Evaluation of Unmanned Airborne Vehicles and Mobile Robotic Telesurgery in an Extreme Environment

Brett M. Harnett, M.S.I.S.,[1] Charles R. Doarn, M.B.A.,[1] Jacob Rosen, Ph.D.,[2] Blake Hannaford, Ph.D.,[2] and Timothy J. Broderick, M.D.[1]

[1]Department of Surgery, University of Cincinnati, Cincinnati, Ohio.
[2]BioRobotics Laboratory, University of Washington, Seattle, Washington.

Abstract

As unmanned extraction vehicles become a reality in the military theater, opportunities to augment medical operations with telesurgical robotics become more plausible. This project demonstrated an experimental surgical robot using an unmanned airborne vehicle (UAV) as a network topology. Because battlefield operations are dynamic and geographically challenging, the installation of wireless networks is not a feasible option at this point. However, to utilize telesurgical robotics to assist in the urgent medical care of wounded soldiers, a robust, high bandwidth, low latency network is requisite. For the first time, a mobile surgical robotic system was deployed to an austere environment and surgeons were able to remotely operate the systems wirelessly using a UAV. Two University of Cincinnati surgeons were able to remotely drive the University of Washington's RAVEN robot's end effectors. The network topology demonstrated a highly portable, quickly deployable, bandwidth-sufficient and low latency wireless network required for battlefield use.

Key words: *unmanned airborne vehicles, robotic telesurgery, extreme environment, battlefield operations*

Introduction

While advances in robotics and computing have resulted in surgical robots that are currently used in operating rooms across the world, similar advances in telecommunications and computing have permitted development of telemedicine, which has seen a global expansion.[1] Surgical teleconsultation is effective in bringing surgical expertise to the previously isolated operating room.[2,3] Teleconsultation could overcome the barriers of time, distance, and interject expertise and order into the care of a soldier in the midst of the chaos of the battlefield. Prompt, definitive care from a distance could improve soldier survival as well as decreasing the risk of delivering medical care for other soldiers.

As the modern battlefield evolves to include more automated devices and remotely controlled vehicles, the integration of telesurgical robotics into battlefield care of injured soldiers becomes increasingly plausible. However, mobile robotic telesurgery (MRT) has not been feasible, primarily because the requirement of low latency, broadband telecommunications connections was not widely available and the robotic systems were not robust enough for use in extreme environments. Dr. Jacques Marescaux's original and our recent basic science and clinical telesurgical experience demonstrated the applicability of remote robotic telesurgery.[4,5] This research successfully used dedicated, terrestrial high bandwidth communications.[6,7] This experience suggested that a remote surgeon could operate on an injured soldier on a distant, not previously feasible battlefield and also demonstrated that shorter latency results in improved surgical performance.[8]

If a portable, suitable network could be provided to support telesurgery in extreme, dynamic environments such as the battlefield, surgical expertise could be distributed throughout the world and save the lives and limbs of our warfighters. Unfortunately, during military conflict, reliable broadband terrestrial communications capabilities to support surgical services are not routinely available. Ideally, a deployed wireless system would provide a high bandwidth, low latency connection between the operating surgeon and the distant robotic system similar to terrestrial systems. In selection of a wireless system for use in telesurgical applications, communication reliability and latency are of primary importance. Various options were considered.

Satellite communication latency is a function of orbital altitude or position of the satellite in space. There are three primary types of satellites routinely utilized for communication: Low Earth Orbit (LEO), Mid Earth Orbit (MEO), and Geostationary Earth Orbit (GEO). While GEO systems have enough bandwidth for use in robotic telesurgical systems, the excessive communication latency precludes GEO system use. MEO satellites have a low enough latency at acceptably high data rates if enough bandwidth is dedicated to the communications link. Unfortunately, there are limited communication MEO satellites currently in operation, and tracking these assets requires additional equipment. MEO-based telesurgery will be possible only with further MEO satellite system development. While there are commercially available LEO systems with low communication latency, the bandwidth per link is far too low for use in robotic telesurgery (approximately 4.8 kilobits per second [Kbps] but greater bandwidth is on the horizon). LEO systems also require frequent hand-offs as each satellite enters and leaves the land-based "footprint."

The military currently uses ad hoc Internet Protocol (IP) networks in certain capacities on the battlefield.[9] While satellites are limited by relatively high latency or low bandwidth, current military aircraft such as Airborne Warning and Control System (AWACS) are a limited resource with high logistical overhead and are not widely available throughout the world. To establish a usable wireless network in the far-forward battlefield, we postulated outfitting multiple small drone aircraft with radio transmitters and extending a "network in the sky" when and where it is needed.

The primary objective of this project was to develop and validate unmanned airborne vehicle (UAV)-based communication and mobile robotic surgical system that would allow a remote surgeon to effectively operate on an injured soldier regardless of the soldier's location or environment.

Experimental Design

These MRT experiments were funded by the United States (U.S.) Army Telemedicine and Advanced Technology Research Center (TATRC) and led by the University of Cincinnati (UC). The collaborative research effort included the University of Washington (UW), AeroVironment (AV), and HaiVision Systems. The team initially developed system components that included the wireless UAV-based communications platform and the mobile telerobotic surgery system. AV developed a new digital data link (DDL), as a payload component on the Pointer Upgraded Mission Ability (PUMA). The PUMA is hand-launched small UAV (SUAV) currently used in Iraq and Afghanistan primarily for local reconnaissance. UW provided their U.S. Army-funded, next generation surgical robot prototype called RAVEN. HaiVision provided a state-of-the-art Motion Picture Experts Group (MPEG) 2 Coder/Decoder (CODEC). UC provided project vision, leadership, and surgical skill. Finally, a set of MRT experiments were conducted in an extreme environment—the high desert surrounding the AV facilities in Simi Valley, CA.

The inanimate MRT experiments were designed to evaluate surgeon performance using telesurgical technique. During these experiments, the surgeon operated from a Remote Command Center (RCC) connected to a robot within the distant Mobile Operating Room (MOR). In the first stage of these experiments, the surgeon operated from the RCC that was stationed at one location to the MOR located at a nearby location. The local communication link was provided by a circling SUAV. In the second phase of these experiments, a surgeon attempted to operate using a second RCC stationed at the UW in Seattle with the MOR in the desert. The communications link, connecting the Seattle surgeon to the remotely located robot, was provided by standard Internet routed to the local SUAV downlink.

In these experiments, surgeons performed several simple surgical tasks such as suturing. The surgeons and engineers used these field tests to determine the ease of the MRT, difficulties of MRT in an extreme environment, visualization provided by the allocated bandwidth, impairment of performance imposed by latency and signal loss, and feasibility of future MRT on the battlefield. *Figure 1* illustrates the overall experiment configuration.

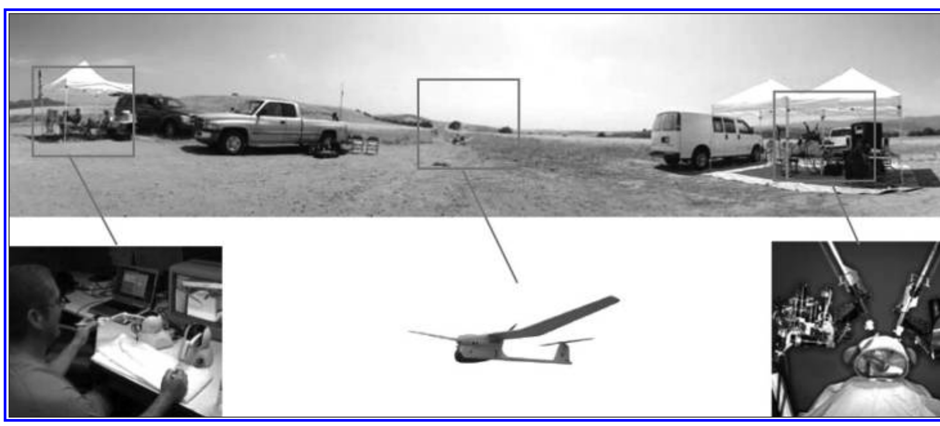

Fig. 1. Experimental configuration.

Fig. 2. University of Washington's RAVEN System.

Fig. 3. Surgeon workstation—Phantom Omni Controllers (Sensable, Cambridge, MA).

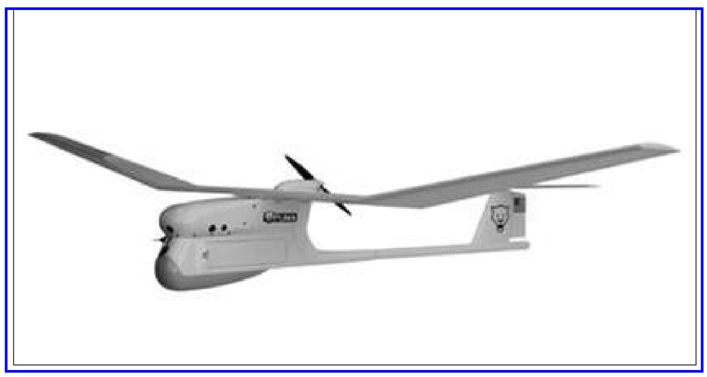

Fig. 4. AeroVironment's (Simi Valley, CA) small unmanned airborne vehicle.

UW's prototype robotic system, the RAVEN (*Fig. 2*), consists of a portable master control station (laptop computer with two haptic controller units and USB foot pedal) and slave (two robotic arms, video source, and control electronics) connected by a digital communication link using IP. The master controllers were the Phantom Omni devices (Sensable, Cambridge, MA) as illustrated in *Figure 3*. The system was designed, built, and benchmarked at the UW BioRobotics Laboratory in Seattle, Washington. It was subsequently ruggedized, packaged, and driven to AV's facilities in Simi Valley. The system was initially assembled and tested inside the facilities to confirm nominal function and estimate the amount of time it would take to unpack and assemble the unit in the desert. This MRT system also included the HaiVision Hai 560 MPEG 2 CODEC (HaiVision Systems, Montreal, Canada).

AV provided use of a versatile SUAV (*Fig. 4*). The PUMA flies at altitudes below 5,000 m mean sea level (MSL) and can provide line-of-sight communication up to a distance of 12 km with low-gain antennas and 20 km with higher-gain antennas. Prior to team arrival in Simi Valley, the DDL system was integrated into PUMA and flight tests were performed. SUAV-based low latency, broadband digital communication was successfully established and refined during these MRT experiments.

During the week of experimentation, the MRT system was deployed in a rural, arid location referred to as the "flying field." There was no electrical power, water, or shade with limited access over rough terrain. Two tents were set up and separated by a distance of approximately 30 m. Initially, close proximity of the two tents facilitated troubleshooting of the prototype mobile robotic surgical system. Electrical power was provided by two portable gasoline-powered generators. The second tent was the location of the surgeon controllers.

This configuration was performed at three different sites. Setup time was measured in hours at the beginning of the week. By the week's end, the time was approximately 30 minutes. Despite close proximity of the two tents, signal transmission from master to SUAV to slave was approximately 5 km. Video was transmitted through use of the Hai 560. This experimental configuration provided an opportunity to evaluate the various communication modalities, performance of the surgeon, and the impact of the environment.

COMMUNICATION CHALLENGES

Of interest, AV's PUMA-based communication system was not fully functional upon arrival of the team. Prior to the team's arrival in Simi Valley, the AV engineers had successfully tested the prototype communication link independent of the PUMA platform. However, once the DDL was integrated into the aircraft, the unit ceased to operate. This unforeseen event prompted a workaround. The workaround was to build a standard Wi-Fi (802.11 g) wireless network. While AV continued to diagnose the problem, the team acquired wireless access points, receivers, routers, switches, and other ancillary devices at a local electronics store. One of the challenges was to construct a self-contained wireless local area network (WLAN) where the endpoints connected to the access point (which would be the aircraft) and not directly to each other. Over a period of two days, a private WLAN was built and tested. This 802.11 g wireless system allowed wireless remote manipulation of the surgical robot while the SUAV was on the ground, but it was more challenging once the system was airborne.

On flight test day 1, the SUAV-based Wi-Fi communication system was deployed in the field. The PUMA was outfitted with the access point, launched, and was flown in a small circle above the experimental site in the field. Directional antennas were used at the downlink points to acquire a signal. A series of tests were conducted to determine the optimal flight characteristics, altitude, and distance to maximize network connectivity. The Wi-Fi's coverage was inconsistent. Various antennae configurations were tried with little effect. Direction and flight attitude resulted in inconsistent radio communications. The aircraft's engine possibly added interference with the Wi-Fi signal evidenced by improved throughput on the descent and decreased engine throttling. However, additional testing suggested that the intermittent loss of signal during flight was likely related to the directional nature of the router antennae on the SUAV.

On flight test day 2, the DDL was finally operational, obviating the need for the backup plan of the Wi-Fi. The original system became operational and a series of successful tests were accomplished, as outlined below.

SURGICAL SYSTEM AND OPERATIONAL ACTIVITIES

The RAVEN was initially assembled in a controlled environment (air conditioned office building) on the first day. It was then disassembled, packed in protective containers, and driven to the flying field. The robot and control stations were assembled, used, and disassembled three times in three different locations. The environment was characterized by temperatures exceeding 100°F, arid, dusty, and windy. In addition to communications, all resources had to be brought in, including food, water, and electrical power.

The robotic arms were mounted and secured to the rails on the side of a portable table made of 80/20 aluminum (80/20 Inc., Columbia City, IN). The table and control boxes were assembled under a tent. The master controller and other ancillary equipment were located in a second nearby tent approximately 30 m away. Gasoline-powered generators were positioned behind the vehicles to minimize noise and exhaust fumes.

The surgical robot is equipped with two video views: (1) a surgical camera and (2) an overview camera. Each camera captured and recorded video independently. Only the surgical camera view was sent to the remote via the DDL to limit bandwidth utilization. The control software has built into it the ability to record all joint and motor positions.

UW's Transmission Control Protocol/IP networking requirements (bandwidth and port usage) for the robot controls included two primary and two secondary communication channels. The primary communication required was video and teleoperation data, which used most of the bandwidth. In addition, we intermittently used remote computer login via a secure shell and/or secure file transport protocol and a teleconferencing chat channel for communication between locations. The secondary channels did not add significant bandwidth requirements. Teleoperation used a single bi-directional User Datagram Protocol (UDP) port sending 2,000, 40-byte (320-bit) packets per second (1,000 each way), about 640 Kbps (*Fig 5*).

Video used three UDP streams with bandwidth scalable (tradeoff quality for bandwidth) in the range of 100–500 Kbps at a minimum. Based on an estimated bandwidth of 1.2 Mbps, it was necessary to send a single video stream to optimize the quality of the operative video image provided to the remote surgeon. (Due to the classified nature of the PUMA DDL, AV would not disclose communication details, bandwidth, or allow third-party tools to sniff the network.) AV did provide us with limited network statistics. In early runs, the PUMA was at one point about 2.4 km out and 125 m above ground level (AGL). [Due to local Federal Aviation Administration regulations, the PUMA was unable to fly more than 125 m AGL.] Communication latency was ~12 ms, packet loss was hovering about 10%, while hardware latency was measured at ~200 ms.

SURGICAL PROCEDURES

Two surgeons operated the surgeon's console, manipulating the surgical arms. Using a video image and the Phantom Omni controllers, they moved the tools along specific paths in space and positioned their tips at predetermined spots on the latex objects (*Fig. 6*). They were able to simulate various maneuvers that surgeons nor-

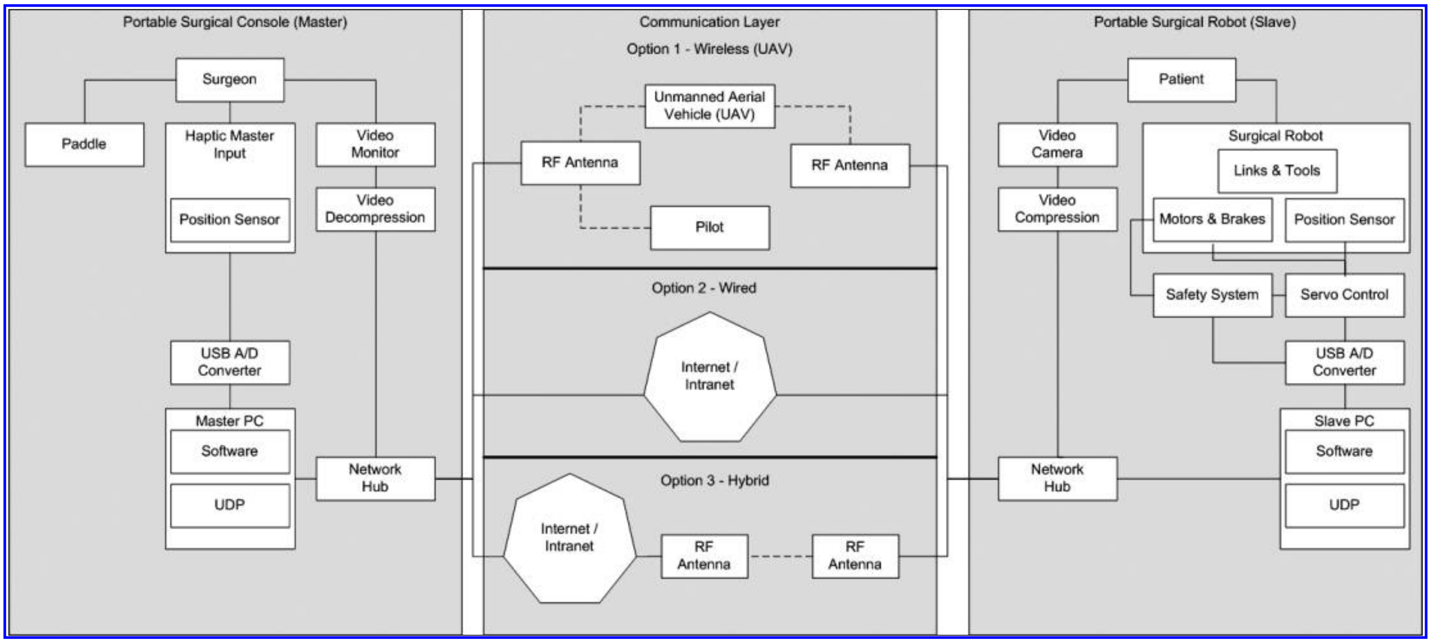

Fig. 5. Block diagram of the system with unmanned aerial vehicle wireless link and wired Internet/intranet connection options.

mally perform. Suturing was difficult because the kinematic control of the prototype robot requires additional refinement. During the experiment, signal transmission delays were 20 ms and CODEC delays were approximately 180 ms. While the total latency of 200 ms was noticeable by the surgeons, it did not substantially interfere with their control of the robot. The surgical experiments were designed to measure various aspects of performance.

INTEGRATION OF A HIGH-PERFORMANCE CODEC

The videoconferencing segment was implemented through a partnership with HaiVision. The Hai560 CODEC used its two video channels to simulate stereoscopic vision, this time the views were a monoscopic surgical view and an overhead view (described earlier). A third channel provided audio.

EXTENDING THE CONNECTION TO SEATTLE

Once the tests were successful in Simi Valley, two of the team members traveled to Seattle. On the last day, the robot and PUMA were deployed in the field at Simi Valley. The network link was established including video. The robot, however, could not be manipulated. During configuration on Friday morning, the server that controlled the robot suffered a catastrophic and unrecoverable hardware failure

Fig. 6. Experimental surgical block.

Discussion

Initial HAPsMRT experiments were successful. This activity represents the first time a SUAV and a surgical robot were deployed in an extreme environment and manipulated wirelessly using a SUAV as a mobile network access point. These tests demonstrated that the PUMA, which is normally used for military activities, could be adapted as a communications platform to transmit images and instrument controls of a surgical robot. This activity also demonstrated that robotic instrument controls could be transmitted using a wireless system as a redundancy (although more work needs to be done).

Communication tools are key elements in successful telesurgical applications. Other telesurgical activities have illustrated this, including Marescaux et al and Anvari et al.[10–12] The use of SUAV or larger systems such as High Altitude Platforms like the Predator has many possible applications, including homeland security and disaster relief, and can serve as a last-mile solution for commercial Internet. These systems could also be integrated into the Global Grid Telecommunication System for optimal use of available communication assets distributed.

This initial demonstration of an SUAV and an MRT was successful, yet many challenges remain, including evaluation of the operational limits of communications including bandwidth, latency, packet loss, jitter, and overall quality of service.

Conclusion

This effort, complemented by the multidisciplinary team of collaborators, provided a strong foundation of expertise that could eventually be available to the military as well as National Aeronautics and Space Administration as it meets its exploration initiatives. MRT is feasible and holds great promise of improving medical care by allowing a remote surgeon to effectively operate on an injured soldier regardless of the soldier's location or environment. This project brought together the necessary military, surgical, robotic, and telecommunications partners to provide the eclectic technology and expertise that will bring mobile robotic telesurgical care of soldiers closer to reality.

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Address reprint requests to:
Brett M. Harnett, M.S.I.S.
Department of Surgery
University of Cincinnati
231 Albert Sabin Way, SRU Suite 1466
Cincinnati, OH 45267

E-mail: brett.harnett@uc.edu

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