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Review Article

Telerobotics in medicine and surgery

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Summary. The application of telerobotic technologies to medicine and surgery strictly depends on research and development in five main areas: functionality, environment, physical constraints, communication, and security. The clinical application of robotic technology in the field of microsurgery, orthopaedic surgery, and minimally invasive surgery has shown promising results, pushing researchers to further develop computer-aided surgery as well as diagnostics systems and microrobots. Telemanipulation, interface technologies, sensors, vision systems, virtual reality and function integration are employed to re-design the operating theatre, thus enhancing future applications of robotics in surgery. Because of the restrictions in the surgical field, the construction of miniaturized mechanisms is required, being grounded on different technologies: silicon micromechanics, surface micro-engineering and LIGA technology. Nanotechnology, memory alloys and superelastic materials are also employed. Other technological issues are: the communication of vocal, visual, textual and numerical information via cable, satellite or laser satellite transmission. Security and confidentiality of data are fundamental for telematics applied to medicine. Problems to be solved are the quality of image transmission and the signal delay as well as those related to working in a dynamic environment.

Keywords: robotics, telematics, telerobotics, telerobotic surgery, teleoperation, telepresence, virtual reality in surgery

Introduction

This review of telerobotics or, more precisely, of the applications of this science in the medical and surgical field, examines this topic from a different angle. Telerobotics has been considered not as a whole, but divided into five main areas – either functional or technical – which are at present the most relevant fields of research and development and also the key issues for the future application of telerobotic technologies in medicine and surgery: i.e. functionality, environment, physical constraints, communication, and security.

Robotics is the science which studies the functioning of devices which are able to automatically execute tasks usually performed and controlled by humans. The devices are connected to digital control systems and sometimes built by exploiting the technology of artificial intelligence. Robots are ideal tools to accomplish manoeuvres which are repetitive, monotonous, and tiring for a human, or manoeuvres demanding a very high degree of mechanical precision. Robots consist of three different components: the arm (with the actuator or manipulator), the execution device which drives the actuator, and a control device (microprocessor) which co-ordinates the other components.

This kind of robot, mainly employed in industries, should be differentiated from those to be used in surgery. Actually, only manipulators may be employed in surgery. These are mechanical or electromechanical computer-assisted devices which are directly controlled by the operator (surgeon). The continuous changes in a dynamic environment,

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Table 1. Sheridan/Satava classification of robotic technology and virtual reality

Teleoperation	One-to-one Master–Slave remote manipulation
Telerobotics	Master selects robotic pre-programmed task
Supervisory control	Programmed independent task is supervised by Master
Telepresence	Master has multisensory input and dexterity with illusion of being at a remote site
Virtual reality	Total sensory immersion in artificial world with illusion of being inside the 'world' and manipulation of imaginary objects

such as the human body, do not allow the use of conventional robots pre-programmed to execute the same task continuously.

The main components of a robot for surgical use are: manipulator, sensors, control system, high resolution video-system, and communication system for real-time operations.

Three different robot technologies may be employed in medicine and surgery: macro-robotics, micro-robotics, and bio-robotics [1].

With macro-robotics systems for hospital and patient care and rehabilitation such as manipulators and wheelchairs, have been developed. New surgical instruments and procedures may also benefit from macro-robotic technology. An example is UB Hand II, a robotic hand developed within the Finalized Project ROBOTICA of the Italian CNR (National Research Council) [2].

Micro-robotics is the technology of choice for the development of robots for minimally invasive surgery and a new generation of miniaturized mechatrons to be employed in conventional surgery. In the biorobotic area, robots "can be seen as a 'metaphor' of biological systems" [1] and represent a link between biological sciences and artificial intelligence. From the practical point of view bio-robotics may contribute to the development of new systems which may substitute or augment biological organs and/or replace human functions [1].

According to the technologies applied, the transmission systems and the interaction, Tom Sheridan from the Massachusetts Institute of Technology (MIT) and, lately, Satava have classified robotic technology and virtual reality as shown in Table 1 [3].

Functionality

Takeyoshi Dohi [4] divided robots used for medical and surgical purposes into several categories according to their function; his classification has been modified by introducing new types of robots (Table 2).

Table 2. Modified Dohi categories of robots for medical and surgical application

Field	Type of robots
Surgical operation	Micro-surgery robot Endoscope robot Orthopaedic surgery robots Minimal invasive surgery robot
Inspection	Sample operating robot Sample transportation robot
Basic research	Robot for cell operation Simulation robot
Education	Training robot for anaesthesia Training robot for emergency recovery Training and simulation robot for conventional and endoscopic surgery
Patient care	Nursing robot Robot for assisting the disabled

According to the modalities of their functioning the robotic systems and devices for surgical use are divided into two main classes: localisers and telemanipulators. The former are divided into passive, semi-active and active devices with the task to reach a well-defined point inside the human body (i.e. a tumour lesion) following the co-ordinates given by the surgeon. An example of robotic localisers is MINERVA, a robot developed by Glauser in Switzerland [5] and evaluated by Fankauser at the Department of Neurosurgery of the University of Lausanne. Another example of a pre-programmed localiser which is employed during laparoscopic procedures is the Automated Endoscope System for Optimal Positioning (AESOP) [6].

In contrast, telemanipulators are not pre-programmed to follow a defined path, but are directly controlled by the surgeon.

The application of robotics in surgery will be enhanced by the improvement of microrobot and biorobot technology.

Microsurgery

The first occasion in which robotic technology was applied in a microsurgical operation was for driving a puncturing cannula in brain surgery, as described by Kwoh *et al.* [7]. A small robotic arm inserts the cannula into the brain tumours, with three-dimensional positioning information acquired from multiple computer tomography (CT) scans (stereotactic positioning). Kosugi *et al.* [8] developed a puncturing cannula simulator which consists of a multi-joint arm (master arm) with an angle sensor and simulates the movement of the cannula during its placement [8].

MINERVA is a robot which may be pre-programmed by the operator using co-ordinates acquired by CT scans to localise a target in the brain and execute stereotactic procedures [5].

One of the most typical micro-surgical procedures is the corneal transplantation. Cutting the cornea is the key step of the operation and determines the degree of postoperative success. Teshima has shown the usefulness of robotic technology in this phase of the operation, through experiments carried out on porcine eyes [9]. The tip of the robotic arm, called trephine, has 3° of freedom and controls the blade movements while touching the cornea vertically, allowing a very gentle approach to the cornea, with a rotary motion.

Orthopaedic surgery

Hip-joint replacement is a successful field of application of image-guided robotic surgery. In this procedure a drilling robotic system has been employed, which is currently used in human trials (ROBODOC) [10]. The rationale for such a robotic application is that the correct positioning of the prosthesis is the most important step of the operation, with great impact on the longevity of the prosthesis itself. A robotic controlled drilling operation of the femoral bone may increase the precision of this manoeuvre by a factor of 50. This minimises bone erosion with benefit for the postoperative results. The procedure consists of manual guidance to the approximate position of preoperatively implanted pins, insertion into the femoral bone and fixing to the operating table, automatic tactile detection of each pin, computing all CT information and robot co-ordinates by the controller, and data transmission to the robot to create a precise implant cavity. After the removal of the guiding pins the operation is completed in the conventional way.

At present, a similar robot is under development at the Rizzoli Institute in Bologna by the group of Dario and SM-Scientia Machinale. This robot is designed to perform the bone resection step of the procedure during total knee-joint replacement [11]. Another prerobotic device (Robotrac) is used effectively in total knee arthroplasty, allowing the surgeon, by holding the femur in any position, to situate the knee with any flexion during the course of the procedure [12].

Minimally invasive surgery

Minimally invasive surgery (MIS) is one of the most interesting fields of application of robotics. MIS is based on three basic requirements: availability of high quality video-endoscopic images, use of high precision surgical instruments and high dexterity in the execution of surgical manoeuvres, with personnel which has to be specifically trained to improve their surgical skills.

The co-operation between the Research Centre in Karlsruhe and the University of Tübingen has contributed to the development of surgical manipulators with 6° of freedom (DOF) (the Advanced Robot and Telemanipulator System for Minimally Invasive Surgery, ARTEMIS, project) and electronic camera and instrument holders to be used during laparoscopic and thoracoscopic procedures [13, 14].

In 1994 Buess and Schurr successfully performed the first experimental laparoscopic cholecystectomy on swine, by means of a Master–Slave telemanipulator system [15]. Endoscopic telemanipulators have a modular architecture which consists of the following subsystems: manipulator, endoeffectors and instruments, three-dimensional video-endoscopic unit, sensors, intelligent control systems, modelling and graphic simulation facilities and man-machine interfaces [16]. All these components are connected through a Master-Slave system. More specifically the Master part consists of the control board, the man-machine interface with 3D video-screen and graphic simulation data presentation. The Slave part includes endoeffectors, 3D video-endoscope and sensors. This kind of surgical telemanipulator is technically feasible, but further developments are required to make it a safe and reliable system for clinical application.

Angelini and Rovetta carried out a research project based mainly on software and communication problems [17, 18]. Several experiments have been performed within this project: linking the Polytechnic of Milan and the University of Rome either by ISDN or satellite, using a Master–Slave robotic system. The last experiment was conducted in co-operation with the JET Propulsion Laboratory in Pasadena (1993). During this experiment the Master–Slave robot IBM SCARA – controlled by a dedicated software – was used; the surgical manoeuvres were executed by a surgeon in Pasadena, through a double satellite link, on a specially assembled dummy located at Polytechnic of Milan, containing a liver with an artificial cyst and coated with a ‘silicon sheet’; they consisted of two incisions into this artificial coat at suitable sites for the insertion of laparoscopic cannulae, and an ultrasound guided puncture and aspiration of the liver cyst. The distance between the two centres was 14 000 km and the overall back and forth distance run by the signal was 300 000 km [17, 18].

The camera driver AESOP is a computer controlled robotic arm (in fact mainly a manipulator) which is used to hold and move the laparoscope and allows to substitute the camera-operator performing his task under the direct guidance of the main surgeon.

AESOP is composed of an external unit and an electromechanical positioner. The external unit consists of a control computer, a power system, system indicator lights, and a power switch. The control computer is connected to all the system’s sensors and actuators and elaborates the surgeon’s commands transmitted through a foot and a hand controller. The program is memorized in a ROM and permits the maintenance of the data even when the system is switched off. The robotic positioner is attached to the operating table and holds and moves the laparoscope [6]. Other endoscope guidance systems have been developed by Buess and co-workers in collaboration with the Karlsruhe Research Centre (FIPS project) [19] and Begin and Gagner who adapted a 6 DOF robotic arm to a universal joint and the camera-optic assembly, with motion control exerted on the surface of a sphere [20].

New fields of application

Laser technology for medical treatments. Robots can be used to guide lasers. Loertscher *et al.* reported the application of a laser in cutting cornea for transplantation (FH laser with 2.7 μm wavelength) [21]. Kakimoto *et al.* developed a surgical system consisting of a measuring system and an incision system. The surgical operation field is measured by a two-axis galvanometer scanner using a He–Ne laser, and the incision is carried out by the same scanner using an excimer laser instead of the previous one. They evaluated this system during experiments on rabbit corneas with good results [22].

Hashimoto *et al.* showed another application for the laser, reporting the removal of liver tumours with a YAG laser and a shape laser probe. They reported that CAS systems may enable this therapy to be widely applied, safer and more precise, and proposed the application of robotic technology to puncture laser probes [23].

Computer-aided surgery (CAS) systems. The progress of medical imaging technology – above all CT scanning, MRI and ultrasound scanning – is astonishing. Conventional imaging techniques provide two-dimensional slice data. Three-dimensional reconstruction of these image data has been studied for exact positioning of a surgical target area. The development of CAS systems has the aim of using 3D imaging for planning and simulating operations and for assisting the surgeon performing surgical procedures. The combination of CAS system and robotic technology enables us to treat without laparotomy and thoracotomy diseases not previously treatable without open surgery, thus improving the quality of the patient's life [24–26].

Diagnostics. The possibility of application of telerobotics during interventional diagnostic procedures has been demonstrated by Pisani and Rovetta who performed a remote controlled prostate biopsy at the Department of Urology of the University of Milan [27].

This procedure was performed by a robotic manipulator controlled by a computer linked via ISDN. The robot provided with 4 DOF has an accuracy of 0.2–0.3 mm. Images from the four stereoscopic cameras positioned around the patient are visualized on the monitor of the computer. A transanal probe with the ultrasound transducer is connected to the robot and transmits the US scans to the computer monitor as a picture in picture. Once the target area for the biopsy is identified the biopsy device is activated by the computer. As result of this command the tru-cut needle is advanced into the prostate gland, a specimen is taken, and finally the needle is withdrawn.

The passage from diagnostics to treatment was made by Wickham and co-workers who developed a robotic system for transurethral electrovaporization of the prostater consisting of a motorized safety frame attached to an electronic gantry, a camera system, and a console housing computer, diathermy unit, US scanner and motion controller [28].

Microrobots. Coming from the research work carried on at the Massachusetts Institute of Technology (MIT), Artificial Intelligence Laboratory, which contributed to the development of Squirt, a robot about twice the size of a dime, provided with mobility and vision, a new microrobot, Cleo, has been developed, with the following features: 24 cm^3 in volume, 12 micro-processors, three micro-engines, two antennas with 16 sensors, and a micro-manipulator. In the future it could be possible to develop a similar but smaller robot to be used in the gastrointestinal tract in order to perform diagnostic endoscopy or endoscopic procedures such as snare resections of polyps [3, 29].

Another example of a surgical micro-robot is currently under development in Japan: a micro-catheter provided with tactile flow and pressure sensors, micro-nozzles and micro-pumps at the tip, which may be introduced into the lumen of brain blood vessels. The micro-catheter, which features a high dexterity tip, allows local release of drugs and solutions for thrombus dissolution [30].

In this respect, two main obstacles have to be overcome from the technological point of view: microrobots need to be further miniaturized and protected against physical and chemical agents present in the biological environment (acidity, humidity, viscosity, corrosive fluids, etc.).

Environment

The application of robotics to surgery will contribute to a revolution in the design of the operating theatre of the future. Buess and co-workers, expanding the concept of the OREST project [31] within the MINOS project are currently developing and evaluating a specialized OR system for endoscopic solo-surgery, using robotic assisted devices (Schurr, MIDSTEP Questionnaire).

The concept and the development of the telemanipulation technology in surgery have been translated from the industrial field. Manipulators are controlled through a Master–Slave type servomechanism. A Master–Slave system consists of a remote control unit (master) and a peripheral unit (slave) for the execution of specific tasks. The control unit is provided with a man–machine interface, while the slave unit is provided with an effector which practically executes any commands [32]. Sensors may also be integrated into the structure of a surgical manipulator. The employment of endoeffectors and endosensors, considered as a whole, may contribute to the construction of intelligent surgical instruments [33].

One of the main problems in the use of actuators and sensors in surgery springs from their miniaturization. Effector and endoeffectors have been constructed similar to the conventional existing surgical instruments. The main functions of these devices are grasping, tissue dissection, suturing, suction, rinsing, bleeding control, etc.

Sensors allow the operator to get information from the operative field such as mechanical pressure, applied forces – also called force feedback, which allows the surgeon to feel, e.g., the force exerted by the grasper to hold the tissue – speed, strain, acceleration, etc. Based on their function, sensors have been divided into: tactile sensors substituting the surgical palpation, diagnostic sensors for *in situ* diagnosis, sensors for the control of the telemanipulator and effector movements, and sensors for monitoring the telemanipulator functions.

Sensors need to be miniaturized because of the restrictions within the operative field. The technologies employed for this purpose are silicon micro-mechanics, surface micro-engineering and LIGA technology. Tactile, chemical, physical and electronic sensors can be constructed using all the above mentioned technologies.

In endoscopic surgery, current-generation vision involves 2D display on the monitor screen. Two-dimensional vision does not allow the direct perception of depth. The evidence of depth may only be indirect and mainly related to motion parallax and monocular cues. Three-dimensional vision systems provide the surgeon with a clear perception of the depth of the operative field. There are two methods to realise a 3D-video system: the field sequential video and the head mounted display. In both systems the images are usually displayed on video monitors and head-mounted displays; high-definition TV and holograms are other methods for displaying 3D video images currently under development [34–36].

Virtual reality has been employed to reproduce the real surgical world through multisensory inputs, allowing simulation of surgical procedures with the aim to replace the learning curve phase of surgeons in training. Virtual reality technologies may be applied to telerobotic surgery, allowing to redesign the control station [35–37].

High speed computing, intelligent information display, and sensors will be the building blocks of the operating room of the future. The concept of the future theatre is based on modular system configuration and function integration, but also includes the use of telemanipulation technology and existing technology from industrial and military fields, like the so-called 'smart materials' [38–41].

Control systems

Interface technology

Communication is the prerequisite of the man–machine interaction and may be achieved with several devices, such as key-board, mouse, joystick, trackball, drawing tablet, pen, with which conventional PCs are presently equipped. More advanced technologies such as voice recognition and optic recognition systems are technologically demanding but may be used more easily by disabled people. Intelligent interfaces can interpret, amplify and execute the operator's intents. Control by expert systems is more flexible, since no specified command is required and any action may be executed through different communication modalities.

In virtual reality the perceptions of the real world are represented through 3D dynamic images and sensory inputs. The aim is to create a close correlation between virtual and real world, acting on the former to produce effects on the latter. The operator is fully immersed in the virtual space or wears a stereoscopic helmet and virtual gloves which transmit both sensory inputs and the operator's commands. In this way, through the interaction with the 'artificial world', any command executed may be transmitted with high precision to a remote robotic arm. Therefore, in telerobotics, virtual reality is an interactive 3D graphic interface with a remote and real environment [42].

Computer graphics are a basic tool for creating high quality, extremely realistic images. The texturing facility may enhance the veracity of the reproduced images. Cell-texturing, an evolution of the above mentioned technology, allows the creation of 3D images, with consequent optimization of the working environment. Three-dimensional techniques may be used regularly for both diagnosis and therapy planning [43]. The 3D reconstruction may also be provided by multimodality integration, with CT and MR image fusion and MRA (magnetic resonance angiography)-DSA (digital subtraction angiography) image matching [44].

Augmented reality is a real-time technology for the superimposition of pre-recorded or elaborated synthesis images on real images, which enhances actual visual input with additional information. This type of man–machine interface may have several applications in telesurgery or robotic surgery, such as broadening of the operative field thus enhancing the space orientation of the operator. The man–machine interface is of paramount importance for the efficiency and safety of surgical manipulation. The interface may consist of a Master arm or a control lever, assisted by a vocal or visual tracking system. A universal Master arm has been developed, which may be adapted to any Slave systems through a dedicated software. A 3D video system allows the operator to monitor all phases of the surgical procedure. Textual information is needed at any time. Both this information and elaborated data are received in real time, enabling the surgeon to proceed with the operation. Computer Aided Design (CAD) is a graphic simulation and modelling technology which may be employed in the telemanipulation area. CAD simulation is based on different methods of reproduction for three-dimensional objects like the Constructive Solid Geometry (CSG), the sweep representation, or the Boundary REPresentation (BREP).

Kinematic Simulation, Monitoring and off-line programming Environment for Telerobotic (KISMET) is a simulation package developed in Germany at the Karlsruhe Research Centre. The applications of KISMET in endoscopic surgery are various: from the geometrical, kinematical and multi-body system dynamics analysis for the design and testing of surgical instruments to the planning of surgical tasks using interactive graphical simulation; from the creation of animations with documentation purposes to teaching and training. Last but not least, KISMET may provide surgeons with on-line support during operations thanks to additional visual and geometrical information [45].

The Green Telepresence Surgery System is one of the most advanced telesurgical systems under development. This system consists of a workstation equipped with stereoscopic monitors, stereophonic audio, and control manipulators with high dexterity and sensorial inputs. This system has been conceived to be used for remote controlled open surgery and, thanks to its features (tactile feedback, high dexterity, 3D-vision), does not require special training [46].

The intelligent Control and Monitoring System (CMS) is the connection and co-ordination unit between the master component and the slave component of a telemanipulator. An example of a control system is ARTEMIS, developed in Germany at the Karlsruhe Research Centre in collaboration with Buess of the University of Tuebingen. This system is based on the principle of the 'Universal Master' Manipulator cONtrol System Utilising Network technology (MONSUN). MONSUN is the result of the experience in the field of telepresence systems developed for nuclear and industrial applications and a realization of the 'open system concept' in computer science and communications as applied to robotics. The transmission of monitoring and control information is realized using standard Local Area Network (LAN) technologies. The ARTEMIS work units are controlled in Cartesian co-ordinates, and the returned data refer to Cartesian co-ordinates as well. Such a system has been successfully employed in experimental laparoscopic operations [13].

Physical constraints

Micro-mechanics

Micro-mechanics studies problems related to the construction of miniaturized mechanisms. These problems mainly concern the manufacture and assembly of micro-components to ensure their functioning. Two different technologies are mainly used to build micro-components: silicon micro-mechanics (similar to micro-chip technology) and LIGA technology. Present technologies still have several limitations, since, in the micrometer range, function and miniaturization vary in a non-linear way, with no direct correlation [47, 48].

Micro-mechatronics

The word 'mechatronics' was coined in 1977 by the Japanese Ministry of International Trade and Industry and means the combination of machines and electronics. Mechatronic products are 'mechanical devices which incorporate computation, sensing, actuation, and control'. Micro-mechatronics are micro-systems which combine mechanical and electronic components. One of the most important areas of application of micro-system technology is the manufacture of micro-sensors and micro-actuators [49–51].

A sensor is a tool which can recognise and measure non-electric phenomena, transforming them into electrical signals which may be digitalized, allowing subsequent data acquisition, control and regulation [52]. Sensors can be divided into: thermosensors, optical sensors (photodiodes, phototransistors, photoresistors, photocells, photomultipliers, quantum detectors, etc.), magnetic sensors (solenoids, Hall effect devices, magnetic resistors), mechanical sensors for pressure, position, proximity and rotation measurements (piezoelectric sensors, ultrasound sensors, encoders, etc.), and sensors for the measurement of environment phenomena (humidity, etc.) [52].

There are four levels of development in sensor technology: the first is that of simple analogical sensors; the second is that of sensors which integrate transmission functions; the third is that of digitalized sensors (the analogic signal is converted into a digital signal), the so-called 'smart sensors'; the fourth is that of fully integrated devices (application specific smart processors) [52]. Micro-sensors are miniaturized sensor systems. At present only chemical, biochemical and physical micro-sensors are available. The last type of sensor may be employed in both endoscopic and robotic surgery. They can measure temperature, pressure, elasticity, surface and optical parameters. An example of these micro-sensors is a micro-spectrometer which may be incorporated in an endoscope [53].

Actuators are components able to mechanically act on the environment in a controlled manner. Micro-actuators are miniaturized devices which may be employed in both robotic surgery and telesurgery and can be manufactured using either LIGA technology or silicon technology. Micro-actuators can exploit electrostatic forces with relatively high voltage. An example of a micro-actuator is a nickel microturbine, 130 micron in diameter, with a speed of 120 000 rpm. The principle of micro-motors is based on the attractive force of two electrodes charged with opposite polarities [54].

Another example of a micro-actuator is that based on fluidic drives. This micro-structure has both switch and action capabilities and may be employed as a pump or a moving mechanism with multiple applications in medicine, surgery and endoscopy (the moving mechanism is based on the 'inchworm' principle) [47].

According to the physical effects exploited for their functioning, microactuators are constructed with different materials: piezoelectric materials are employed to generate magnetic forces, magnetic materials are employed to generate electrostatic forces, bimetallic materials for hydrodynamic forces and intelligent gels and shape memory materials for thermal pneumatic forces [48, 53, 54].

Micro-systems

The concept of 'system' comes from Aristotle's statement 'The whole is more than the sum of its parts' [55]. Like other systems, micro-systems involve the construction of components and the study and solution of problems related to their relationships to each other. In the future, micro-systems technology will solve many technical problems of robotics, increasing the possibility of application in surgery [48, 55, 56].

As mentioned above there are three different technologies for the construction of micro-structures (which are part of micro-subsystems and micro-systems): (1) silicon micro-mechanics; (2) surface micro-engineering; and (3) LIGA technology [47]. Silicon micro-mechanics is closely correlated to micro-electronics, exploiting many technologies applied in this field. The principle of silicon micro-mechanics is based on anisotropic wet chemical etching, which allows the manufacturing of 3D silicon structures. With surface micro-engineering technology micro-structures are created directly on the surface of a substrate using thin film and special etching techniques. This method has the advantage of a free lateral pattern generation as well as the availability of multiple coating materials.

LIGA, an acronym for Röntgentiefen-Lithographie, Galvanik und Abformung technology is under development in Germany at the Karlsruhe Research Centre and is widely employed for the construction of micro-mechatrons for surgical applications. This technique involves three different and subsequent phases (X-Ray-Lithography, Electroforming and Moulding), from which the term LIGA derives; its advantage lies in the possibility of using a variety of materials (plastics, alloys, metals, ceramics) for the construction of microstructures. LIGA technology is a surface technology with the limitation, in its early stage of development, of only allowing the manufacture of 2D structures. Further developments in this area, such as the construction of objects using multiple radiograph sources, may allow to manufacture 3D structures. Silicon micro-mechanics and LIGA technology may be combined to build up LIGA micro-structures from fully processed silicon wafers, thus increasing the applications of microsystem technologies [47, 48].

Nanotechnology

The word nanotechnology relates to the research, development and application of lateral structures, multilayered structures, and surface structures on the scale of nanometer (less than 0.1 μm). There are two different ways to build up nanostructures: the top-down and the bottom-up approaches. The top-down approach involves the miniaturization of microscopic components by lithographic, chemical, and mechanical methods. The bottom-up technique involves the synthesis of 0-, 1-, 2- and 3D nanostructures from atoms and molecules, using multiple microscopic radiograph scanning. With this process nanostructures are built up from particles (quantum scale) isolated on a support and then arranged with ultrathin film technologies. Ultrathin films are transformed into 2D biocompatible ultrathin molecular films by the Langmuir Blodgett technology. Nanosized particles are consolidated into three dimensional nanocrystalline structures by high temperature sintering [57].

Because the physical and chemical properties of polycrystalline materials mainly depend on the dimension of the constituting microcrystals, and because lowering the crystallite size increases strength, hardness and low temperature ductility of the material, nanostructures may be employed in surgery to replace ceramics and noble metals when too high loads have to be bare [57].

Shape memory alloys and superelastic materials

Shape memory alloys have the characteristic of returning to their original shape after substantial, temperature-induced deformation. This group of compounds (like the nickel-titanium alloy known as Nitinol) may be useful for biomedical application such as the construction of specially designed surgical instruments. These alloys are originally shaped by a special metallurgic process. Those alloys with the property of exhibiting a shape memory effect can undergo reversible transformations passing from an austenitic phase to a martensitic phase. In the former phase the alloy is relatively stiff, while in the latter phase the alloy becomes malleable. The transformation between austenitic and martensitic cristalline structures entails the increase of ductility and may occur under temperature variation or application of external stress [58, 59].

While shape memory alloys recover their previous shape after heating above a certain temperature, superelastic materials, after being released from constraining means, recover their pre-stressed shape because of their elasticity. Superelastic materials can be strained without deformation much more than conventional metals and ten times more than ordinary springs. Any device built with superelastic materials can be deformed thousands of times, always recovering its original shape and never reaching the breaking point, thus enhancing its safety during use.

Also new polymers like polynorbonene have shown shape memory properties during the polymerisation process and are presently under investigation [32, 60].

Communication

Telematics

The term 'telematics' derives from the French word 'télématique' and means acquisition, elaboration, memorisation and diffusion of vocal, visual, textual and numerical information using a system composed of computers and communication media.

A network is a whole of inter-connected computers. These computers may be different from each other, featuring different power and computing capacities. There are also several ways of connection. The most diffuse communication system is the telephone line, through which data from the inter-connected computers may be transmitted.

An informatic network has many advantages: real time communication at any point of the network with possibility of exchanging or simply consulting data; sharing resources with access to dedicated sites/stations, specific applications or services; system inter-changeability which entails, as a consequence, that the network function is never compromised when a system breakdown occurs, since all functions may be replaced by another system; easy access to the network from any terminal provided with suitable connection.

Basically, there are two types of networks, with different features: local area networks (LAN) and wide area networks (WAN) [61]. LANs allow the inter-connection of computer equipment on a common bus over a distance of up to 10 km, within a private area. LANs have low costs, related only to the equipment used. Ethernet is the most widely used local area network in Europe; it works over a distance of 1 km. LANs have a higher speed than WANs, with a data rate of 10 Mbps. LANs are highly reliable with a very low error rate during transmission. When shared by several users, Ethernet LAN has user-perceptible transmission delay, which is a disadvantage for the remote control of robots. WANs allow the inter-connection of computer systems over a distance of hundreds or thousands of km, and the number of inter-connected computers is extremely high. Most WANs have a knitted structure. Lines for connection are usually provided by a public provider, therefore the use of WANs is expensive. This is the reason for connecting as many computers and systems to the same line as is technically possible. The network knitted structure guarantees alternative pathways in case of a single component failure and equal traffic distribution over several pathways. Most WANs have a data rate of 2 Mbps for long distance connection, with a not negligible error rate during transmission.

There are two functional levels of connection: logical and physical. Request, request interpretation, and answer belong to the logical level. Physical connection allows the physical data exchange through special devices which link systems to networks. A modem is the link device for telephone lines.

In telematics computers may be used as terminals or network nodes. The information processed can be divided as follows: information with a numerical pattern – the so called data – and information with an analogical pattern, that is sounds or images, which need to be converted and transformed into a numerical pattern.

Data transfer between computers requires special communication rules. This body of rules is called a protocol. Syntax, semantics and chronology are the main components of such a protocol. Based on the specific function, the Open System Interconnect (OSI) standard divides this protocol into seven levels. From the lower to the higher, they are: the physical, connection, network, transport, session, presentation, and application level [62].

Transmission

Data transmission may be realized through two main communication systems: dedicated lines and shared lines.

Transmission is also related to the medium of communication used: cable-transmission or radio-transmission. As mentioned above, the most diffuse communication system is that through the telephone line which may be realized with different modalities.

The analogic data transmission is the most widely used method of transmission, which entails the transformation of data into tones. A Modem (MOdulator.DEModulator) converts the binary numbers into tones and transfers them via the telephone line. To speed up the transfer, tones are converted into pulses, which are again converted into tones by the telephone exchange and, finally, into binary numbers by the receiving modem. Analogic transmission has several drawbacks which do not usually affect vocal communication, but which may alter data transmission. These problems are mainly related to the conversion of tones into electrical signals.

Compared to analogical transmission, digital transmission has a higher speed with a lower error rate. Even the digital signal may be disturbed during its transfer, but at the level of either the network amplifier or the terminal errors are removed by an analyser, thus reproducing the original signal with a high fidelity.

The Integrated Services Digital Network (ISDN) provides a digital connection from end to end. Its evolution is the B-ISDN (Broadband ISDN) network [63]. Being purely a digital connection, the data carried can be an integration of voice, text, and computer data. ISDN is a CCITT standard with minor differences in interpretation from country to country. Unfortunately, because of these differences, ISDN terminals designed for use in one country may not work in another. The introduction of ETSI standards CBR3 and CBR4 should solve such a situation. The intention is that any terminal equipment complying with these standards will be compatible with Euro-ISDN and will work in any country with a Euro-ISDN network.

The ISDN network transmits at 3.1 KHz and 7 KHz. There are two data rates available to users: the Basic Rate and the Primary Rate. The former comprises two channels, each carrying 63 kbps (B channels), and a third channel carrying 16 kbps (D channel); the latter comprises 30 B channels and two D channels. B channels carry the user data (voice, images, etc.), while D channels are used for signalling (dialling, engaged tone, etc.).

The Asynchronous Transfer Mode (ATM) is the future solution for broadband high speed services of telematic networks. ATM is a packet-based transmission technique. Thanks to the high speed made possible by fibreoptics, ATM networks allow simultaneous real time transmission of text, data, voice, and static or dynamic images. Data to be sent are packed into blocks or cells of 53 bytes. The network processes ATM cells one at a time. Cells can carry different types of data and originate from or be destined for different place/equipment. This freedom of multiplex cells results in flexible bandwidth. ATM networks accommodate all services regardless of their required bandwidth. The CCIT standard data rates for ATM traffic are 155 Mbps and 622 Mbps. ATM is media independent.

Radio transmission is based on the same principles, with the signal travelling through the air instead of cables. This kind of transmission is affected by a high rate of signal disturbances and is not indicated for long distance connections.

Satellite transmission

Satellite transmission allows a close-to-real-time signal (voice and data) broadcasting throughout the world. For satellite transmission stationary geoid artificial satellites, with a circular orbit of 36 000 km in height, are used. The time delay for the signal to go back and forth, taking into account the passage through the surface of receiving/transmitting stations (36 000 × 4 = 144 000 km to run), may reach 1 s, thus disturbing the quality of communication.

Receivers and re-broadcasting usually work on frequencies of 4–6 GHz, but frequencies may even extend from 12 to 14 GHz and from 21 to 30 GHz.

The advantages of satellite communication are: broad bandwidth (about 500 Mbps for the present satellites equipped with ten transponders, 48 Mbps each); extensive geographic covering; costs unrelated to distances; ease of broadcasting. Due to the considerable bandwidth and the broadcasting capacity, satellite communication is suited for multimedia data transmission. However, both

Table 3. Advantages and disadvantages of satellite transmission

Advantages	Disadvantages
Bandwidth: present satellites – ten transponders, thousands of vocal conversations, 500 Mbps	Broadcasting (data protection required)
Geographic covering	Eclipses
Costs not depending on transmitter/receiver distance	Atmosphere related noises
Easy broadcasting	Interferences with other radio signals
	Availability of spectre band
	Availability of stationary orbits
	Transmission delay

widespread covering and easy broadcasting carry the risk of interception, thus requiring the protection of transmitted data. Also, either satellite or sun eclipses may cause disturbances of satellite transmission. Other limitations of satellite transmission are mentioned in Table 3.

The development of the Very Small Aperture Terminal (VSAT) – which is less than 2 m in diameter antennas, easy to install, with 64 kbps transmission capacity – permits direct long-distance communication [61].

Laser satellite transmission

The Lasercom system is the latest development in the field of satellite transmission, born of the improvement of laser technology, and the increased reliability of lasers, even in the presence of sunlight. With this system, data, voice and image transmission is realized through a network of infra-red lasers with which several geoid satellites are equipped, allowing a much speedier transmission to and from any place on earth. Laser beams can transport information at a data rate of 1 billion bytes per second, that is 50 times the rate of present television satellites (20 Gbps). A further advantage of this system is that, contrary to what happens with present satellite networks, direct communication between satellites is possible, thus avoiding delays related to the passage of signals through a surface receiver. Since laser beams may be disturbed by clouds while passing through the atmosphere, the connection between earth and satellites is still realized via radio transmission.

Information highways

Information highways allow multimedia interactive information exchange. High speed networks are required, with digital data and compressed data selection. The number of services available is increasing progressively, with a relevant place for telemedicine and telesurgery services. With the application of new communication technologies, telephone lines will be provided with digital broadband connection and digital signal compression, thus allowing highly reliable transmission of a large amount of information.

A 'global village' will offer a number of benefits to the healthcare system. With the virtual cancellation of distances and time lapses, the efficiency of services like telediagnosis, telenursing or patient-telecare, as well as teletreatment/telesurgery will be enhanced or made possible. Telediagnosis comprises teleconsulting, connecting in real time several centres and making possible the transfer of expertise, locally not available, from remote sites. Telediagnosis is also a possibility to perform exams, like ECG and EEG, on patients in remote locations, without any need for experts or physicians to move from their hospitals. Patient-telecare comprises patient telemonitoring inside or outside the hospital, thus optimising patient admission and discharge. Teletreatment will be possible in situations and cases which do not require the physical presence of a physician (dialysis patients, oncology patients), while telesurgery with telementoring will bring expertise and skills to those remote sites or dangerous areas (ambulances, war fields, etc.) lacking them [64].

Security

Security and data protection

The security and confidentiality of data are basic elements of telematics applied to medicine. Security concerns the protection of any patient data record, while confidentiality concerns the degree to which medical information is broadcast. Specific laws are required to regulate data management and to guarantee data security and confidentiality in informatics and telematics; any data must be preserved – unaltered, undamaged and not lost – during any possible transfer.

On 22 September 1980 the Council of Europe approved the Convention on Protection of Persons Against Computed Personal Data Management. The countries which joined this Convention must issue laws which comply with the principles stated in the Convention [65].

Any information or telematic system is highly vulnerable. Data may be damaged or altered by active agents, such as viruses, or systems may be attacked by passive agents through 'spying' and the purloining of confidential information. Security is especially lacking in WANs where information is protected but at the same time shared among a number of users.

An information system for medical use contains in its memory banks patient data requiring maximum confidentiality, usually guaranteed by professional secrecy. In telemedicine this information may be transmitted to remote sites through telecommunication lines. This makes any data vulnerable from the point of view of confidentiality and security.

There are several ways to guarantee the integrity and confidentiality of data stored within an informatic or telematic system. The simplest and lowest level of protection is provided by computer operating systems which may request specific information or passwords to access the memory. Another method of protection is user-identification through magnetic cards, passwords, checks on personal characteristics, etc. Any of these methods has advantages, but none of them ensures 100% protection. A more advanced system for data and network protection uses cryptographic technology.

In 1986 MIT, which has a local network linking more than 25 000 computers, adopted a security system called Athena that employs the Kerberos authentication system. This system uses cryptographic technology and the Data Encryption Standard (DES) to exchange cipher information before permitting access to server and network. The above mentioned safety system is also adopted in Internet [66].

Transmission related problems

Telematics technology for diagnosis and treatment (operations via telesurgery) poses other problems of data transmission regarding both the quality of the transmitted images and the time lost in transmitting them. Even more important is the time lapse between the transmission of a long-distance command and the moment when it is really performed on the patient. From the technical point of view, these problems are mainly related to data compression and decoding, as well as signal delay. Moving Picture Experts Group (MPEG) is a standard for image compression, based on Joint Photographic Experts Group (JPEG) algorithms: this transforms a RGB signal into a YUV signal.

MPEG provides a good solution to the problem of compression of motion images, since it allows only the transmission of dynamic objects, thus avoiding the continuous transmission of static objects. MPEG 2 compression allows compression with a 200:1 ratio. The advantages of MPEG 2 cover both the enhancement of the compression capacity and the possibility of eliminating any redundancy within a single frame and between different frames. MPEG is the compression standard used for satellite transmission to transmit several signals on the same band.

The time lapse between the long-distance command and its execution may be potentially dangerous, particularly when satellite transmission is used for telesurgery, since the received image of the operating field is not a true real-time image of the moment when the surgical act is actually performed. The operating field (relationships between anatomical structures) may have changed, due to inadvertent movements, breathing, heartbeats, hiccups, etc. The need for integrating safety mechanisms (feedback, alarms, automatic stop devices, etc.) into the system derives from these facts. This will ensure the dependability of any technology possibly employed during a medical treatment and avoid inadvertent damaging of anatomic structures during telesurgery manoeuvres.

Problems related to a dynamic environment

The development of man–machine interface technologies which provide the operator with suitable visual and sensory information, similar to those perceived in conventional surgery, is the solution of most problems related to the work in a dynamic environment. Prerequisites will be optimal visual control, enhanced by image acquisition and processing from CT and MR images, stereoscopic vision, and the integration of real images and pre-recorded synthetical images. Sensory information and force feedback from the remote environment have to be transmitted with suitable speed and interfaced at the control system level to allow real-time reaction of the operator in both routine and emergency situations.

The security systems are important sub-systems in telerobotic surgery. They should detect functional failures at any level of the whole system and react according to the situation. Automatic hardware control allows prompt interruption of any action of the machine, with the possibility of switching to manual control.

Conclusions

The use of artificial intelligence technology and expert systems in this field of research will implement results to the maximum.

Table 4. Existing research projects in telesurgery based on telemanipulation

Product	Classification	Value added	Development status	Limitations	Future needs
SRI (Stanford Research Institute) Telepresence Surgery Systems	Telemanipulator	Allow new procedures Increase access	4 DOF Prototype validated	DOF Latency HCI	Networking HCI optimisation Tactile/Haptic
JPL (Jet Propulsion Laboratory–NASA	Telemanipulator (micro-ophthalmic)	Improved outcomes Enhanced dexterity	?	?	?
MIT (Massachusetts Institute of Technology)	Telemanipulator	Improved outcomes Enhanced dexterity	?	?	?
MIC Tübingen/Karlsruhe	Telemanipulator (MIS)	Allow new procedures	Prototype	No force feedback HCI	HCI Force feedback
University of Rome 'La Sapienza'/ Finsiel (MIDSTEP)	Telemanipulator	Expertise to remote sites (decrease costs)	Prototype four sites/two systems	Data security Liability (medico-legal)	HCI optimisation Image registration

Table 5. Existing research projects in telesurgery based on teleconsulting

Product	Classification	Value added	Development status	Limitations	Future needs
UVA/VNI Telesurgical Microscope	Telementoring/ teleconsulting	Increase efficiency of specialist surgeon Training	Simulation (Telegrip) Components selected	No manipulation	Simple manipulation of OR field
John Hopkins/ICE	Telementoring/ teleconsulting	Training Decrease costs	Clinical trials Incorporating aucillary devices	No manipulation Video display resolution Latency	Eval latency effects HCI Incorporate other devices Teleanesthesia
US DOD (US Army)	Teleconsulting (Bosnia–US) MIS	Decrease costs (patient transfer)	System installed COTS	Communication access Not validated with actual cases Improvised access scheduling	Network management Support software
US DOS (US Army)	Teleconsulting (dentistry)	Access to specialists Decrease evacuation needs (cost)	Intra-oral camera available	As above	As above

In Asimov's first law of robotics it is said: "[the] robot cannot permit the human being to be damaged anyway, because of malfunctioning or lack of intervention". Robots should be provided with intelligent control features to improve safety. Dockery *et al.* say that the use of artificial intelligence, advanced machine-environment interfaces, and patient care technologies will contribute to a new generation of Intelligent Assistive Technologies (IATs) [67]. There are three levels of IATs: from the first level, based on the present technology integrated with an intelligent database – exploited in some educational projects [68] – passing through neural networks, to the last and as yet utopian level of Intelligent Virtual Reality (IVR), which will originate from the combination of artificial intelligence and virtual reality technologies [67].

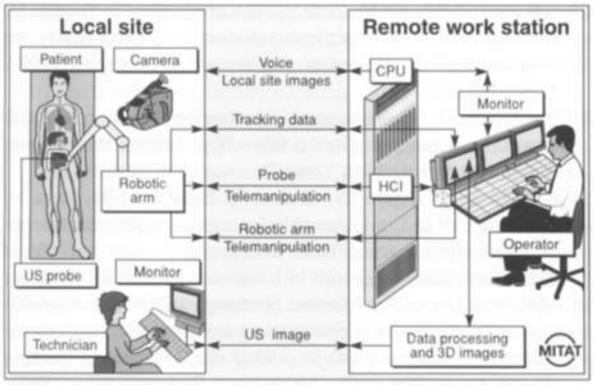

Figure 1. MIDSTEP Project: representation of the robotic system for teleinterventional ultrasonography, in course of development. The realization of the demonstrator involves research and development work in the fields of image acquisition, image processing, network systems, robotics, human computer interface, security systems and integrated systems.

It is a matter of fact that telerobotics will be more and more applied to medical and surgical practice. Tables 4 and 5 show the research projects in the area of telepresence that are presently carried on in several centres world-wide.

In 1996, the first research project on teleinterventional ultrasonography was started, funded by the European Union, which involves 11 industrial or clinical partners and gathers together experts and researchers from six European countries (Figures 1, 2). Such a widening in the applications of these technologies necessitates considerable efforts to implement the standardization of all related technical issues and to solve a number of non-technical issues such as: cost benefits analysis; psychological, physiological, and legal acceptance by patients, physicians, hospital boards, regulatory bodies; definition of regulatory issues and liability.

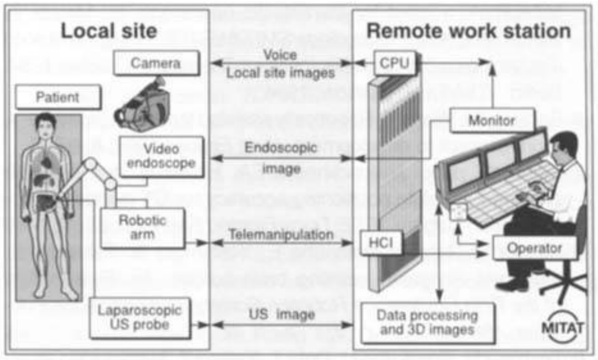

Figure 2. MIDSTEP Project: representation of the robotic system for remote controlled laparoscopic ultrasonography. Contrary to the system for teleinterventional ultrasonography, this demonstrator is conceived to be used within a local area network.

An important step forward is the creation of international task-forces and the organisation of international workshops with the aim of focusing and examining needs and requirements of these technologies and proposing solutions for all relevant issues, addressed not only to future researchers, but also government bodies. Following this approach, in 1996 two important meetings were held: the Robotics and Computer Assisted Medical Interventions (RCAMI) international workshop [69] and the SMITROB constitutional meeting. SMITROB (Task-force Robotics and Microsystems in Minimally Invasive Therapy of the Society of Minimally Invasive Therapy – SMIT) is presently proposing the development of test criteria for the standard evaluation of robots and manipulators for medical use, the definition of quality and safety standards for robotic application, the assessment of technologies and the evaluation of cost-benefits of robotic applications in medicine and surgery, and the improvement of dialogue among researchers and scientists working in this area (Schurr, personal communication, SMITROB constitutional meeting, Cernobbio 18 September 1996).

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