Transforming a Surgical Robot for Human Telesurgery

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***Abstract*—This paper discusses the technology and developments behind transformations made to a commercial robotic surgical system, Computer Motion, Inc.'s Zeus™, in order to make it possible to fully and safely support minimally-invasive human telesurgery performed over very large distances. Because human life is at stake, issues relating to safety, detection of errors, and fail-safe operation are principal in importance. Therefore, it was paramount that all of the safety features of the commercial product Zeus™remained intact during this transformation. This paper discusses the commercial robot and its safety features as well as the real-time communications system added to it as part of Operation Lindbergh, the first transatlantic human telesurgery. Particular attention is paid to the limiting effects of latency. Key techniques developed during this project are discussed, including the need to send the full robot state in each transmitted packet rather than incremental or modal data, thereby treating all telecom problems uniformly as dropped packets. The use of hierarchical design (incorporating Zeus as a drop-in component rather than modifying its internals) allowed the project to focus on the new issues arising due to teleoperation while gaining the robust, error checking, and fail-safe aspects of the design from the use of the unmodified commercial robot. The concept of *local mode* was created and used during initialization and during communications abnormalities and outages in order to keep the local and remote subsystems active and safely quiescent.**

***Index Terms*—Minimally-invasive surgery, robotically-assisted surgery, telemedicine.**

I. Introduction

As PART OF a technology demonstration entitled Operation Lindbergh, we undertook the adaptation of a commercial surgical robotic system, Computer Motion, Inc.'s Zeus™ (Goleta, CA), in order to create a version that could support teleoperation across long distances. Operation Lindbergh achieved the first remote human telesurgery. Prior to this project, there have been telepresence and teleoperation experiments [3], [5], [10] with the objective of assessing the effects on a surgeon's ability to operate with latent feedback. There have been partial operations [11] and tele-assist maneuvers [7], [12]. Operation Lindbergh is the first surgery where the operating surgeon was removed from the operating room to perform minimally-invasive surgery on a human patient. In this case, the surgeon was in New York City and the patient was in Strasbourg, France.

There are several reasons for the interest in telesurgery. Most everyone will, at some point in their lives, undergo some form of surgery. It is unfortunate but true that the quality of surgical proficiency is not consistent across geographic or economic boundaries. Those who live in rural or underdeveloped areas are likely to have more limited access to high-quality healthcare.[1] New state-of-the-art procedures can even be difficult to obtain in large metropolitan areas. The technology described here shows that we now have the ability to remove distance barriers from surgery. This ability can ultimately benefit patients by: 1) providing surgical care to patients who would otherwise go untreated; 2) improving the overall quality of care by enabling expert surgeons to proliferate their skills more effectively; and 3) reducing the cost by eliminating unnecessary patient and surgeon travel. Clearly, there are many nontechnical obstacles to making this an everyday reality, including issues of licensing, reimbursement, liability, etc. However, this starting point provides a metric that will allow us to begin evaluating such issues.

The authors would like to frame this project as a proof-of-concept of a new generalizable capability. By integrating telerobotic systems with standard telecommunication systems, surgeons from one location were able to interact collaboratively with surgeons from another location. In some sense, this is an extension of the telecommunication infrastructure that already exists, but with added physical interaction capability. Telephones enable verbal interaction, fax machines enable written interaction, video conferencing enables visual interaction, and robotics is the only means to enable physical interaction over a distance. The application chosen here is one of surgery, for the reasons explained. However, in the future, it may be appropriate to physically interact using robotics and the growing telecommunication infrastructure for a wider range of applications.

II. The Robot

The Zeus robot [4] is particularly well suited to telesurgery for two main reasons. 1) It is already in a master–slave configuration that naturally and cleanly separates into two distinct parts. There is a master console from which the surgeon controls the surgery and a set of positioners and camera-control equipment that is mounted on the operating room table. Though designed for use where the surgeon is in the same operating room

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[1]Modern wireless technologies can often be employed to bring such previously isolated areas into full network connectivity.

(a)

(b)

Fig. 1. (a) Surgeon-side and (b) patient-side equipment.

with the patient, the equipment comprising Zeus includes console-related electronics and positioner-related servo controllers with cabling interconnecting the two. 2) It is a fail-safe machine that has been used extensively in standard minimally-invasive surgeries.

A. Surgeon's Console

Fig. 1(a) shows the surgeon's console. In addition to providing a stable platform upon which the control handles are mounted, the console includes a high-quality video monitor for displaying the view from the endoscope and a touch-screen panel for setting various options and interacting with the central control computer. There is remarkably little processing performed on the control handle signals within the master console equipment, especially as compared with the video signals. In essence, the handles' positions and orientations [five degrees of freedom (DOF)] are acquired by a fully redundant set of sensors with the outputs of those sensors appearing directly at the cable socket for attachment to the servo control electronics residing near the slave robots. Outputs from the surgeon console sensors include analog voltages, quadrature readings (from optical encoders) and digital inputs/outputs (I/Os). Every sensor channel is represented by two implementations so that errors can be detected and appropriately dealt with.

B. Patient-Side Robots

On the patient-side there are several subsystems [Fig. 1(b)]: three servo control units for three robotic arms (two positioning the instruments and one positioning the endoscopic camera), and one instrument driver/controller to manage the control of graspers, scissors, or other instruments. The signals feeding these various control units come directly from the sensors in the surgeon's master console. There are also digital commands expressed as packet-oriented messages issued by a central processor housed in the surgeon's console and exchanged via RS232 serial connections.

Each controller associated with the patient-side equipment has its own power supply and case. Each unit acts quite autonomously, controlling and driving its resources in accordance with the sensor readings coming from the master console. Coordination between the various positioners and controllers occurs through the serial message exchanges with the central computer that is housed in the master console.

III. Transformation for Telesurgery

Separating the Zeus system into a set of surgeon-side equipment and a set of patient-side equipment was accomplished by the introduction of two telecommunications computers. Each computer provided a direct cable attachment to its local equipment. It intercepted the signals flowing in the cables and arranged appropriate conversions so that the signals could be transmitted over a telecommunications link and then recreated on the other side. In addition, we incorporated a switch for the patient-side staff so that if needed, they can block the remote control of the robotic instruments. Overall, the approach was implemented without modifying the standard Zeus product. Thus, Zeus-TS, the telesurgical version, retains the robust error checking and fail-safe behavior of standard Zeus, even while operating in a teleoperative mode. Another advantage of this implementation is that any standard Zeus can be easily converted into a telesurgical Zeus-TS.

A. Telecommunications Computers

The new equipment added in order to complete the adaptation in support of telesurgery included a surgeon-side interface (attachment point for the cabling emerging from the master console sensors), a surgeon-side telecommunications computer, a patient-side interface (attachment point for the cabling emerging from the positioner control units), and a patient-side telecommunications computer. Both telecommunications computers were standard ruggedized Pentium-based compact-PCI units with 100 base-T ethernets for attachment to a network. These systems run the VxWorks real-time operating system [13] with custom application software that implements the appropriate conversions, network exchanges, and safety implementations to produce reliable surgical teleoperation.

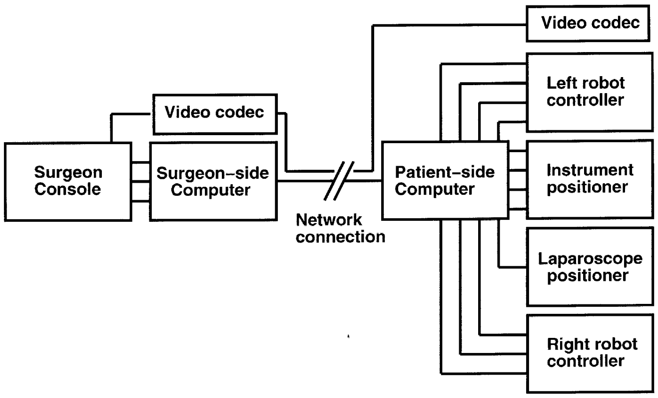

Fig. 2. Telesurgical system after separation.

Fig. 2 depicts the system after the real-time telecommunications computers have been added. Note that each of the units that comprise Zeus sees precisely the interface they were designed to expect. The only differences experienced by these individual units will be in the timing. This is the next area of discussion.

B. Timing and Synchronization

One of the concerns shared by all participants of Operation Lindbergh was the effect (and *amount*) of latency on the surgeon's ability to operate. A study [3] has recently been published on the effect of communications latency on the ability of a laparoscopic surgeon to perform various surgical manipulations. The study found that latencies of up to 700 ms could be tolerated. Based on experience with transcontinental [6] and transatlantic telecommunication circuits, the minimum round-trip latency for Operation Lindbergh was anticipated to be in the range of 110–140 ms. Section IV describes a set of experiments that were conducted as part of this project to evaluate the effect that various amounts of latency had on telesurgery. It was found that latencies up to 330 ms were manageable and safe for the type of surgery that was to be performed, given the excellent quality-of-service conditions of our networking infrastructure.

The Zeus surgical robot is a sampled system, utilizing digital signal processing techniques to filter and smooth sensory inputs. This is extremely helpful for the telesurgical application as well, since digitized sensor readings will be reconstructed at the remote end and small amounts of telecom burstiness, jitter, and quantization effects are filtered out there. There were only two areas where timing and synchronization issues appeared and had to be addressed in our separated system.

C. Handle Locking

Standard laparoscopic graspers have a locking mechanism built in. The purpose is to maintain grasping force on tissue without requiring the surgeon to continuously squeeze the handles. In Zeus-TS, we emulated this "handle locking" feature. When enabled by the surgeon, handle locking utilizes force feedback to create the feeling of a detent in the action of the control handles. In locking mode, as the handle is slowly squeezed it exhibits an increasing amount of force on the user until a particular point, at which the handle electronically locks into position. At this point, the force feedback is lessened, creating the feeling of the tool coming into a locked position. At the same time, the tool is held in this position at the patient-side equipment.

Because of the sensitivity of a human subject to the timing associated with force feedback and because packaging constraints did not allow the full force feedback loop to be closed between master and remote site, the communications computer on the surgeon side provides the required force feedback in a way that is directly similar to what is done by the force feedback circuitry residing in the patient-side equipment controller. The impedance of the force feedback motor (located on the surgeon side) normally seen by the controller (residing on the patient side after separation) also had to be simulated by the incorporation of a resistive network in order to keep the patient-side equipment from faulting due to detection of an open-circuited force feedback motor.

D. Packet Acknowledgment

The various controllers comprising Zeus exchange packet-oriented messages with the central computer located in the surgeon's console. These messages implement various keep-alive watchdog timeouts and they carry various parameter settings from the surgeon as well as status coming back from the patient-side controllers. All message exchanges are based on a simple custom packet-based protocol. Packets have sequence numbers, and every packet that is sent is acknowledged by the receiver. In the standard Zeus system, the timeouts for message exchanges have a short fixed setting well below the communication delays we expected and experienced during our transatlantic cases. There is also the use of the Socrates™ system as part of Zeus-TS. Socrates allows remote control of the robot holding the endoscope (in addition to providing access to operative data for the remote surgeon). The interface for Socrates is a custom graphical user interface that controls a serial communication (packetization) method similar to the Zeus serial communication. This packet stream travels through the same communications mechanism as the other serial streams of Zeus-TS.

If a packet is not acknowledged within the timeout period, it is considered an error and appropriate actions are taken to recover. With a large physical separation between the surgeon side and the patient side, we knew it was not possible to meet the acknowledgment deadlines. It would have been relatively easy to simply change the timeout deadlines inside Zeus, but our hierarchical buildup strategy (using Zeus as a drop-in component) strictly forbade any changes to be made.

Fig. 3 depicts the approach developed for remoting the serial communications. The protocol used between Zeus modules requires acknowledgment for the reception of each packet. Many transactions cause a response data packet to be sent back. Such response packets also get acknowledged when received. In the Zeus-TS setup, the local communications computer intercepts the serial stream and locally acknowledges all packets. Once each packet has been received and acknowledged, it is queued for transmission to the other side. Once received, it is delivered in order and without loss or duplication to the receiving equipment, just as if it had been in the same room with the sending equipment. When acknowledgments are generated by local equipment due to the receipt of a packet from the remote

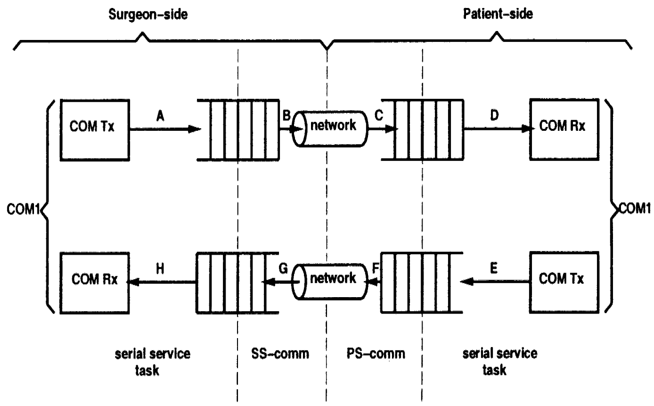

Fig. 3. Serial channel structure (one of four identical setups).

side, they are intercepted by the local communications computer and processed accordingly. The software to handle these RS232 messages with local acknowledgment replacing remote ones was perhaps the most complex part of the overall telesurgical adaptation. There is nothing intrinsically difficult going on but the correctness of the timing and sequencing had to be assured, even in the face of dropped or corrupted packets along the communications path. The methods for dealing with communications anomalies are the subject of Section III-F.

E. Network Communication

The communicating computers use 100 base-T ethernet operating with internet user datagram (IP/UDP) protocol. Ethernet was the communications interface of choice because of its wide acceptance, availability, and reliability. Because of this choice, the system can easily be staged or tested almost anywhere without any special communications circuits or equipment.

For Operation Lindbergh, the New York site was connected to the Strasbourg, France site via a single private virtual channel provided by a commercial telecommuncations carrier. The provider, France Telecom, chose to use a 10 Mb/s constant bit rate (CBR) virtual asynchronous transfer mode (ATM) circuit whose bandwidth was reserved out of a transatlantic OC-3 fiber. Of the 10 Mb/s available, 70% was allocated for transporting the high-quality video image (full-motion phase alternating line (PAL) video displayed on a 21” high-resolution medical-grade monitor). In addition to the robot control packet traffic, there was sufficient capacity left for bidirectional low-quality (webcam) video as well as several IP-phone calls.

Robot control used far less bandwidth than the video. The payload of the UDP packet sent from the surgeon side to the patient side was 152 bytes in size with 128 packets sent each second. The payload of the UDP packet sent from patient side back to surgeon side was 88 bytes in size with 128 packets sent per second. Thus, the total communications bandwidth required for the UDP payload corresponding to the remote controls for the robot was only 30 720 b/s. With IP/UDP overheads and ATM/SONET framing added by the telecom gear, the bandwidth used by the robot was well under 60 Kb/s, including all embedded serial communications streams as well.

F. Communications Anomalies

Any teleoperated system must be greatly concerned with the overall quality of its communications. Modern fiber-based telecommunications systems offer very high-quality links with the probability of a bit error in the fiber channel on the order of 10^{-9} or better. With multigigabit signaling and limited carrier-provided error detection and correction, even such excellent error rates still predict a few bit errors per second. These statistics demonstrate that failures are expected rather frequently, and therefore, our protocols must be able to tolerate them as a normal part of system operation.

As in any real-time system, the timely delivery of process data is of paramount importance. Though not *strictly* true, one could say that having the data on time is almost more important than having perfect data correctness. Naturally, one would hope to have perfect error-free data delivered on time and in a continuous stream without glitches or interruptions of service. Unfortunately, this is not always possible. A number of anomalous situations can occur:

- single- or multiple-bit errors in a packet or fragment;
- dropped packets (or packet fragments);
- delayed packets (burstiness, jittery packet flow);
- out of order packets.

Single- or multiple-bit errors are detected in three ways. At the ATM level, there are header checksums. These are added and checked by the ethernet-to-ATM [2] mux/demux hardware. At the ethernet level, there is a 32-bit frame check sequence. This is a cyclic redundancy check (CRC) polynomial that is computed and attached to all ethernet frames by hardware in the ethernet media access layer. Finally, there is a software checksum of the UDP packet payload. Certainly, one or all of these methods will catch any corruption of packet data that occurs. Detection of an error by any of these methods results in the discarding of the erroneous packet.

Dropped packets are detected by a check of sequence numbers placed in each packet by our application software. When a packet with a nonconsecutive sequence number arrives, its checksum is checked (as described above) and then, if well formed, its sequence number is inspected. If the packet corresponds to newer information than previously seen, we use it and simply record the fact that one or more packets have been lost. If, on the the other hand, the sequence number indicates an out-of-order packet containing information older than the most recent known-good packet, then we simply discard it. Old information is not useful in a real-time control system.

The system deals with delayed packets and burstiness by keeping track of packet arrival rate. The number of packets arriving each second is compared with the expected number (128). An arrival rate higher than 128 is possible due to burstiness but is not typical. The largest arrival rate we have ever seen with this system is 130. Excessively bursty circuits might potentially cause a problem, because it would appear that jerky movement of the robot had been specified. With the filtering inherent in Zeus, we have not found this to be the case, even when operating on a large, busy ethernet rather than a CBR ATM link with reserved bandwidth and excellent quality-of-service.

When the packet arrival rate falls below the 50% point (i.e., 64 or fewer packets arriving in the previous second), the system considers the communications link to be broken and the robot is placed in *local mode* until the packet rate climbs back within nominal range.

G. Local Mode

Because the Zeus system itself has been built to be fail-safe in the face of hardware and software faults, there are many redundant signals and cable-sensing hardware checks. If any of the primary and redundant paired signals are found to be in an incorrect relationship, the response will be to shut down and report the error.

This behavior is an essential part of the fail-safe techniques needed for telesurgical applications, but there is one complication. Since all signals at the interfaces to Zeus equipment are emerging from one of the two computers that have been interposed to provide remote communications to the telesurgery system, and since the signal value to be driven on each such interface is nominally received in a communications packet from the other side, system startup must be dealt with in a specialized way.

The approach taken is the creation of *Local Mode*. The surgeon- and patient-side computers have a defined default value for every analog and digital output that they are capable of driving. Whenever the communications between the two telesurgical sites is not established, the systems go into local mode, and in this mode, the default values are driven onto the interface signals. These values are chosen so as to keep the Zeus controllers from performing a fail-safe shutdown. Specifically, all primary and redundant pairs are driven to appropriate quiescient signal values as measured in a normal, unseparated Zeus system. The goal of local mode is to ensure that the Zeus controllers will never shut down *due to a fault in communications* but without compromising their regular built-in fail-safe capabilities should a real internal hardware or software fault occur.

There is one important distinction that needs to be made here. The behavior at startup (before communications have been established) is a bit different from the behavior that occurs during communication interruptions after normal operation has begun, i.e., after normal communications has once been successfully established. In the startup case, the local-mode defaults are driven onto every interface signal as described above. After communications have been successfully established, it will be the case that all local-mode signal values have been replaced on each interface by the remote value arriving in the communications packet from the other-side system. In the case of a communications interruption after startup, the local mode behavior is different on patient- and surgeon-side systems. On the surgeon side, the standard local-mode behavior remains, just as described above. But, on the patient-side system, all signal outputs destined toward the operating table equipment are left at their last value, causing the system to stop all motion and essentially freeze in its last position. Simultaneously, the surgeon-side computer detects the loss of communications and its own change into local mode turns on various light-emitting diodes (LEDs) and notifications so that the surgeon is made aware of the service interruption. Once communications have been restored, the system automatically moves from local to online mode, and its operational capabilities are restored. The timescale of communications interruption can range from a small part of a second (barely perceptable during system usage) to much longer (which would likely necessitate conversion of the telesurgery to a more traditional, locally performed surgical procedure).

IV. Latency Experiments

As part of the development of the telesurgical adapations to Zeus, a set of animal experiments was conducted. The first such test occurred in July 2000 in Strasbourg, France [1]. This was the first time that the telesurgery system had been used for a live operation, though many times before it had gone through "dry run" tests. The purpose of this experiment was to gain experience with telesurgery and investigate the effects and limits of latency by performing a laparascopic cholesystectomy on a swine model.

A. Initial Latency Tests

The surgeon-side and patient-side systems were staged within the same operating room at IRCAD/EITS, a teaching center in Strasbourg, France. Though the two parts of the robotic system were co-located, their connection went over telecommunication circuits, up to Paris and back with extra routing within France, in an attempt to maximize latency. Though the virtual circuit included 16 ATM switches and traversed over 3000 km, there was only 11 ± 3 ms round-trip latency. This was somewhat dissappointing, given the estimate of $110 - 140$ ms of latency anticipated for the transatlantic connection. Nevertheless, the telesurgical experiment proceeded.

During this animal testing experiment, there was one minor problem with the telesurgical add-on (a critical printed circuit board was damaged during shipping) and there were major problems with the quality of the video. Surprisingly, there were no serious issues or challenges arising from latency effects. In order to investigate the true limits of latency, we artificially added latency during the surgery. The telecommunications provider, France Telecom, had a broadband tester that could add delay, insert single- as well as multiple-bit errors, and add burstiness and/or jitter to the packet stream. With this piece of equipment, it was possible to add up to 224 ms of delay to one of the two directions.[2] In order to gain the effect we needed for accurate simulation of transatlantic latency, we needed to add an equal amount of delay in the other direction as well. For this, it would have been necessary to obtain a second broadband tester or to arrange some sort of delay via software.

The Zeus-TS software had been created with the capability to artificially add delay to either or both directions of packet flow. The software also had means to probabilistically drop packets, simulating any desired amount of corrupted packet traffic to/from the telecom circuits. The packet delay feature was used to match the delay added in one direction by the broadband test

[2]ATM circuits always have the topology of a ring. Thus, every ATM interface has an outgoing and an incoming direction.

equipment in order to accurately simulate various degrees of latency.

In all, four experienced laparascopic surgeons tested the system while several different latency settings were applied. We varied the delay from the minimum (direct-wired connection within the operating room) to 5.5 ms (actual one-way ATM virtual circuit within France) to 56 ms added, then 112 ms added, then 224 ms added artificially. The artificial delays (56, 112, 224 ms) were added in both directions. Thus, the total latency was the sum of the virtual round-trip circuit plus twice the added delay.

Because the video codec information did not flow through the Zeus-TS computers, it was not possible to add delay to the video streams via software. This fact vastly complicated things and made our experiment much more difficult to perform and evaluate. It was decided that the most accurate simulation possible with the available equipment would be to add extra delay between the surgeon-side computer and the telecom circuits, so that the robot was delayed significantly more than it would have been with a real transatlantic delay, while the video feedback returned to the surgeon with only the delay added by the broadband tester. This setup made it possible to balance the delays in order that the overall effect remained realistic.

Another complication to our latency experiments was the qualitative nature of evaluation. It was a subjective judgement of each surgeon as to whether he could or could not perform the operation with each setting of latency. At the end of the set of experiments, it was generally agreed by all that the "comfort zone" for performing telesurgery with respect to latency was about 330 ms. Anything less than this delay between commanded action and observed response seemed to be relatively easy for the surgeons to deal with. Latencies higher than 330 ms were more problematic. Some surgeons felt they could learn to adapt to delays up to 500 ms, but they were not comfortable in doing an operation on a human subject under such conditions. Given the expectation that the transatlantic feedback latency would be less than half of the 330-ms qualitative limit, all present were confident in the prospect of performing a fully remote human telesurgery.

B. Transatlantic Animal Testing

Following the latency experiments described above, the telesurgery system was repackaged and extensively tested in compliance with European CE Mark and U.S. Food and Drug Administration standards. The previous issues with poor video quality were solved through selection of a higher quality video codec and allocation of more bandwidth for video.

In July 2001, the systems were installed in New York (surgeon side) and Strasbourg (patient side). As required by various regulatory bodies, a second set of animal surgeries was conducted. This time, the experiments were performed using the actual transatlantic circuits and all aspects of the setup were identical to that of the planned human telesurgery. Fig. 4 shows the patient-side setup during these animal trials.

The transatlantic virtual circuit was tested and found to have a round-trip delay of 88 ms. The video codecs added about 70 ms for their processing of the video images. Thus, the end-to-end latency, as perceived by the surgeon from the instant that he moves any of the master console handles until he sees the resulting motion on his video screen, was approximately 155 ms, well within our previously determined comfort zone. In addition, the video image quality was extremely high. The surgeons were pleased with the setup.

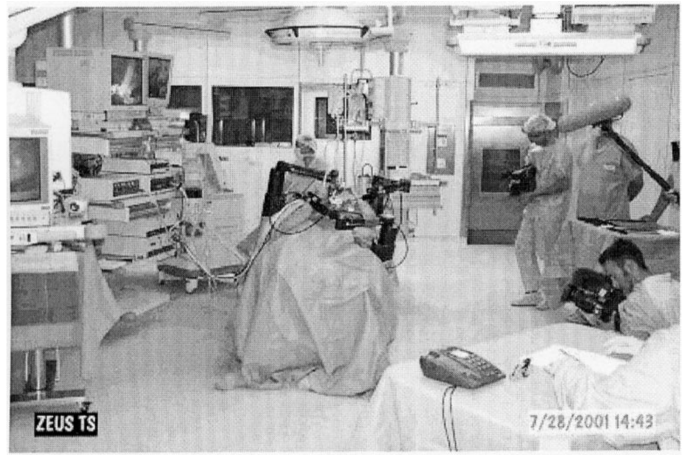

Fig. 4. View of patient-side equipment in Strasbourg, France.

TABLE I
ZEUS-TS ANIMAL STUDY DATA, JULY 2001

Date	Pig No.	Wt (kg)	Gallbladder Dissection (min)
7/26/01	1	45	80
7/26/01	2	40	46
7/26/01	3	50	29
7/27/01	4	30	41
7/27/01	5	35	57
7/27/01	6	32	28
Average		39	47

Six experimental lap choles were performed on swine models. All were successful. In case #5, however, there was a perforation of the gall bladder. The lead surgeon, Prof. Marescaux, stated that such events do occasionally occur in standard nonrobotic lap choles. In this case, the perforation was attributed to weakness in the gall bladder wall and was not related to the use of robotics.

Table I summarizes the gall bladder dissection times for the six animal cases. The gall bladder dissection time was the elapsed time from the first gall bladder manipulation by the surgeons in New York until the gall bladder was completely dissected. The average dissection time of the gall bladder for the six animal cases was 47 min. The network latency measured during each case (88-ms round-trip plus video codec times) remained remarkably constant, with a variation of $\pm$ 50 μs.

The result of the July 2001 transatlantic animal trials was that the system was fully ready for the human case as soon as the regulatory bodies approved it. Further, we determined that it was prudent to have an external webcam view of the operating room provided at the surgeon's site.

V. OPERATION LINDBERGH AND CONCLUSIONS

Operation Lindbergh was staged on September 7, 2001. A 68-year-old human female patient in Strasbourg, France, was successfully operated upon by surgeons located in New York City, corresponding to a separation of more than 4,300 miles. The operation lasted 54 min, a duration considered nominal even for normal, nontelesurgical laparascopic cholesystectomy. Within two days, the patient was released from the hospital without complication.

Operation Lindbergh [8] has demonstrated that the technology exists today for safe and effective remote telesurgery. The limiting factor for telesurgery is the latency of the video feedback. For Operation Lindbergh, the 155 ms latency was found to be well within the comfort zone. The surgeons who used the Zeus-TS system stated that they felt they could use it to do any of the minimally-invasive procedures for which they can use a standard Zeus, e.g., nissen fundoplication, colectomy, spleenectomy, appendectomy, lap chole.

The latency experiments performed in preparation for this project have shown that surgeons can adapt to telesurgical latencies up to 500 ms, with 330 ms being the maximum latency recommended. The animal tests, as well as the ultimate human Operation Lindbergh case, have demonstrated that laparoscopic procedures (specifically lap chole) can safely be done via telemanipulation and that the operation times are comparable to that of normal nonrobotic procedures.

Though we have demonstrated the concept and feasiblility of remote telesurgery, we have done so using quite extensive (and expensive) telecommunications resources. It is realized that the demonstration as conducted in Operation Lindbergh does not represent a cost-effective approach, nor does it constitute a viable scenario. Rather, it represents the first important step toward the goal of closing the distance gap between expert surgeon and patient and toward making remote telemanipulation applications more generally available. Future work will involve the reduction of bandwidth and increasing the flexibility of telecomunications infrastructure needed for telesurgery, as well as improving the Zeus-TS platform.

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References

[1] S. E. Butner and M. Ghodoussi, "A real-time system for telesurgery," in *Proc. IEEE Int. Conf. Distributed Computing Systems*, Mar. 2001, pp. 236–243.

[2] R. Cole, D. Shur, and C. Villamizar, "IP over ATM: A framework document," *Internet Eng. Task Force, Internet Draft*, July 1995.

[3] M. D. Fabrizio *et al.*, "Effect of time delay on surgical performance during telesurgical manipulation," *J. Endourology*, vol. 14, no. 2, Mar. 2000.

[4] M. Ghodoussi, S. Butner, and Y. Wang, "Robotic surgery – The transatlantic case," in *Proc. 2002 IEEE Int. Conf. Robotics and Automation*, May 2002, pp. 1882–1888.

[5] P. Green, J. Hill, J. Jensen, and A. Shah, "Telepresence surgery," *IEEE Eng. Med. Biol. Mag.*, vol. 14, pp. 324–329, May–June 1995.

[6] J. Jamison *et al.*, "vBNS: Not your father's internet," *IEEE Spectr.*, vol. 35, pp. 39–46, July 1998.

[7] B. Lee *et al.*, "A novel method of surgical instruction: International telementoring," *World J. Urology*, vol. 16, pp. 367–370, 1998.

[8] J. Marescaux, J. Leroy, M. Gagner, F. Rubina, D. Mutter, M. Vix, and S. Butner, "Transatlantic robot-assisted telesurgery," *Nature*, vol. 413, pp. 379–380, 2001.

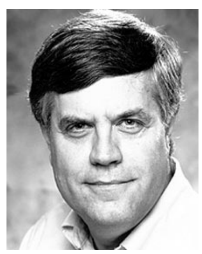
[9] A. Rovetta, R. Sala, F. Cosmi, X. Wen, D. Sabbadini, S. Milanesi, A. Togno, L. Angelini, and A. Bejczy, "First experiment in the world of robotic telesurgery for laparoscopy carried out by means of satellites networks and optical fibers networks," in *Proc. 19th Int. Conf. Industrial Electronics, Control, and Instrumentation*, 1993, pp. 51–56.

[10] R. Satava and I. B. Simon, "Teleoperation, telerobotics, and telepresence in surgery," *Endoscopic Surgery*, vol. 1, pp. 151–153, 1993.

[11] M. O. Schurr, H. Breitwieser, A. Melzer, W. Kunert, M. Schmitt, U. Voges, and G. Buess, "Experimental telemanipulation in endoscopic surgery," *Surgical Laparoscopy and Endoscopy*, vol. 3, no. 6, pp. 167–175, 1996.

[12] P. G. Shulam *et al.*, "Telesurgical mentoring," *Surgical Endoscopy*, vol. 11, pp. 1001–1005, 1997.

[13] *VxWorks Programmer's Reference*, Wind River Systems, Inc., 1996.



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