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A Study of Telerobotic Surgery and Telementoring in Space Missions

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***Abstract*— Several nations are actively seeking to achieve human space exploration beyond the Earth's orbit and the need to improve current surgical treatment during spaceflight is critical. Starting with the concept of telemedicine for space flight in the 1970s, terrestrial telesurgery has advanced over the last 30-40 years to telerobotic surgery and telementoring spanning continents, creating the testing ground for medical care in space missions. Telerobotic surgery has been advantageous for not only providing telepresence to surgeons and closing geographical distances but also for minimally invasive surgeries, which are a necessity in weightlessness. Numerous experiments have been conducted by aeronautical space programs resulting in improved techniques for telesurgery in extreme conditions, such as underwater laboratories and zero-gravity models created by parabolic aircraft flights.**

There are challenges for telesurgery over astronomical distances in overcoming signal latency, the time lapse between moments when the surgeon moves the controls and the robot response. The dependence on camera images for surgical navigation requires advanced visualization techniques to help human controllers familiarize with extreme operative environments. This study provides an analysis of the current research in achieving improved data transfer from space flights and providing possible solutions to improve the quality of telesurgery.

I. Introduction

Telerobotic surgical platforms allow surgeons to perform surgery on patients from remote locations using robotic tools. The concept of telesurgery is pragmatic and crucial in space missions, where the astronauts in space can be urgently operated on by skilled surgeons located on Earth.

II. Experiments Leading to Space Telesurgery

Various telesurgery operations have been conducted on Earth to simulate telesurgery in space using different telerobotic instrumentation.

A. Minimally Invasive Surgery

Robot-aided surgery originally resulted from the need for terrestrial minimally invasive surgery. In the weightlessness of space, minimally invasive telerobotic surgery is necessary in containing the patient's body fluids. Engineers at the University of Nebraska created a coin-sized teleoperated robot with wheels in 2006 that can be inserted into the abdominal cavity through a small incision. Further innovations by this team have produced self-assembling robots and external magnet-controlled *in vivo* robots that can be swallowed [1].

B. Operations Spanning Continents

The Lindbergh operation was the first transatlantic human operation (7,000 km distance), performed on September 7th, 2001 using Zeus surgical robot with a lag time of only 155ms, far below the 700ms threshold for reliable operation [2]. Raven-II [3], a recent open platform surgical robot used in several universities, will improve the integration of telesurgery results with the robotics results from the greater robotics community.

C. Aquatic Telerobotic Trials

The NASA Extreme Environment Mission Operations (NEEMO) conducted many underwater experiments simulating an analog environment for space exploration. Aquarius, the permanent undersea laboratory in Florida, enables astronaut crew members (with and without surgical experience) to simulate medical procedures with surgical robots using teleoperation and telementoring. The 12th NEEMO was conducted in May 2007 and it proved the feasibility of telesurgery with telerobots Raven and M7. The robotic arms were controlled by surgeons in Seattle through a commercial internet connection, resulting in an average latency of 70ms [4].

D. Telesurgery in Zero Gravity

Russian cosmonauts, in 1967, performed the first reported weightless surgical experiments. Later in 1998, in the STS-90 Neurolab, standard operations were performed on rats. Further surgical experiments by several international space agencies in weightlessness were conducted such as the first human experiment by the European Space Agency with the removal of a cyst aboard an Airbus A-300 Zero-G airplane, as well as a first attempt at teleoperated suturing by NASA in September 2007. It was determined that advanced telerobotic solutions performed comparably to humans [5].

III. Collaboration on Long Distance Communication

Plugfest 2009, an international collaboration consisting of 14 heterogeneous telerobotic devices (each with a master and corresponding slave robot) communicating between 9 locations around the world, provided a proof of concept that intercontinental connections are possible with a common data interface and Cartesian-space teleoperation commands [6]. Plugfest 2009 showed 21-112ms latency within the United States and 115-305ms latency for intercontinental communication [5]. This multiplatform concept can be applied to space telerobotics in the future.

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IV. LIMITATIONS AND CHALLENGES

Long-distance space teleoperation is largely restricted by signal latency [7], for example, the 50-100ms roundtrip latency between the Earth and the International Space Station including multi-satellite hops (< 10ms per hop) [8]. Space operations in weightlessness also add difficulty in maintaining accurate and synchronized visual and haptic feedback to the surgeons operating on Earth. In addition, astronaut crew members without prior surgical experience are initially at a disadvantage in mastering telerobotic platforms and correctly predicting the next steps during a medical procedure.

V. PROPOSED SOLUTION

Predictive display requires a dynamic (real-time) simulator that can be improved with recent advanced technologies such as data mining and specialized artificial intelligence as exhibited in systems such as IBM Watson supercomputer [9]. The adaptive learning tactics of the simulator will play a critical role in improving the quality of correct predictions. The self-learning capability of the system will incrementally improve the success of the simulator over time.

Numerous telerobotic surgeries are conducted worldwide and big data collected from all terrestrial surgeries can serve as data foundation for telerobotic platform training when it is initially used for space missions. Once the dynamic simulator adapts to the new surgery data arriving from the weightlessness of space, it will update its storage of surgery data predictions.

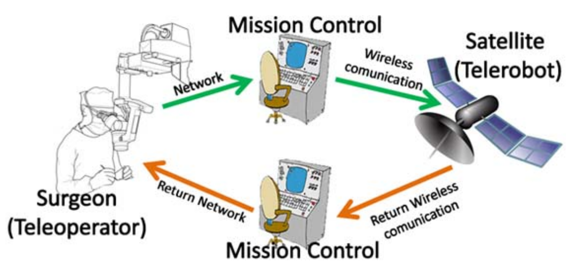

Figure 1. Roundtrip communication in space telesurgery

The operator's perception of teleoperation with time delay is that the visual feedback from remote cameras is out of date by the amount of the communications round-trip time delay [10] as shown in Figure 1. One method of aiding the operator is to provide them with simulated visual feedback that operates in real time; in effect, predicting the visual input before it is available from the remote sensors. With the simulated predictive display, the operator perceives no delay between their actions and "apparent" reactions at the simulated manipulator. The simulated image may be overlaid with the delayed video image from the remote cameras, providing the operator with both a real-time simulated display of the manipulator and a detailed and accurate display of static objects from the delayed video [11].

The communication latency between a ground station on Earth and a spaceship is significant as the spaceship moves farther away. This increase in latency prohibits instantaneous real-time video communication and this is a formidable challenge to overcome for telesurgery in space. We propose a semi-autonomous approach that allows a surgeon at a ground station to send a surgical plan with a sequence of predefined mini surgical procedures. This plan would take into account various possible scenarios including de facto actions for unknown situations. All predefined mini procedures are already stored in the spaceship and readily accessible on demand. In addition, new mini procedures and revised mini procedures can be sent to the spaceship over time. The size and complexity of the surgical plan will be directly proportional to the communication latency so that the telerobot can perform previously issued plan while the new plan is being created. This requires an increased degree of remote autonomous behavior of the telerobot.

VI. CONCLUSION

To improve the performance of the telesurgery in space, the surgeon at the ground station should be agile and adaptive to create the next surgical plan based on the response from the telerobot for the previous plan. Also, the surgeon should be familiar with all predefined mini procedures and various possible scenarios. The intelligence of the telerobot will be based on the set of predefined mini procedures and the complexity of these procedures. Additionally, the granularity of the control on the telerobot from the ground station is inversely proportional to the communication latency.

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