 2) technology that enhances precision, focusing on preoperative planning, image guidance, and including autonomous robots. A broad overview of medical robotics can be found in [1]–[3]. The developed instrumentation should be used by surgeons/interventionists. They have to implement the new method and the new instrumentation in their clinical practice. To limit training on patients, alternative solutions for training surgical skills are searched for. This article will end with a discussion on problems with the development of instruments to be used in the clinic and the clinically driven approach that may support this process.

Tools and Systems Supporting Manipulation Controlled by the Surgeon

Minimally invasive operation techniques are based on the access to the body of a patient via a limited number of cylindrical cannulas (trocars), inserted via small incisions in the skin. Despite many benefits for the patient, minimally invasive procedures yield a series of disadvantages to the surgeon [4], [5]. The surgeon has no direct three-dimensional (3D) view on the operation field, the instruments have limited degrees of freedom and limited force feedback, and there are hand–eye coordination problems [6].

Surgical Robotic Systems and Manipulators

Recently, computer-assisted surgery has entered the operating room, bringing opportunities for new advancements and improvements. In robotic manipulators, a computer is placed between the hands of the surgeon and the end-effector of the instruments. The initial work in this field has been performed in Karlsruhe and Tuebingen (see Table 1 for a description of the research institutions) [7]. The most common surgical robotic system currently on the market is the DaVinci system (Intuitive Surgical, Figure 1). This system consists of a master console, where the surgeon sits and is looking at a 3D binocular display of the operative field. A three-armed robotic system is placed next to the operation table, with two arms for manipulating the instruments and the middle arm for controlling the two-channel optical system. The main advantage of this master–slave system is the introduction of extra degrees of freedom to control the instruments inside the body, the so-called endo-wrist approach. The surgeon's movements of the hand and fingers are transferred to the tip of the instruments, allowing the surgeon to control the tip of the instruments intuitively [8]. The main disadvantages of using currently available robotic systems are their high price, the time loss during set-up of the equipment, and the lack of force feedback.

Based on the know-how of the lightweight robot and dexterous hand developments, the DLR institute is designing and constructing a universal surgical robot with an independent gripping force sensor to detect manipulation reactions [9]. A mechanical minimally invasive manipulator (MIM) was designed at the Academic Medical Center (AMC) in Amsterdam [10] (Figure 2) as a small, economical, and mechanical alternative for the computer-assisted "robotic" systems. The instrument is coupled by a mechanical link to the manipulator's handle in such a way that movement directions of the handle correspond to identical movement directions of the instrument tip in all degrees of freedom. Although the manipulator is completely balanced, the total mass (5.5 kg) should be reduced to lower the inertia of the system and to enable even more precise manipulation.

Since the robotic systems are too complex and costly for daily use, several groups are working on deflectable instruments having more degrees of freedom than standard instruments. At TuebingenSc, a handheld manipulator (Radius System) was developed [11] that was recently introduced on the market (Figure 3). At IMM a deflectable and rotatable endoscopic instrument was developed based on a miniaturized spheric articulation that can be manipulated by a single control wheel [12]. At Delft, a miniature steerable mechanism was developed for use in endoscopes, instruments, and catheters.

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The steerable mechanism consists only of standard parts such as cables, coil springs, rings, and tubes and was inspired by the tentacles of a squid (Figure 4) [13]. The handheld instruments are simple but still have control problems in that manipulation is less intuitive compared to the robotic systems.

Many other instruments have been developed supporting the minimally invasive approach. At Dundee, the Dundee MultiTool (DMT) was designed to enable the internal deployment (by thumb extrusion) of a small dissecting forceps (pick-up), needle driver, and scissors [14] and a new grasper enabling prehensile grasping by finger-like jaws [15]. More fundamental research on grasping safely has been performed at Delft and can be found in [16], [17].

Fig. 1. The da Vinci system (Intuitive Surgical, Santa Barbara, California).

Camera Holders to Support the Minimally Invasive Techniques

During minimally invasive procedures an assistant is controlling the endoscope. Camera holders are able to return camera control to the surgeon and stabilize the endoscopic image [18]. At Karlsruhe, a passive camera holder with a stationary point and electromechanical brakes, called the Tiska [19], was developed. The AMC developed another design based on a parallelogram mechanism with stationary point balancing with a spring and adjustable friction (Passist) [20], [21]. A hand-controlled motorized active endoscope positioner was developed at Karlsruhe (Felix) [22]. The PER is an active system for endoscopy developed at TIMC/IMAG [23]. The positioning mechanism is fixed to the endoscope and strapped to the patient at the incision location, so no rigid base is necessary. The manipulator moves with the patient during breathing, repositioning by the surgeon, motions of other instruments, or any other displacement of the abdominal wall. PER relies on cable actuation using electrical motors. The surgeon may interact with the system using a joystick.

Table 1. Institutions mentioned in text.

AMC	Instrument Development Department, Academic Medical Center, Amsterdam, The Netherlands
CRIM	CRIM laboratory, Scuola Superiore Saint'Anna, Pisa, Italy
Delft	Department of BioMechanical Engineering, Delft University of Technology, Delft, The Netherlands
DLR	Institute of Robotics and Mechatronics of the German Aerospace Center, Wessling, Germany
Dundee	University of Dundee, Ninewells hospital, United Kingdom,
EPFL	EPFL Institute, Lausanne, Switzerland
Karlsruhe	Institute of Medical Technology and Biophysics Forschungscentrum Karlsruhe, Germany
IMM	Institute Mutualiste Montsouris, Paris, France
Imperial College	Mechatronics in Medicine Laboratory at Imperial College in London, United Kingdom
IRCAD-EITS	IRCAD-EITS Institute, Strasbourg, France
Leuven	Leuven at the Katholic University of Leuven, Belgium
LIRMM	Laboratory of Computer Science, Robotics, and Microelectronics (LIRMM), Montpellier, France
München	Technical University of München, Germany
Oslo	Ulleval University Hospital, Oslo, Norway
TeubingenSc	Teubingen Scientific, Germany
TIMC/IMAG	TIMC/IMAG institute, La Tronche Cedex, France
Trondheim	SINTEF Health Institute in Trondheim, Norway
Tuebingen	University of Tuebingen, Germany

Enhancing Vision and Touch

Although tools with haptics are not clinically used, many augmented devices have been developed to measure properties of living tissues. The systems provide sensing and display functions to improve the surgeon's ability to sense tactile or haptic phenomena. At CRIM, a prototype of a new mechatronic tool was developed, integrated in a system for computer-assisted arthroscopy [24], [25]. The tool has a cable-actuated steerable tip and incorporates sensors for the detection of the tip position and contact with the surrounding tissue. A semi-automatic collision-avoidance mechanism prevents contact between the tip and some anatomical regions selected preoperatively (active constraints). DLR is developing novel instruments with additional degrees of freedom at the distal end (to retain full dexterity) and integrated force torque sensors. The use of force-feedback input devices together with advanced control algorithms enables the generation of realistic contact impressions [26]. At EPFL the BiopsyNavigator was developed that combines visualization with haptic rendering in order to provide haptic feedback to the surgeon during a biopsy using patient-specific data [27]. At München, an experimental endoscopic robot system was developed that is capable of both measurement and reflection of forces [28]. Finally, in Leuven a 5-mm diameter tri-axial force sensor has been developed for minimally invasive robotic surgery using strain gauges. The new sensor is based on a flexible titanium structure of which the deformations are measured through reflective measurements with three optical fibers [29]. An alternative approach without sensors was used at Delft. To be able to feel the forces applied to the tissue, a frictionless gripper was designed using rolling links [30]. To safely manipulate tissue, optimal visual feedback is also required. A flexible endoscope was developed at Delft improving the depth perception and eye–hand coordination (Endo-Periscope). The steerable tip can also be used to look behind organs and to observe places and cavities that are difficult to reach with conventional rigid endoscopes [31].

Systems to Enhance Precision

Geometric precision is often important especially in orthopedics and neurosurgery. Hence, these systems have as characteristics that the movements are guided by pre- and peroperative images. The ROBODOC is one of the first robots to be successfully introduced for joint replacement surgery. Since then, several other systems have been developed; however, most are not (yet) in clinical use. A pioneering research group at Imperial College developed Probot to aid in transurethral resection of the prostate [32]. A special-purpose robotic frame was designed to hold the surgical instrument. The geometry of the system is designed to allow a cavity to be hollowed out from within the prostate and restrict movements outside an allowable range. This restriction provides an additional margin of safety. Another special-purpose robot called Acrobot (from Active Constraint Robot) has been developed for safe use in the operating room for total knee replacement surgery. The surgeon guides the robot using a handle with feedback from a force sensor attached to the robot tip [33].

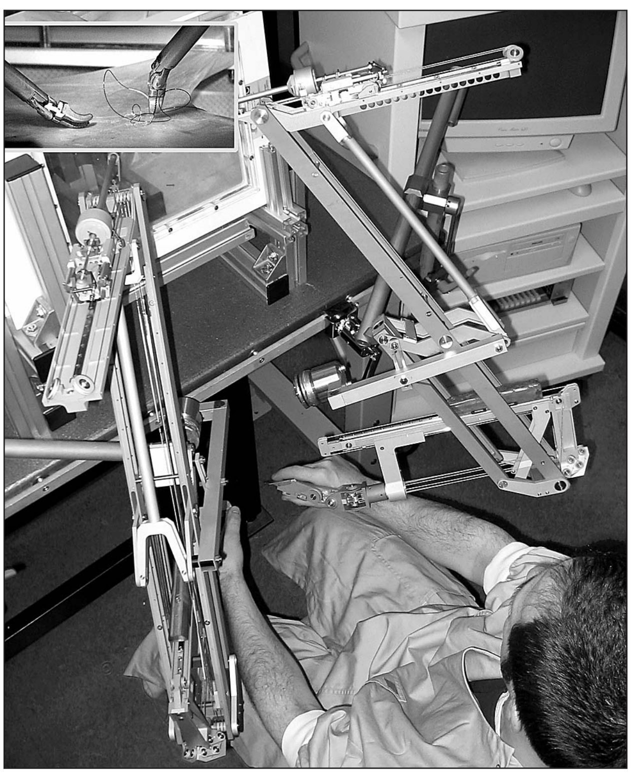

Fig. 2. Mechanical minimally invasive manipulator (MIM) developed at the Academic Medical Center, Amsterdam. The manipulator and the surgeon console are connected by a mechanical linkage system.

At LIRMM, a computerized system called SCALPP was developed for the harvesting of skin to be used in surgical procedures for burn victims and in orthopedic surgery [34]. At TIMC/IMAG, a robot for tele-echography called TER was developed. Performing an ultrasound examination involves good eye-hand coordination and the ability to integrate the acquired information over time and space. These specialized skills are not always present; therefore, teleconsultation is seen as an interesting alternative to conventional care. The teleoperated TER system [35] allows the expert physician located in the master site to move the virtual probe placed on a haptic device (Phantom) and to control the real echographic probe placed on the slave robot. The slave robot architecture is a lightweight, parallel, uncoupled robot placed on the patient's body.

The PADyC of TIMC/IMAG is a passive arm with dynamic constraints [36]. The concrete objective for PADyC's development was to build a general-purpose mechanical device to be held by the surgeon that allows him to feel the virtual world of patient data (including safety regions around anatomical obstacles to be avoided), while moving in the real

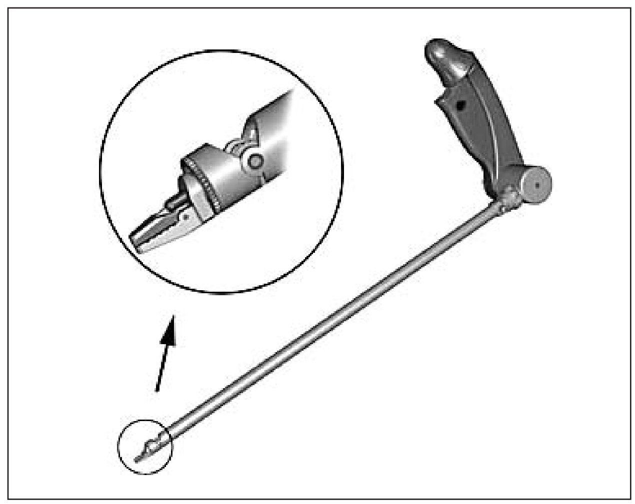

Fig. 3. The Radius System, which is a hand-held manipulator (Tübingen Scientific, Germany). It is a simple instrument with a steerable tip with seven degrees of freedom, which does not compensate for scaling and mirroring.

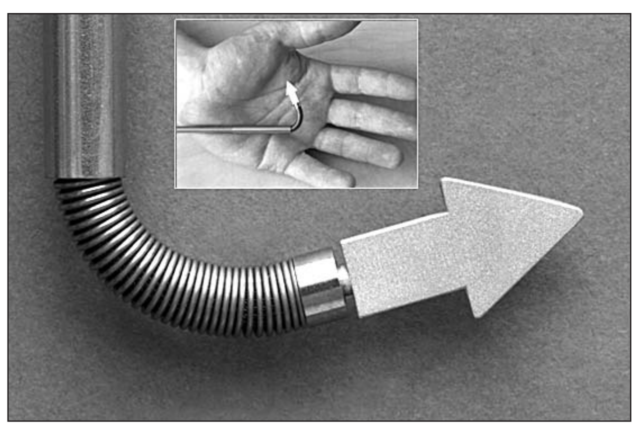

Fig. 4. Close-up of the steerable tip of the Endo-Periscope III designed at the Delft University of Technology. The arrow visualizes the camera's line-of-sight. The tip can be steered in all directions between -110° and $+110^\circ$.

world. The actuation of the PADyC comes exclusively from a human operator. This choice of a passive device also was aimed at providing intrinsic safety. Different types of constraints (region, trajectory, position, etc.) are implemented with the system depending on the task to be executed.

At the AMC a force-controlled robotic device has been developed in the frame of a European project (ROBOSCOPE) intended for the control of a neuroscope (neuroendoscope) in brain surgery [37]. The instrument is designed to let the surgeon feel mechanical boundaries in his working space (active constraints). The mechanism is a motorized parallelogram manipulating a neuroscope in four degrees of freedom. It is a master–slave system with the master (sensor ring) located on the slave (motorized arm). By manipulating a four-degree-of-freedom force sensor ring (master) at the tip of the robotic arm, the force exerted is translated into a velocity of the instrument (slave). This gives the surgeon the impression that he manipulates the instrument himself.

At Karlsruhe, the ROBITOM, (Robot for Biopsy and Therapy of the Mama carcinoma) which is a manipulator system, was developed intended for breast cancer diagnosis and therapy directly in the iso-center of closed MRI systems. The system should be suitable for use in strong magnetic fields; therefore, the system relies on technical plastics. The system should enable the radiologist to remotely take a precise biopsy of a localized lesion in the MRI [38].

Instruments to Move Through the Colon

Colonoscopy is a standard medical procedure in which a long and flexible endoscope is inserted into the rectum for inspection of the large intestine and for simple interventions. Pushing the endoscope tip from the backside via a long and flexible tube leads easily to buckling when the tip meets with sharp curves in the intestinal wall. Buckling is accompanied by painful cramps and makes it difficult to complete the procedure. Inchworm devices specialized for locomotion in the colon have been developed at the Scuola Superiore Saint'Anna, in Pisa, Italy [39]. These devices have two types of actuators: a clamper and an extensor. The clamper is used to adhere or clamp the device onto the substrate while the extensor generates a positive displacement.

A new way of locomotion developed at Delft [40] is based on a rolling donut that is positioned around the endoscope tip. The donut functions like a circular caterpillar and is constructed from three flexible stents that have high friction with the intestinal wall. The resulting rolling-stent endoscope contains a new steerable mechanism by which the tip can be bent in all directions over a very large angle.

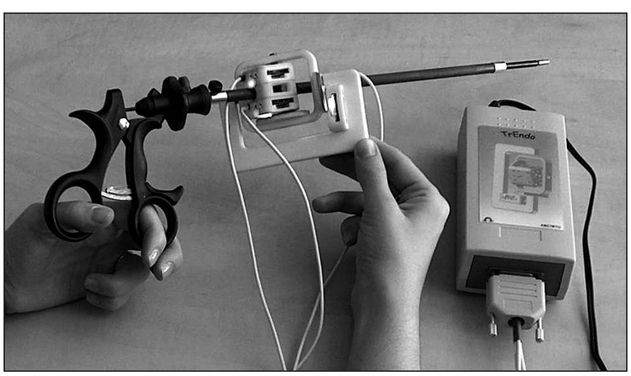

Fig. 5. The TrEndo tracking system for laparoscopic instruments (Delft University of Technology and AMC).

Training and Simulation

Traditionally, surgical training is obtained in the operating room under supervision of an experienced surgeon. The minimally invasive surgical technique is difficult to learn, and learning curves of more than 30 procedures [41] are reported. So, more efficient and effective training facilities are a real medical necessity. Several training methods are becoming available to train minimally invasive surgical skills outside the operating room; e.g., Pelvitrainers (a box in which instruments can be inserted), and virtual reality trainers, with and without a haptic feedback, have been developed. In Dundee an advanced computer-controlled system (ADEPT) has been developed for the objective evaluation of endoscopic task performance. The target object consists of a sprung base plate incorporating various tasks. It is covered by a sprung perforated transparent top plate that has to be moved and held in the correct position by the operator to gain access to the various tasks [42], [43]. Imperial College is focusing on assessment of training. They have developed a computer-based device that tracks the movements of a surgeon when operating and which computes scores of how dexterous he or she is on the basis of time taken, distance traveled, and the number of movements [44]. A new sensor system for the tracking of any laparoscopic surgical instrument has been developed at Delft. The TrEndo system consists of a two-axis gimbal mechanism incorporating three optical sensors (Figure 5). The gimbal mechanism is to guide the laparoscopic instrument, mimicking the degrees of freedom of a trocar, whereas the optical sensors are used for recording the movements of the instrument. Optical computer mouse sensors are applied to reduce costs and to simplify interfacing [45].

In Oslo, in cooperation with SimSurgery, a virtual reality simulator was developed to train minimally invasive surgical skills. The system includes a suturing and knot tying module [46]. At Delft a new virtual simulator was developed, called the Simendo (DelltaTech, Delft) (Figure 6). The simulator is developed for hand–eye coordination training. The system is designed as a plug-and-play feature on a PC and is therefore affordable and mobile and can be used even at home [47].

At IRCAD-EITS, virtual reality is applied to assist surgical strategy and for surgical simulation in liver surgery. A computer interface was developed to manipulate the organ and to define surgical resection planes according to internal anatomy [48]. Furthermore, a realistic radiofrequency ablation simulation tool was developed, coupled with a 3D reconstruction and visualization project. It helps radiologists to have a better visualization of patient's anatomic structures and pathologies and allows them to easily find an adequate treatment [49].

At Trondheim, a 3D navigation technology is proposed based on preoperatively acquired magnetic resonance or computed tomography data used in combination with a laparoscopic navigation pointer [50]. The laparoscopic navigation pointer has an attached position tracker that allows the surgeon to control the display of images interactively before and during surgery. The technology helped the surgeons to understand the anatomy and to locate blood vessels.

Clinically Driven Instrument Design

Many research groups in Europe are working on new technology supporting surgical techniques. In the past it has been shown that many of the developed systems never enter the operating room, or only in specialized academic centers. During the instrumentation development process, it is therefore very important that the engineers and surgeons are cooperating closely together. There are two principally different approaches to clinical problems: technologically driven approaches and clinically driven approaches [51], [52]. In the technologically driven approach, a new instrument is developed at the request of a medical professional or based on a new technique or a bright idea of an engineer. In this case, engineers are showing their medical counterparts what is technologically possible and how pinventive they are. This results in hi-tech instruments/systems, such as robotic systems, that are often not affordable by the practicing medical doctor. In the clinically driven approach, as developed and used at Delft, the surgeon is observed by the engineer in his work environment using, e.g., task-analysis methods. These analyses are then used for problem assessment, instruments design, and evaluation of new technologies [53]. The surgeon's activities during and after the actual surgical procedure are discussed by the engineer and surgeon together in order to detect fundamental problems and limitations occurring during the surgical process. In this way, as a joint enterprise, the functional specifications for an instrument can be defined. This is a complex process, since the medical professionals and the engineers speak different languages, have different cultures, and do not know each other's field. The engineer is not able to understand the medical needs and problems if the medical process has not actually been observed. So, engineers have to spend quite some time in one of the operating theaters in order to define a realistic clinical problem that is considered to be important by the surgeons involved. In this way, the integration of technology and medicine can be guaranteed.

Conclusions

Although this overview does not cover all the research on the development of instruments and systems that support surgical procedures, it shows that many institutes are working in this challenging field. The research involves technology that enhances surgical skills such as master–slave systems as well as more automatic systems to enhance precision. To limit training on patients and to support surgical decision making, the development of (virtual reality) surgical trainers will become a field where the contribution of engineers is essential.

Jenny Dankelman obtained her degree in mathematics, with specialization in system and control engineering in 1984 at the University of Groningen. Her Ph.D. was obtained in 1989 at the Man-Machine Systems Group, Mechanical Engineering Department, Delft University of Technology (DUT) based on her research of the dynamics of coronary circulation. This work was performed in close cooperation with the Department of Medical Physics of the Academic Medical Center at the University of Amsterdam. She continued her postdoctoral research on coronary circulation for three years at both universities. Since 1992 she has been a researcher at the DUT Man-Machine Systems Group and since 2001 she has been a professor of biomedical engineering. She is cooperating with surgeons of several (academic) hospitals. Her interests and research projects are in the fields of medical instruments, training and simulation tools, and patient safety, with a focus on minimally invasive techniques.

Fig. 6. The Simendo for training basic minimally invasive surgical skills (DelltaTech and Delft University of Technology).

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Henk G. Stassen graduated in 1964 with a degree in mechanical engineering and in 1967 obtained a doctorate in control engineering, both from the Delft University of Technology. His academic career has been at Delft, first in control engineering and since 1977 as a professor of man–machine systems. He is a member of the Royal Dutch Academy of Science, the Dutch Academy of Technology, and the Dutch Investigation Safety Board. His research interests are man–machine systems and biomedical engineering (coronary circulation, endoprosthesis, and minimally invasive surgery).

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