Telesurgery With Miniature Robots to Leverage Surgical Expertise in Distributed Expeditionary Environments

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ABSTRACT This study aimed to evaluate the capability of performing telesurgery via radio transmission for military arenas where wired internet connections may not be practical. Most existing robotic surgery systems are too large to effectively deploy with first responders. The miniature surgical platform in this study consists of a multifunctional robot suite that can fit easily into a briefcase. Methods: The focus of this study is to explore the implications of radio control of the robot. The hypothesis is that an in vivo robot and its control boards can be controlled using off-the-shelf wireless components. An experiment was designed with off-the-shelf wireless components to test the capability of our newest generation of miniature surgical robot to become battery-operated and wireless. Results: Wireless transmission of control signals has provided proof of concept and has exposed areas of the software that can be built upon to improve responsiveness. Wireless transmission of the video feed can be adequately performed with basic off-the-shelf components.

INTRODUCTION

As the military disperses surgical facilities so that patients receive care closer to where they are stationed, it becomes important to maintain and improve outcomes by making the most sophisticated diagnostic and interventional care as widely available as soon in the continuum of care as is possible. Since it is not possible to deploy limited medical personnel and resources to all arenas, secure high-speed data links available can be leveraged to more efficiently deploy specialists. Several robotic surgery systems have been developed, and some have demonstrated telesurgery over the internet. However, current systems, such as the da Vinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, California), are prohibitively large and cannot be easily deployed. Smaller systems would lend themselves better to deployment in Combat Support Hospitals (Level 3), or with Forward Surgical Teams (FSTs) (Level 2). When an emergency surgery is required, or when the patient cannot be immediately transferred to the next-level care facility, the availability of advanced surgical options can make all the difference. Improved evacuation procedures and an emphasis on rapid transit to higher levels of care are decreasing combat died of wounds and death on the battlefield.[1–3]

Research at the Center for Advanced Surgical Technology and the Advanced Surgical Technologies Lab at the University of Nebraska has the goal of enabling telesurgery through remotely controlled miniature surgical robots. This is a force multiplier for a consolidated medical footprint, making expert highly skilled surgeons available for procedures in remote-distributed environments that lack conventional surgical resources. The miniature robots are small and simple enough to be deployed and set up by an FST; an experienced surgeon could then log in remotely and perform emergency procedures.

Presented here is the introduction of a wireless communication system that would allow deployment of these robots to be controlled remotely by a skilled surgeon. Testing was focused on the performance of wireless response of the robot, future work will evaluate the effects on robot operation. This advance in surgical technology can reach remote locations where existing communication infrastructure is not available. Research is ongoing to increase the clinical capabilities of the robot, but developing a wireless control network would greatly increase range of potential deployments of the telesurgical technology.

BACKGROUND

Advances in surgical technology have improved the patient experience greatly. Laparoscopic surgery revolutionized how many procedures are performed. Research and development have begun producing robotic Minimally Invasive Surgery (MIS) systems that further improve patient safety;

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including decreased operative blood loss, postoperative pain, faster return of normal function, and fewer analgesics.[4,5] However, these improvements have not made their way out of the hospital-based surgery suites. With operations all over the world, the U.S. military deploys thousands of personnel to dozens of countries. Some areas are war torn and present a front line where soldiers or civilians may be injured or are in need of emergency care. Other cases may involve humanitarian aid for populaces of affected countries. Bringing advanced surgical technologies to these emergency scenarios could save thousands of lives all over the world.

We have designed a compact surgical robot suite comprised of a miniature surgical robot, high-quality vision system, user interface software, haptic controllers, and telestration and telesurgery capabilities. This system has been tested in vivo in multiple porcine surgeries, and fits into the abdomen through a two-inch incision at the navel, thus enabling remote, MIS. The design of this robot has been licensed to a private company, Virtual Incision Corporation, which has performed two first inhuman surgeries and is currently in discussions with the FDA to submit 510(k). This study focuses on controlling the compact surgical robot suite wirelessly. In the future, using existing high-speed defense communication backbones and protocols, skilled surgeons located anywhere will be able to remotely assist in complex procedures taking place hard to reach or remote locations where FST are deployed.

The commercially available da Vinci Surgical System has been the leading clinical robotic MIS system since it received FDA approval in 2000, and is currently the *only* surgical robot with U.S. FDA approval for use in laparoscopic surgery.[6] Surgeons can control laparoscopic tools from a remote workstation. The system can filter tremors, and provides 3D vision,[7] increasing the quality of the surgery. The da Vinci system has successfully demonstrated the ability to perform procedures on a porcine model over the internet. The distances were 1,300 and 2,400 miles. Round-trip delays of 450 to 900 milliseconds were demonstrated. The system used public internet for communication.[8] Later testing across a 17 MB/s bandwidth VPNe network over 1,770 miles showed 370 milliseconds of delay.[9]

Other systems are under development. The Raven-II is a collaborative research effort that is built around three 3-degree of freedom (DOF) arms with interchangeable 4-DOF instruments. Although the da Vinci is a commercial product, the Raven-II is an open-source platform jointly built by seven universities.[10] The system is capable of similar teleoperation to the da Vinci, and has been controlled by various off-the-shelf controllers.[11] The Raven-II has also demonstrated telesurgery capabilities; from 100 m (wireless) to 4,700 miles (commercial internet). The system was tested from Seattle, Washington, to London, England, and exhibited 140 milliseconds of internet latency.[12] Similar robotic systems are being developed[13] using arms outside the body to position tool tips. The Raven and da Vinci have both demonstrated telesurgery capabilities; deploying these systems, with large arms and actuators around the patient, do not lend themselves to easy set up in emergencies or remote sites. In an emergency, there is a huge range of injuries that may require treatment. Not every scenario will be applicable for these robotic systems. Most of the current robotic surgery systems focus on abdominal surgery due to the large workspace available, which leaves a gap that negatively impacts the systems' applicability. However, as the systems' functionality increases, there is no doubt that the ability for a surgeon to remotely control two dexterous tools would save lives. Although current procedures for evacuation are improving, the rate of combat casualties has decreased.[1] Inevitably, there will be situations where evacuation beyond Level 2 is not possible; a wireless system could improve the treatment of combat injuries in these scenarios. Nothing will be able to replicate a controlled surgical setting. However, it is possible to deploy the proposed system for surgery with the skills and equipment available to a FST that include administering anesthesia and inserting a port. Since the type of injuries can vary greatly, and the robots being developed are mostly specialized, there is not much overlap. Different surgical procedures pose unique difficulties including access to a specific site, large workspace, numerous veins, and vessels to control.[14] An insertable robot has easier access to the entire abdomen; where the da Vinci and Raven have difficulty maneuvering due to the robotic arms outside of the patient. Insertable robots simply need to be rotated on the axis of insertion to reach the entire abdomen. The system is more manageable to deploy and set up requires minimal motion compared to the larger systems that are currently available.

Several different types of insertable robots have been developed; however, the only robot with FDA approval for use in laparoscopic surgery in the United States is the da Vinci Surgical System. The BioRobotics institute in Pisa, Italy, has developed a two-arm robot, SPRINT, which is inserted through a single port; control has been demonstrated, but a specialized trocar is necessary.[15] SPRINT uses an off-board control system, with cables running to external controllers, which negatively impacts its ability to be transported easily, as in an emergency situation. Further, the system has demonstrated no telesurgery capabilities.[16,17]

A snake-like robot, developed by Waseda University, is inserted through a single port; the system deploys tools from the main tubular body. The robot is positioned by a robotic arm; the end effectors are actuated using a cable drive system. The system has no telesurgery capabilities[18] and the positioning arm and off-board actuators make deployment difficult.

The i-Snake robot, from Imperial College London, is inserted through a standard trocar and has a flexible head that deploys; in addition, two cable-driven arms are inserted to manipulate tissue. However, the system cannot properly position tools for tissue manipulation. The system has demonstrated no telesurgery capabilities.[19,20]

The IREP robot from Vanderbilt is similar to the i-Snake—it features two cable-driven arms and a head that provides vision. The cable-driven arms have a cumbersome actuation housing, making transportation and deployment difficult. Limited force at the end effectors and lack of wrist dexterity limit the system. The system has demonstrated teleoperation, but only over a local area network. This would not be applicable to deploying surgical tools and technology in hard-to-reach or emergency areas.[21,22]

Previous work has demonstrated the functionality of our insertable robots.[23,24] These two-armed in vivo robots have performed over 75 in vivo procedures, including cholecystectomies and a partial colectomy in live porcine models. The robots have demonstrated the capability of manipulating tissue in all quadrants of the abdominal cavity in a live porcine model.[25] Although the robots have only been tested in the abdomen, it is possible that in these emergency scenarios the robot could be used for a more general purpose. Even if the robot is not inserted in the abdomen the surgeon still has control of the tools, and can have the person deploying the system orient the robot wherever is necessary. The robot is actuated by onboard motors and control boards, thus there is minimal cabling or housing that needs to be transported with the robot.

Surgical systems have been developed that have teleoperation capabilities. However, the systems that have more fully developed these features are bulky, and cannot be deployed cheaply, efficiently, or easily to emergency areas; whether that is a front-line or humanitarian aid to an affected area. The robotic system presented here has proven capable of surgical procedures, and the size and simplicity of the system make it adaptable to both external and internal procedures. By testing and implementing the proposed wireless system, the transportable robotic system can provide surgical care to remote areas with FST capability. With this system, U.S. military personnel could virtually deploy a miniature surgeon to emergency areas. This surgical robotic technology can greatly benefit from the military's communication infrastructure. This robotic system, bolstered by the military infrastructure, could reach remote locations, and provide immediate care from experts. The hypothesis being tested is that by controlling the current in vivo robot with off-the-shelf wireless controllers, a uniquely small and compact robotic surgery system can be deployed remotely. The wireless robotic system presented here, coupled with available video technology, could expand the capabilities of current evacuation protocols on a war or humanitarian front.

METHODS

The miniature in vivo surgical platform consists of a two-armed, gear-driven, multifunctional robot and a remote surgeon interface (Fig. 1). The surgical robot is normally attached to the control computer via a direct USB connection. This USB connection was easily made wireless using a pair of radio frequency (RF) transceivers, XBEE multipoint RF Modules (Digi International, Minnetonka, Minnesota). The video was transmitted on a dedicated set of radios.

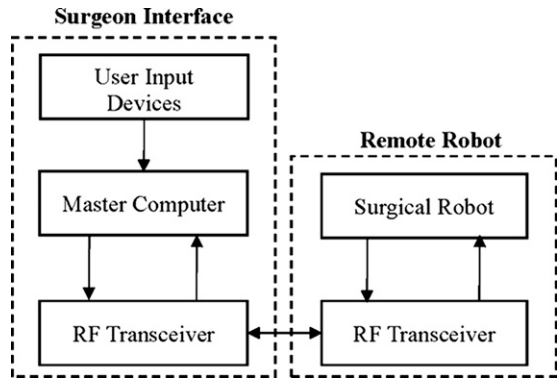

FIGURE 1. Block diagram of remote surgical platform.

The miniature in vivo robot consists of two, 4-DOF arms each composed of a 2-DOF shoulder, elbow, and wrist. Each arm is about six inches long. Various tools may be used for each end effector, including grasper, cautery, and suction/irrigation tools. Each joint is driven by on-board brushless DC motors and miniature gear trains and each link houses custom, modular motor controllers, reducing the cabling along each arm to four wires: a 12V DC power bus and a RS-485 differential serial bus. The serial bus is converted from RS-485 to USB and input into a miniature computer (RaspberryPi, 900 MHz quad-core ARM Cortex-A7 CPU, with 1 GB RAM, running Raspbian, Caldecote, United Kingdom) USB hub. An off-the-shelf RF transceiver was also connected to a USB port and a Python script was written to connect the two communication ports to each other. The remote robot is shown in Figure 2. Future studies will move toward removing the miniature computer from the system. The mobile robot platform only requires a 12V-3A and a 3V3-650 mA power supplies, both of which could be drawn from a single battery pack.

The remote surgeon interface consists of user input devices, a mobile laptop computer (Dell Precision M6500 running Windows 8.1 with Intel Core i7 processor at 1.87 GHz, and 10 GB RAM, Round Rock, Texas), a custom software package, and an off-the-shelf USB-RF transceiver, as shown in Figure 3. A Custom software architecture (University of Nebraska-Lincoln, Lincoln, Nebraska) is used to handle user input, robot control, and communication with the motor controllers. The robot is operated using off-the-shelf Geomagic Touch haptic controllers (3D Systems, Rock Hill, South Carolina). These motorized haptic devices provide a bidirectional communication interface between the controller and master computer, outputting absolute position coordinates and receiving force inputs from a suite of plug-ins. Force input is applied to produce the barriers of the robotic workspace and transmit forces from the actual robot to the hand of the operator. Scaling and clutching features were also used to gain finer control of small motions.

The latency of the robot control communications was tested by measuring the response time of the on-board motor

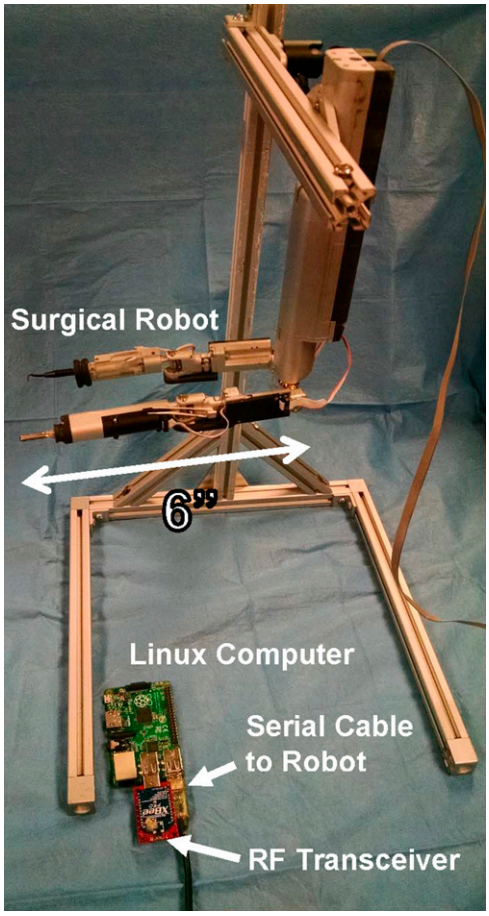

FIGURE 2. Remote surgical robot.

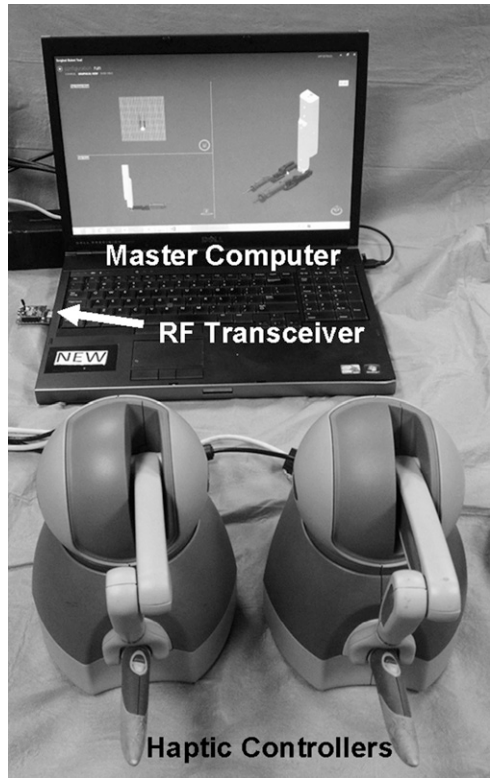

FIGURE 3. Remote surgeon interface.

controllers to a robot command from the custom control software. A timer was stared when a message was sent to the robot, and stopped when it received the reply from the motor control boards. The time was measured for 3,000 successful responses and averaged. Although a response time benchmark for "smooth" operation has not been quantified, the response time of the wired robot platform has been deemed to be responsive enough to perform surgical tasks by the surgeon-author during benchtop and in vivo tests.

Providing a real-time video connection that is synced with the hand controllers is vital to a successful procedure. Exploration of this component started with a transmitter/receiver pair of Partom 5.8GHz 1200mW (Shenzen Partom Technology Development Co., Ltd., Guangdong, China) radios designed for analog audio/visual transmission. The Partom module is a common first-person view video setup for use in radio-controlled aircraft. Mushroom antennas were used for both the transmitter and receiver, providing a gain of −3 dBi and a rated range of 3 to 4 km of open air transmission. This particular product also recommended a set of 14 dBi panel antennas for a range of more than 14 km. These units performed as expected and will be explored further for use in carrying the control commands as well.

The performance of the remote platform was compared to the performance of the completely wired local system. The same laptop computer was used for both cases. The video system was verified, but not range tested at this time.

RESULTS

The existing computer software was tested while communicating with the robot at several different baud rates. The baud rates of the USB-RF transceivers as well as the on-board robot control boards were varied. The time required for 3,000 successful responses was recorded. The recorded time is based on the quality of the wireless connection. The results of these tests are shown in Table I.

Wired connections consistently timed in at around 20 milliseconds per successful round trip. The current robot uses six motor controllers, resulting in about eight messages per second to each motor controller. This communication

TABLE I. Results of Wired and Wireless Communication Response

Baud Rate	Wired Response Time (milliseconds)	Remote Response Time (milliseconds)
9,600	48.325	233.311
38,400	19.480	78.526
57,600	19.679	80.978
115,200	19.178	85.412

speed has been determined to provide smooth operation of the robot for the number of controllers used in the current kinematic configuration. The wireless setup used in this proof of concept varied from 78 milliseconds per successful message loop at a baud rate of 38,400 to 233 milliseconds at a baud of 9,600.

DISCUSSION

Through testing, several potential bottlenecks were identified and discussed.

The experiment described here used a Raspberry Pi Linux computer to handle the messaging between the robot and the USB-RF dongle. The overhead and slow speed of this computer was taken into consideration. The same code was run on a more powerful desktop running Windows 7 with an Intel Core i7-2600K CPU at 3.4 GHz and 8 GB RAM. This computer showed approximately a 15% improvement in the 1,000 message test, but still had overhead slowing it down. The next step will be to design dedicated circuitry to connect the robot directly to the radio module.

Although the primary robot control software is efficient enough for wired communication, additional improvements could be implemented to help lessen the effect of dropped packets. The same can be said for the embedded software on the robot control boards. Work will be continued to combine both video and robot control signals into the same RF transceiver. A spooling function or command buffer could be implemented for smoother control of the robot, but this smoother control would come at the expense of response time.

CONCLUSION

The introduction of a radio network to our current robotic system can improve the military's ability to provide remote surgery care in situations where FST are available. Current technology is capable of teleoperation; however, the most robust systems are large and incapable of deployment to the emergency scenarios highlighted. Smaller robots have been developed, but not with satisfactory teleoperation. The system highlighted is capable of both. Wirelessly controlling the in vivo robot is an initial step in making a mobile surgical system; small and simple enough that it can be deployed in a wide variety of urgent cases and bringing expert surgeon control to remote locations. The robotic system requires minimal medical training, including administering anesthesia and making an incision. The minimal training makes the logistics of deployment easier, in situations where evacuation may not be possible. The collected data show that wireless control is possible, but the system is limited by hardware. Further development can mitigate these issues.

Our group has been able to control the surgical robot over a wireless network, demonstrating platform capability for telesurgery. Military capability in remote robotic guidance has already been amply demonstrated by the successful use of unmanned aerial vehicles, and numerous high-speed defense communication links and protocols already exist—all of which will ease the implementation of robotic telesurgery. This technology provides a viable solution to the lack of immediate surgical care in remote or inaccessible locales and can have a revolutionary effect on remote surgical care. The work shown here is a proof of concept showing that controlling the current in vivo robot with wireless off-the-shelf components is feasible, and leaves room for promising future work.

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