

In-space surgery: impact of robotic technology on future exploration missions

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Abstract

Human space flight projects have always been cost demanding due to the increased security measures required to keep the astronauts safe. The continuous development of robotic technology still does not allow us to completely replace humans; however we can provide them with additional support not only throughout the exploration tasks, but also in maintenance, life support and space medicine. Teleoperated surgical robotic systems offer a technological solution to replace or greatly enhance the capabilities of flight surgeon on board of any spacecraft. High fidelity intervention, better health care support and patient care can be achieved. There are several limitations of these systems at present, but already capable of surpassing conventional methods. In addition to presenting the most advanced systems, the paper gives a survey of the most important technological limitations and outlines the concept of a future robotic support mission.

1. Introduction

Human space exploration was given a new boost by targeting again the Moon and the Mars. U.S. President George W. Bush announced first in 2004, and then Michael Griffin, Director of National Aeronautics and Space Administration (NASA) declared in September 2007 that they are determined to send humans back to the Moon by 2020 and to Mars before 2037. A report from the Robotic and Human Lunar Expeditions Strategic Roadmap Committee released in late November 2007 scheduled the first NASA Mars mission to be launched in February 2031. What is more, in May 2007 China National Space Administration affirmed

its plans to build a lunar base by 2017 as a stepping stone towards Mars exploration. This timeline turned the focus on human space flight research, including space health care and support systems. To achieve these ambitious plans, increased medical support is required.

Throughout the previous decades' rocket, space shuttle and space station missions a significant amount of data had been collected primarily on short term journeys. Based on previous experience, NASA estimates that the probability of serious illness or injury during a 30-months-long Mars mission with six crew members is about 90% [1]. NASA is actively working on Medical Operations Requirement Documents for these missions. The Johnson Space Center Space Medicine Division has published a technical report [2] in 2007 addressing both technical and ethical questions concerning long duration space missions, being first to deal with the possibility of casualties.

Surgical support is one of the major issues of the upcoming missions' design. Even though no such medical case has been reported previously, the chance of sudden illness, such as appendicitis, intracranial hematoma or renal calculus, cannot be excluded. The extravehicular activities also pose danger to the astronauts, and serious bone-mass loss may increase the chance of critical fractures. Today, the only alternative is to bring back the astronauts to Earth. In future space exploration, patients will have to be operated on board of the spacecrafts or space station.

Open surgery is contraindicated, as weightlessness makes almost impossible to deal with body fluids. The recent development of *Computer Integrated Surgery* (CIS) and surgical robotics promises a successful alternative to conventional laparoscopy that may provide an indispensable health care support for future missions. Teleoperated either from the

Earth or by one of the astronauts (i.e. the flight surgeon), robotic surgery has several advantages, and the dexterous manipulators could also help the astronauts in their everyday operations and research.

2. Surgical robots on Earth

The very first human robotic intervention was performed in 1985—a brain biopsy taken with a modified NOKIA Puma robot in Memorial Medical Center, Long Beach, CA [3]. In the past 20 years, CIS technologies have undergone significant development, and entered the mainstream clinical practice recently.

The most well-known and widely-used surgical robots are the *Zeus* and the *da Vinci* [4]. The *Zeus* was developed by Computer Motion Inc. (acquired by Intuitive Surgical Inc. in 1993) at the beginning of the 1990s, and made computer aided *Minimally Invasive Surgery* (MIS) reality. *Zeus* has two 6 degrees of freedom (DOF) slave manipulators and a camera holder arm, all designed based on the *AESOP* camera holder (Computer Motion Inc.). The *da Vinci* (Intuitive Surgical Inc.) was the first to offer 3D vision system due to the dual endoscopes—mounted on a separate manipulator. *Da Vinci* also consists of two 6DOF slave manipulators, but it can be upgraded to 7DOF by adding the *EndoWrist* dexterous tool (Figure 1.). The new *da Vinci-S* system offers advanced ergonomic functions, HD quality visual feedback, and has a fourth slave arm to increase the robot's performance.

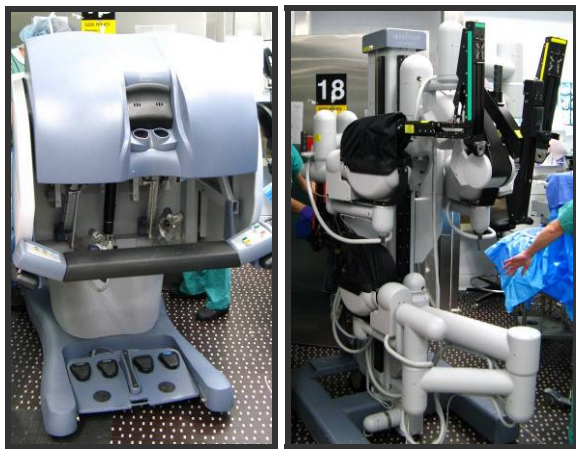


Figure 1. Master controller and slave manipulators of the *da Vinci* complete telesurgical system

Both *Zeus* and *da Vinci* operate as a complete telesurgical system. It means that the manipulators (with the surgical tools) are controlled directly by a human surgeon, and there is a regular computer

network based communication link between the master controller and the slave manipulators. The movements of the surgeon's hands are mapped to the robot's coordinate system, and it performs the desired trajectory. Tremor filtering or motion scaling can also be applied. The operation can be followed through visual system, which consists of the endoscopic CCD camera and a screen in front of the operator. While *da Vinci* has a private communication protocol, *Zeus* uses User Datagram Protocol (UDP) over Internet Protocol (IP) [5]. UDP/IP provides very few error recovery services, offering instead a direct way to send and receive datagrams. Robots are developed to have appropriate tolerance towards noise, lost or corrupted packages. The big advantage of UDP connectionless protocol that it runs on top of IP networks (basically the Internet). This fact made it capable of performing the world's first intercontinental telesurgery in 2001 between Strasbourg and New York.

Da Vinci was the first complete telesurgical system to receive the U.S. Food and Drug Administration's (FDA) approval in 2001 for laparoscopic radical prostatectomy, and since then it has been verified for six other procedures. In the past 6 years, approximately 60 000 operations have been performed with more than a thousand *da Vincis* around the world.

There are several other systems in clinical use. The *MeRoDa* database [6] lists more than 200 ongoing research projects and several dozen systems in clinical use world wide. The majority of these are special purpose robots, focusing on a certain type of procedure, such as the total hip/knee replacement *RoboDoc* (Integrated Surgical Systems Inc.), or the interventional radiology robot, *Cyberknife* (Accuracy Inc). The above mentioned systems cannot be used in extreme environment such as in space or on-earth exploration mission, as they are too big, heavy and require additional staff to operate.

The major advantages of robotic surgery are the reduced patient trauma (therefore faster recovery), less complications, higher precision, ability to fuse preoperative and in-vivo data, performance stability and task level automation. MIS means less blood loss that is crucial, as fluids behave differently in weightlessness, hardening the blood clotting. Surgical malpractice can also be reduced significantly by applying safe zones (virtual fixtures) that only allow the robot to operate within the predefined area. The safeguard teleoperation concept developed originally for mobile space robots could be useful in surgery. The robot can autonomously perform the routine tasks with the real time supervision of a human professional, however in case of any malfunction or

sudden events, the human operator can take over the control.

New surgical techniques, such as the Natural Orifice Translumenal Surgery (NOTES) or no-scar surgery offer less invasive solutions for surgical operations [7]. In April 2007, the world's first incision-free surgeries were performed: a transvaginal cholecystectomy in France and a transgastric appendicitis removal in the U.S.

3. Surgical robots for Space

Several research groups have tried already to develop a system that may be capable of providing all the listed advantages of the complete telesurgical robots, but keeping it small in size, light-weight and easy-to-operate. Initial launch weight of a space craft is always a critical factor, just as the limited amount of space on board of the vessel. Prior to a long duration human space flight, thorough optimization is done to achieve the best overall design, therefore the surgical robots intended for space must meet these criteria.

NASA was the very first to invest into this field, the Jet Propulsion Laboratory and the MicroDexterity Systems Inc. developed the *RAMS* (Robot-Assisted Micro-Surgery) in 1994–1997 [8]. The *RAMS* consists of two 6DOF arms, equipped with 6DOF tip-force sensors, providing haptic feedback to the operator (Figure 2.). The robot was originally aimed for ophthalmic procedures, especially for laser retina surgery. It is capable of 1:100 scale down (achieving 10 micron accuracy), tremor filtering (8–14 Hz) and eye tracking.



Figure 2. The RAMS microsurgical arms at JPL (Photo: NASA)

The 22 kg *Raven* robot was developed both for space experiments and military use by the BioRobotics Lab., University of Washington [9]. The Defense Advanced Research Projects Agency

(DARPA) Defense Sciences Office funded the research to acquire a light-weight and dexterous system for the TraumaPod project that shall realize battlefield surgical robotic support for U.S. soldiers by 2010. The *Raven* has two articulated arms, each holding a stainless steel shaft for different surgical tools (Figure 3.). It can easily be assembled even by non-engineers, controlled by two commercially available Phantom 6DOF haptic interfaces, and its communication links have been designed for long distance remote-control. Besides the possibility of haptic feedback, additional sensors are mounted on the robot to provide more information to the surgeon and to avoid any critical failure due to communication delay.



Figure 3. The Raven robot in a telemanipulation test (Photo: NASA)

SRI International in Menlo Park, California started to develop the *M7* robot in 1998. The system consists of two 7DOF arms, and weights only 15 kg. It is equipped with motion scaling (1:10), tremor filtering and haptic feedback. The controller has been designed to operate under extremely different atmospheric conditions, and for this purpose the robot only contains solid-state memory drives [10].

The German Aerospace Center (DLR) has already built several generations of light-weight robotic arms for ground and space application. Their latest 7DOF surgical robot is called *KineMedic* [11], and as one arm is only 10 kg and capable of handling 30 N payload with high accuracy, it is considered for space use as well. Its industrial version is equipped with a dexterous 4-finger artificial hand, and has already won several awards.

To significantly reduce the size and mass of the surgical systems, the engineers at the University of

Nebraska together with the physicians of the University of Nebraska Medical Center developed an innovative surgical device, the mobile in-vivo wheeled robot [12]. Equipped with a camera, the coin-sized robot can enter the abdominal cavity through one small incision, navigate around the organs and take biopsy. Even though this concept alternates from the complete telesurgical systems, it may provide the same benefits to the patient.

It is necessary to make the surgical equipment more serviceable, being capable of performing repetitive tasks that take a long time in the daily routine of the astronauts (e.g. verification of physical systems). Adequately designed robots could help humans in physical exercising, based on the concept of rehabilitation robots and exoskeletons recently developed, such as the RehaRob (Budapest University of Technology, University of Wales Cardiff and University of Rousse) [13]. Another important issue is the use of robots for micro-manipulation experiments. More research should be done with the robotic enhancement of human capabilities.

The modern materials and manufacturing technologies will allow building even smaller and lighter arms, however stiffness and accuracy will always be considered to be major concerns that limit downsizing. The complete research, design, development and test can easily take up to 10 years, as every single system has to undergo thorough mechanical and clinical testing and trials. The flawless operation of any space-system has paramount importance.

4. Studies of in-space surgery

Several aspects of the extreme-long distance teleoperation and telesurgery can already be studied on Earth. Both NASA and the European Space Agency (ESA) have conducted several experiments to learn about the feasibility of these procedures.

The first extreme-long distance telesurgical procedure across the Atlantic—the Lindbergh operation—was performed with a Zeus in 2001 [14]. The surgeons were controlling the robot from New York, while the patient laid 7000 km away in Strasbourg, France. Ever since several operations have been performed all around the world, and the Centre for Minimal Access Surgery (CMAS) at St Joseph's Healthcare in Hamilton, Canada has been building a remote surgery network for everyday use.

NASA uses its undersea laboratory—called Aquarius—to simulate space and other remote areas. The *Extreme Environment Mission Operations* (NEEMO) take place a few kilometers away of Key Largo in the Florida Keys National Marine

Sanctuary, 19 meters below the sea surface. Thirteen NEEMO projects have ran since 2001, and there were three projects focusing on teleoperation recently.

The 7th NEEMO project took place in October 2004, and the mission objectives included a series of simulated medical procedures with Zeus, using teleoperation and telementoring [15]. The four crew members (one with surgical experience, one physician without significant experience and two aquanauts without any medical background) had to perform five test conditions: ultrasonic examination of abdominal organs and structures, ultrasonic-guided abscess drainage, repair of vascular injury, cystoscopy, renal stone removal and laparoscopic cholecystectomy. The Zeus robot was controlled from the CMAS, Ontario, 2500 km away. The signal delay was tuned between 100 ms and 2 s to observe the effect of latency. The results showed that the non-trained crew members were also able to perform satisfyingly by exactly following the guidance of the skilled telementor.



Figure 4. The M7 light-weight surgical robot on board of Aquarius sea habitat (Photo: SRI International)

During the 9th NEEMO in April 2006, the crew had to assemble and install an M7 mobile surgical robot, and perform real-time abdominal surgery on a phantom [16]. Throughout the procedure, the time delay went up to 3 s using a microwave satellite connection to mimic the Moon–Earth communication link. The M7 robot was also used to arrange and manipulate rock samples from the ocean's ground. In another experiment, pre-established two-way telecom links were used for telementoring. The crew had to prove the effectiveness of telemedicine through the assessment and diagnosis of extremity injuries and surgical management of fractures. The effects of fatigue and different stressors on the human crew's performance in extreme environments were also measured. Each of the four astronauts taking part in

the experiment had to train at least 2 hours with the small wheeled MIS robots designed at the University of Nebraska.

The 12th NEEMO project ran in May 2007, where suing operations were performed on a simulated patient with the M7 and Raven robots. They measured the capabilities of surgeons controlling the robots from Seattle in simulated zero gravity environment. A group of three professionals guided the robot, using a commercial Internet connection, and transmitting the signals wireless to the buoy of the sea habitat. The communication lag time was increased up to 1 s. The robots had to perform several tasks, such as suturing and *Fundamentals of Laparoscopic Surgery*. In another setup, the M7 was able to insert the needle into a simulated vessel by itself (Figure 4.).

Important lessons have been learned throughout the NEEMO missions. Medical Operation Requirements Documents of upcoming space missions are composed using the experience gained. Beside teleoperation and the control of robots, there are other serious issues involved with in-space surgery. Most importantly, the behavior of organs and body liquids differs in weightlessness during surgical procedures.

The world's first operation in weightlessness was performed in 2003 on a rat on board of ESA's Zero-G plane (a modified Airbus A-300). In 2006, surgeons removed a cyst from a patient arm, while the Zero-G aircraft was performing 25 parabola curves, providing 20–25 s of weightlessness every time [17]. ESA plans to perform teleoperation in 2008 with a robot—controlled through satellite connection.



Figure 5. Zero-Gravity suturing with an M7 robot (Photo: NASA)

NASA had its first zero gravity surgery experiment in late September 2007 [18]. On a DC-9 hyperbolic aircraft suturing tasks were performed with an M7 robot (Figure 5.). The performance of classical and teleoperated robotic knob tying were measured. Both the master and the slave devices were equipped with acceleration compensators, otherwise

it would have been almost impossible to succeed on the tasks. The results showed that humans can still better adapt to extreme environments, however, advanced robotic solutions do not fall far behind.

The various zero gravity fluid experiments conducted on the International Space Station (ISS) and throughout the space shuttle missions may help to better understand the behavior of blood vessels and soft tissues during surgical procedures. ISS's new Columbus experimental module (scheduled to launch in December 2007) will give place to bioengineering research in the Biolab, the European Physiology Modules Facility and the Fluid Science Laboratory to find answers to these questions.

5. Teleoperation in space

Teleoperation requires communication link between the master and the slave device. An extensive space communication network has already been built with satellite transmitters for ongoing missions. Planetary and deep-space exploration require more advanced networks beside high-fidelity Earth-orbit channels. Communication links for teleoperation have four major characteristics: connectivity, error tolerance, lag time and bandwidth.

Connectivity depends mainly on the transmitting medium and the used protocol. Space environment with zero-gravity and vacuum offers a good medium for radio- and microwave signal transmissions, propagating at almost the speed of light. Communication protocol determines the form of datagrams, describes actions taken in case of packet loss or corruption and also link recovery time after a signal drop. To meet the special communication requirements in space, the Space Communications Protocol Standards (SCPS) was developed and tested by the U.S. Department of Defense and NASA in the 1990s [19].

Communication lag time causes most problems with teleoperation, especially in real-time applications such as surgery. Depending on the distance from Earth, occurring latency can be ms–min order. The International Space Station is on Low Earth Orbit (LEO) at 394 km mean attitude, and the propagation delay is 2–300 ms. The Earth–Moon average distance is 380 000 km, resulting a 2–3 s latency. However, planet Mars orbits 56–399 million km from Earth, causing a 6.5 to 44 minutes of delay in transmission. Video compression and decompression plus control signal creation takes an additional 50–200 ms. With present day systems, surgical task performance is possible up to 0.7–1.2 s delay; above that, the surgeon loses the ability to

react on time to the changing conditions of the operating room.

Based on ground tests [20], 10 Mbps bandwidth is enough for teleoperation with NTSC quality, but 40 Mbps is required for HD quality visual feedback. The ISS has been equipped with a 150 Mbps connection in 2005, but NASA only plans to develop a 5 Mbps connection to Mars by 2010 as a part of the new space communication architecture [21], and upgrade it to 20 Mbps by 2020.

6. Future mission support

The first astronauts traveling to settle on the Moon or to reach Mars should have their own surgical robot on board to provide high level health care support in case of any emergency. The teleoperation concept developed for shorter distances on Earth can only be used within a limited range due to the difficulties described above—primarily the communication lag time. Figure 6. shows the presently achievable telemedicine support architecture for long distance missions. There are three distinguishable layers of the concept, depending on the range and latency.

To service shuttle missions and the ISS on LEO present day telerobotic architecture may be

appropriate, as the average latency stays within the range 0.2–1 s. A compact size surgical robot might be helpful on board of any spacecraft orbiting to avoid emergency evacuation for health problem reasons. Provided adequate haptic feedback, autonomous motion scaling, natural organ movement compensation and routine task performing (such as suturing, vessel coagulation) the same concept could be used even for a Moon-base, dealing with a 2–3 s delay.

As human space exploration aims even further, new concepts have to be introduced to achieve highest fidelity support. Telementoring means that the robotic equipment is guided directly by the flight surgeon on board of the spacecraft; however, he/she only follows the detailed commands of the professional tutors mentoring from the Earth. Master surgeons on the ground may receive the same visual and control feedback as the flight surgeon, can determine the proper action and instruct the astronauts accordingly. Recent experiments showed that telementoring can even be effective with approximately 1 min latency. The flight surgeon can still benefit from the advantages of robotic surgery, while keeping the ability to adopt and quickly react to any unforeseeable events.

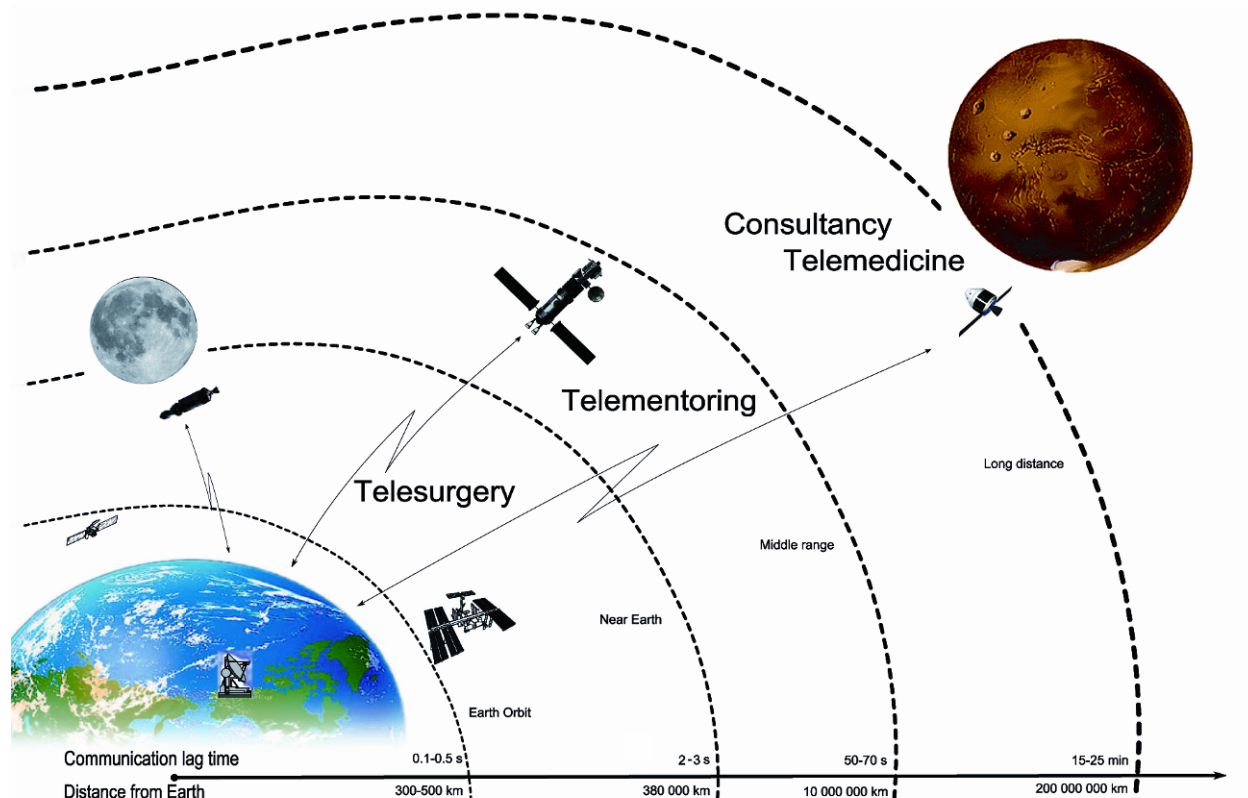


Figure 6. New concept of complete telesurgical support for long duration space missions

No question, the vast majority of a 2.5-year-long Mars mission would be out of reach for any kind of real-time, or close to real-time communication. Beyond approximately 10 million km, the latency prevents effective teleoperation. In the mean time, crew can still consult with the ground staff, and given high quality pre-mission models of the astronauts (3D PET, CT, etc. data), surgery can be simulated on Earth, using the detailed model of the patient. The result can help a lot the flight surgeons to prepare for the operation. In certain cases, the entire process might be recorded, and sent as a motion command sequence to the robot. Assuming automatic adaptation to the changing workspace (e.g. based on image processing), the surgical system might be able to perform the major parts of the procedure without further human interference.

7. Conclusion

In the case of long duration manned space missions—such as the scheduled Mars mission or the permanent Moon base—there is an increased health risk. Space medicine has to provide high quality technological solution to the new challenging situations.

Complete telesurgical systems can increase the overall mission security as with the help of these manipulators, advanced health care support can be provided which significantly increases the chance of a successful mission. With the combination of real-time teleoperation, telementoring and consultancy telemedicine, an entire human space flight mission could be covered with surgical support.

The significant amount of space used by the robot is only acceptable if astronauts can benefit of its presence on every day basis, beside the pre-, intra- and postoperative phases.

Surgical robots are able to greatly extend the astronauts' capabilities, and will lead to a breakthrough in human space exploration.

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