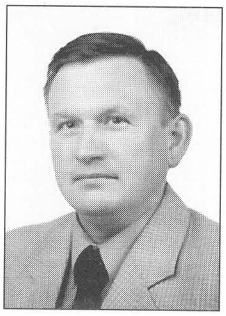
Jacek CIEŚLIK
AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF MECHANICAL ENGINEERING AND ROBOTICS,
DEPARTMENT OF ROBOTICS AND MACHINE DYNAMICS

New tools for medical robots



Dr inż. Jacek CIEŚLIK

Graduated at AGH-UST in mechanical engineering. Awarded Ph.D. (1990) from the AGH-UST on Vibro-Acoustics (Usability of Sound Intensity Methods in Vibro-Acoustic Investigation). Published: 90 papers in Journals and Refereed Conference Proceedings in the field of Acoustical Engineering and Vibration Control, Mechatronics. Author of 9 books on Acoustics and Mechanical Engineering, 2 patents. Full Member of the Polish Acoustical Society, Polish Society of Theoretical and Applied Mechanics. Major scientific interests - energy methods in structural acoustics, theory of machines and mechanisms, mechatronics in education and medical applications.

e-mail: cieslik@agh.edu.pl

Abstract

During last two decades minimally invasive surgery (MIS) has become the principal method for many surgical operations. Contrasting open surgery, MIS only needs small incisions in the patient's body. This leads to a radical reduction of tissue trauma and therefore shorter healing times. In the beginning surgeons had to manage with limited manipulation area of the end-effector and poor visual feedback. These drawbacks were overcome by introduction of dedicated robotics systems. Despite the advantages the systems offer, there are also needs of surgeons that have not been met. The most essential issue is the lack of sensitive force feedback. This often leads to unpleasant side effects like damaging thread material or even lacerating healthy tissue. It results in fatigue of the operator, due to visual compensation of the missing haptic feedback. Inclusion of force feedback in systems for robotic surgery is thus a fundamental factor in improving reaction to tissue contact. The main target is to provide the surgeon with an operation environment very similar to manual instrumental surgery (i.e. the surgeon can feel forces exerted on the instruments). For that reason some examples of work done by the different research centers in this field are presented.

Streszczenie

W ciągu minionych dwudziestu lat chirurgia minimalnie inwazyjna (MIS) stała się podstawową metodą dla większości operacji chirurgicznych. W stosunku do tradycyjnej chirurgii MIS wymaga wykonania kilku niewielkich otworów w ciele pacjenta. To skutkuje w zmniejszeniu bólu i urazów pacjenta oraz szybkim powrotem do zdrowia. Początkowo chirurdzy musieli zmagać się z ograniczonym polem operacyjnym narzędzi oraz niedostateczną widocznością tego pola. Te przeciwności zostały pokonane przez wprowadzenie specjalistycznych zrobotyzowanych systemów. Oprócz zalet, jakie posiadają te systemy, istnieje szereg niespełnionych jeszcze oczekiwań chirurgów. Podstawowym problemem jest brak sprężenia zwrotnego siły wywieranej przez chwytak. Prowadzi to często do niepożądanych skutków ubocznych przejawiających się w zniszczeniu nici chirurgicznych lub zdrowej tkanki. Prowadzi to do zmęczenia chirurga wywołanego wytężoną obserwacją narzędzi będącą skutkiem braku odczuwania siły nacisku. Włączenie sprężenia zwrotnego siły w układzie robota chirurgicznego jest wiec podstawowym czynnikiem poprawiającym kontakt z operowaną tkanką. Głównym zadaniem projektowym jest zapewnienie chirurgowi podobnych warunków na polu operacyjnym jak dla operacji wykonywanych ręcznie (tzn. odczuwania sił wywieranych na instrumenty). Przedstawiono wyniki prac nad wykonaniem takich narzędzi przez kilka ośrodków badawczych.

1. Introduction

The new surgery techniques introduced into medical practice significantly changed the quality of life after surgical procedures. Some earlier complex operations have become a routine in modern medical centers being done often as an ambulatory treatment. A huge amelioration, apart from technical improvements in the operating room, was brought by introduction of the minimally invasive surgery (MIS) in the 1980s. In contrast to conventional open surgery the operation area is accessed through small incisions. Two of them are used for instruments; one for endoscope and the additional one sometimes is used for CO_2 insufflating. There are obvious advantages compared to open surgery: reduced trauma and pain due to the smaller incisions and shorter rehabilitation time which results in shorter hospital stays. The surgeon has to deal with orientation problems due to reduced sight, finding anatomical structures often becomes a challenge. The instruments have to be handled around so called trocar points on the patient's abdomen, restricting the degrees of freedom inside the body to four and resulting in a reverse hand motion. The surgeon's hand tremor gets amplified by the long instruments, and there is no haptic feedback, compensating its absence visually has been found quite fatiguing.

2. Robotic Surgery Systems

During the 1990s several robotic systems for surgery leaved research institutes and entered dedicated medical centers for evaluation purposes or even daily practice [1, 2, 4, 8, 9]. The first application area is represented by the systems Caspar™ from Universal Robotic Systems Ortho GmbH and Robodoc™ from Integrated Surgical Systems. Integrated Surgical Systems provides also the system NeuroMate™ which together with PathFinder from Armstrong Healthcare Ltd. represent robotic neurosurgery. The two most technically mature systems are Zeus™ from Computer Motion Inc. and da Vinci™ from Intuitive Surgical Inc., described here in more detail. Both are general purpose teleoperation systems for abdomen and thorax surgery, but mainly evaluated in the field of heart surgery. There is on both systems only position control possible and therefore no autonomy can be achieved. None of them provides instrumental side force/torque sensory, nor (the possibility of) haptic feedback at the master console. Motion scaling, tremor filtering, optical magnification and stereo vision are available with both systems. The instruments differ in the number of degrees of freedom; the da Vinci system has 7, while the Zeus setup has only 6.

When performing telesurgery with the da Vinci system, the surgeon sits at the surgeon control console, head tilted forward and eyes peering down. During the procedure, the surgeon's hands are held in a comfortable position and inserted into the system's master interfaces. A computer is used to monitor hand positioning, which is sampled at > 1,300 times per second as the case proceeds. Using motion sensor information and kinematic models of the master and slave, the computer system issues the actuator drive commands necessary to move the robot arms and provide feedback. The position of the endoscope camera, mounted on a robotic arm, can be adjusted by the surgeon for the best view of the surgical site. Accurate visualization is critical because visual cues are used to compensate for the loss of haptic feedback. The visual magnification (x2 to x10) is matched by hand-motion scaling capabilities. This increases surgical precision and fine motor control by reducing the surgeon's large hand movements to the scale of the camera view. Normal hand tremors are filtered simultaneously while permitting natural hand movements much like open surgery.

When viewing the surgical field through the console, the surgeon can see the end-effectors of the robotic arms (the instrument tips). The surgeon receives some force sensation, or haptic feedback, from the instruments. This feedback is limited to interaction with rigid structures, such as tools collisions, and not soft tissues. The surgeon relies on visual feedback in tasks such as suturing. Careful attention must be paid to visual cues when pulling on a suture, or it will easily break before the surgeon feels the excessive tension.

A small mechanical joint called the EndoWrist (Intuitive Surgical) is a key component of the system. The highly mobile EndoWrist gives the surgeon the ability to reach around, beyond, and behind. The motion of the EndoWrist is monitored by the computer system so that the control algorithms can translate the surgeon's motions to the robot's wrist. The system translates the surgeon's hand movements into the same movements of the instruments (Fig. 1), avoiding the reverse-fulcrum-induced movements of traditional MIS. The wrist can roll, pitch, yaw, and grip, allowing the surgeon a total of 7 degrees of freedom for each hand. The system can apply a force being the fraction of newton for delicate suturing upto the several tenths newtons necessary to retract large tissue structures.

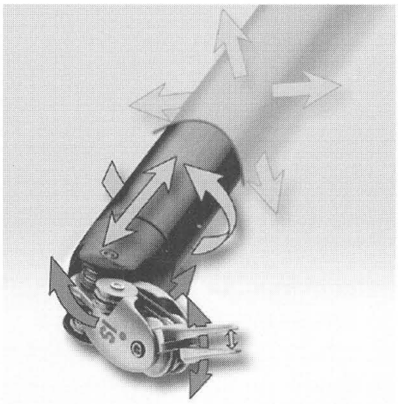


Fig. 1. Robotic gripper EndoWrist (da Vinci, Intuitive Surgical) with 7 degrees of freedom driven by the system of wires. The first 2 degrees of freedom (DoF) are the ability to pivot about the entry port in 2 planes *(hatched arrows)*. The next 2 degrees are the facility to move in and out as well as the ability to roll the instrument *(light gray arrows)*. The final 2 DoF are the ability to pitch and yaw the wrist *(dark gray arrows)*. These 6 DoF allow for an arbitrary choice of position and orientation of the jaws, which is not possible with conventional endoscopic instruments. Final small bidirectional arrow is for grasp, which is the seventh DoF.

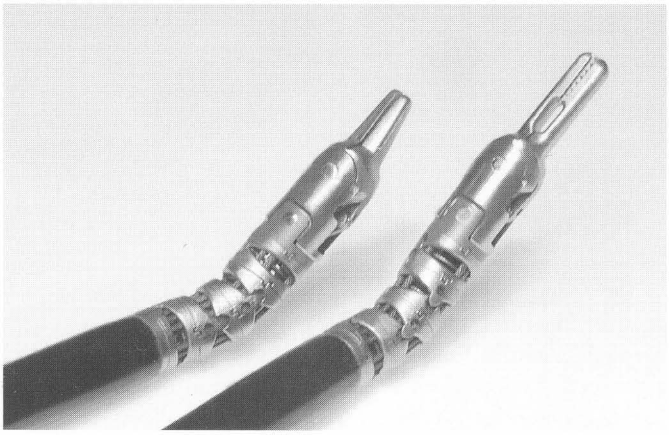


Fig. 2. Robotic gripper da Vinci (Intuitive Surgical) with increased degrees of freedom driven by the system of wires and less diameter.

The instrument end-effectors, are a combination of standard surgical instruments and novel mechanism designs. Conventional surgical instruments are the result of 150 years of surgical experience in manipulating and cutting various types of human tissue. Therefore, the very ends of the instrument tips are made to look like conventional instruments used in open surgery, while the rest of the design is entirely new. The instruments can be sterilized and interchanged during surgery. Central to achieving adoption of a technology is that the instruments provide surgeons with a feeling and performance similar to their traditional instruments. In its current configuration this surgical device is unlike most industrial telemanipulators. Recall that an important driver of industrial devices was the essential need to separate the master controller from the slave end-effector for safety reasons. Current conventional surgical applications find distance separation a distinct disadvantage. The surgeon at the controller console, assisting surgeons, and nurses at the patient's side interact frequently with the slave end-effectors, removing and changing surgical instruments. This requires very safe and human-friendly engineering in the tool interface. Telerobotic surgery also requires a fundamentally different priority. Most industrial telerobots have simple safety systems that protect themselves in the event of failure. In less complex applications, the robot is the high-value item. A telesurgical system has to protect the patient first.

3. Future of robotics in surgery

However, to build on past success and to fully leverage the potential of surgical robotics in the future, it is essential to maximize a shared understanding and communication among surgeons, engineers, entrepreneurs, and healthcare administrators. Robotic surgery has demonstrated some clear benefits. It remains to be seen where these benefits will outweigh the associated costs over the long term. In the future, surgical robots should be smaller, less expensive, easier to operate, and should seamlessly integrate emerging technologies from a number of different fields. Such advances will enable continued progress in surgical instrumentation and, ultimately, surgical care.

New applications of the technology are beginning to emerge as creative surgeons do their work; unpredicted uses in areas such as urology as well as bariatric and plastic surgery have been found. Giving the surgeon the ability to control >2 arms has proved to be unexpectedly useful, essentially allowing surgeons to become their own assistant. Nevertheless, present-day robotic surgical systems have limitations that have slowed the widespread introduction of the technology. A major barrier is cost. A second major concern is the cumbersome and unwieldy nature of robotic systems that require considerable space and additional tune for setup. In the time-pressed operating room, compact functionality is highly desirable, and current robotic systems have yet to deliver in this regard.

Another area that will require optimization is the process of approval of safety and regulatory issues. It has been a challenge for robot manufacturers to convince the law regulatory that these systems are acceptably safe. Progress needs to be made, for example, in defining what it means to be safe with highly mobile electromechanical devices. This is difficult enough when real-time human judgment is still in the loop, but when progressively more autonomous capabilities are introduced, even more difficulties will arise in setting standards of acceptable risk.

The future robotic surgical systems will begin to provide a centralized platform within which existing and emerging technologies can be used. It is quite easy to imagine integrated imaging, navigation, and enhanced sensory capabilities being available in the next generation of telesurgical systems. Equally reasonable will be the introduction of general skill-training simulations and patient-specific rehearsal capabilities.

Another major progress in robotic technology will be a reduction in the scale at which these systems operate. Present-day systems have increased surgeon performance in existing procedures; however, the physical scale is largely unchanged from conventional manual procedures. Robotics has the potential to greatly scale down a surgeon's motions so that, in cooperation with the computer, surgical manipulations on a microscale would be possible. This would enable performance of procedures that are currently impossible given human force and position resolution. Progression in the miniaturization of robotic mechanisms will most likely require entirely new materials and manufacturing processes combined with scalable designs to ensure performance and ease of assembly.

Smaller mechanisms will lead to many new applications for robotics in medicine. Catheter-based treatments could benefit substantially by integrating robotic technologies to create "active catheters" with a high degree of control. An active catheter could be steered with much greater accuracy than that of a passive, undercontrolled catheter. Such a device might be useful in minimally invasive diagnosis and/or treatment of deeply remote anatomy that would be otherwise impossible to reach. This trend toward less invasive, more specifically targeted surgical treatments has been in motion for some time. Surgical treatments have increasingly become more focused, and smaller robots are just the next step in that journey.

To operate a miniature robotic device, sensors and actuators on an even smaller scale will be necessary. Recent advances in the area of microelectrical mechanical systems (MEMS) offer promise for fulfilling this need. MEMS are integrated microdevices that combine electrical and mechanical components. These working machines have gears no bigger than a grain of pollen, and current technology permits them to be batch-fabricated, tens of thousands at a time, at a reasonably low cost for each device. Systems can sense, control, and actuate on the microscale, and function individually or in arrays to generate effects on the macroscale. The technology has been used to build devices such as microengines, microtransmissions, microlocks, and micromirrors. Current applications in industry also include accelerometers, pressure, chemical and flow sensors, micro-optics, optical scanners, and fluid pumps. It is clear that these types of sensors could have important medical uses, from providing force feedback with a microforce sensor, to measuring bio-chemical data and overlaying it on a visual image to identify hidden infection.

With regard to force feedback, the inclusion of high-fidelity force sensors has the potential to improve force sensation beyond what the human hand can sense on its own.. For example, surgical ablation of larger tumors in the abdomen or lungs is often performed with an ultrasonic cutting instrument or radiofrequency ablation. A force-feed-back type probe would be beneficial here in identifying the edge of the tumor to ensure complete ablation and to protect healthy tissue.

An important component of robotic system is its computational capabilities. Much research effort has been put forth in using computation to give artificial intelligence (AI) behaviors to robots. One of the primary motivations for developing AI applications for medicine is to keep physicians from having to learn through making mistakes while performing critical tasks. Heuristic knowledge, or the ability of system to learn based on real life experiences, is the basis for AI. Future directions for AI include neuromorphic engineering, genetic algorithms, and artificial evolution. The combination of these techniques holds promise for developing robots that learn, remember, and even evolve.

Finally the notion of the development of active and autonomous tools deserves exploration. Developments in this area may be far off, but they would revolutionize surgery by using a robot to autonomously perform intricate but widely varying tasks with a high level of responsibility. This will require considerable algorithm development and expansion of computing power, but given the progress in the past 50 years, this does not seem unreasonable. New issues in terms of ethics and standards would then become even more relevant.

4. Examples of new surgical robots grippers

Some end-effectors of surgical robots are equipped with additional DoF. The total number of DoF including the shaft of the surgical instrument often increases over 10. This makes the gripper mechanism redundant enabling the highly efficiency in operational field. Different important problem is the placement a force and torque sensors, possibly close to the tool tip [3, 7].

Developed at the Technische Universitat Munchen, [5], the Endo[PA]R (Endoscopic Partially Autonomous Robot) system is an experimental setup with interesting feature, the capability of providing the user with haptic feedback. Since the shaft of the surgical instrument (da Vinci) is made of carbon fiber, force sensors are very sensitive and reliable and applied directly on the shaft of the instrument. As shown in Fig. 3, the strain gauges sensors are applied at the distal end of the instrument's shaft, i.e. near the gripper. At the top of Fig. 3, one can see the perpendicular arrangement of strain gauges as full bridges. One full bridge of sensors is used for each direction. The signals from the sensors are amplified and transmitted to a PC system. Since the position and orientation of the instruments is known, occurring forces are transformed back to the coordinate system of the robot devices. The user has the impression of direct haptic immersion.

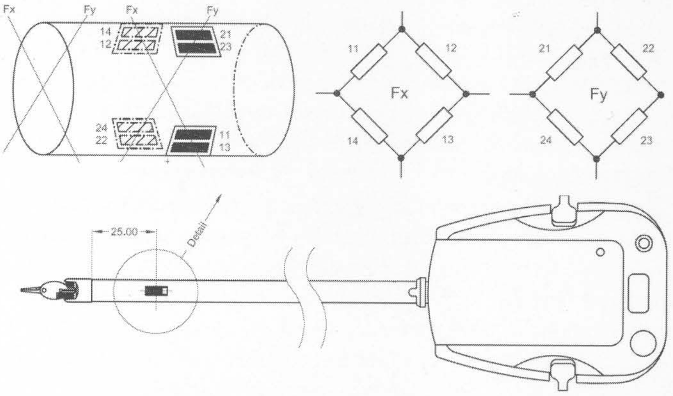


Fig. 3. Application of Strain Gauges to da Vinci instrument

Another solution of sensorized forceps elaborated at the Technical University of Munich [6] is shown on Fig. 4 and 5 - a pair of for-ceps with two additional actuated degrees of freedom near the tool tip. This enables the surgeon to move the instrument's tool tip in 6 DoF inside the human body. The drives for the joints and the for-ceps themselves are realized as electromechanical actuators and are located outside the body. As the instrument is equipped with sensors close to the tip, real manipulation forces are measured. Figure 3 shows a CAD model of the tool tip and Figure 4 shows the first prototype. The forceps have a diameter of 10 mm. Forceps can handle forces up to 10-15 N and can be sterilized [6].

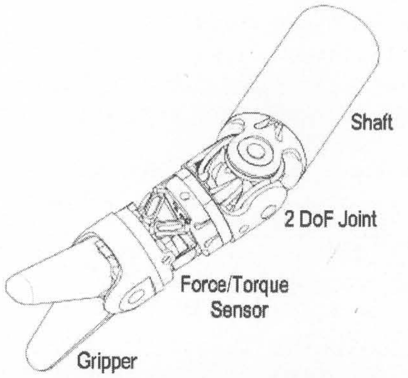


Fig. 4. CAD model of the tool tip with hexapod and force/torque sensors

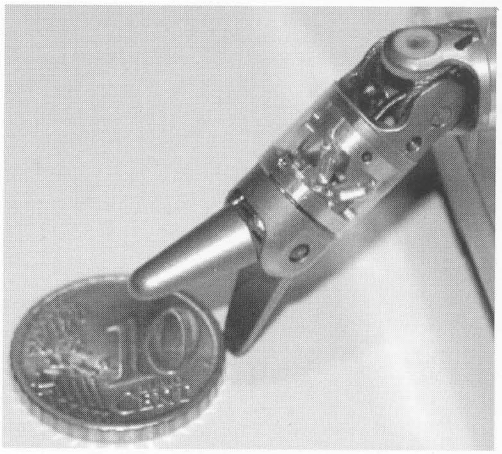


Fig. 5. Prototype of forceps with force/torque sensors

One of the most difficult operations, due to the lack of dexterity of conventional systems, is suturing with needle and wire; the arms with grippers have to mime the movements of the surgeon fingers.

5. Comparison actuators for robot gripper

The main expectations for the surgical robot gripper are: 40 N grasping force, 10 mm external diameter, about 25 mm length, possibility to work in an humid environment, high reliability and body compatibility. Nowadays many new design of grippers reject the cable actuation, despite it is widely used in the surgical field, for two reasons; it is difficult to embed the cables inside a poll-articulated miniature arm. Besides the cable actuation, high grasping force, can affect the global rigidity of the arm. The three types of other actuators are considered: electric motors, piezoelectric and shape memory alloys (SMA). Each of them has certain disadvantages and problem needs to be solved. The main target is to reduce the size of actuators.

In general there are many other kinds of actuators that can be used for the design of small elements of surgery robot. To each of the actuators corresponds a proper size that guarantees optimal energy efficiency. For each actuator it is important to take in consideration its performance, efficiency, easiness of use, power requirements, actuator machining costs and on site performance. To facilitate the actuators selection is provided Table 1.

6. Conclusions

Many of these emerging technologies have dedicated research and development groups working feverishly on the next stage of evolution. For these developments to be really relevant in surgery, however, they will require input and guidance from the clinical community. The surgeons' role in this technology is to educate and collaborate with technical developers, and to find and refine areas in their own specialties where these technologies will be useful.

On the other end of the spectrum, there are now a group of engineers coming to be known as "clinical engineers," who have a technical background but are also educated in clinical applications. They may serve as the intermediary between surgeons and other engineers. This educational cross-pollination must continue, preferably at an increased rate and in a more structured manner. Only then will each community be able to respond to one another's needs, requirements, constraints, and philosophies sufficiently to pave the path toward advancing the state-of-the-art of surgical intervention and, ultimately, enhancing patient care.

Today's medical robots already do work in surprisingly useful ways and yet comprise a technology only in its infancy. Tomorrow's medical robots will deliver functionality and breadth of utility beyond our current dreams.

7. References

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Tytuł: Nowe narzędzia robotów medycznych.

Artykuł recenzowany

Table 1. Characteristic of actuators possibly to apply in surgical robots

Actuator	Main use	Advantages	Disadvantages
Piezoelectric	Rotation, translation and deformation	• High torque at low speed and high holding torque at zero power (ultrasonic) • High bandwidth (kHz) • High power/weight ratio	• High voltage and special waveform required. • Have low strain, rotation and deformation (% 0.1)
Electrostatic	Rotation	• High torque at low speed • Easy to produce and use	Motors have only micron size
Magneto- and electro-strictive	Translation	• Some electro-strictive polymers have muscle-like performance (high power/weight ratio)	• Magneto-strictive have low power/weight ratio, low displacements, are difficult to use • Electro-strictive polymers are new and not sufficiently tested
Shape Memory Alloy	Translation deformation	• Simple and robust • High actuation force • Simple two-state (on/off) action • Relatively high elongation • Easy to install, to produce and to use	• Low strain (% 4) • Low bandwidth (< 1 Hz) • Inefficient with batteries • Requires complex mechanism for position control • Not usable in all environments
Electro- and magnetorheological	Viscosity change	• Simple to use • High bandwidth	• High voltage required • Transmit, doesn't make power • Still at study level
Electro-Magnetic	Rotation	• Different size and types available • Commercial products are easy to produce • Easy to use, to control • Reliable	• Requires gearbox and some electronics • Low efficiency
Fluid	Translation deformation	• High force and displacements	• Difficult to control • Pumps are voluminous
Thermal	Translation deformation	• High power/weight ratio	• Low displacements