THE INTERNATIONAL JOURNAL OF MEDICAL ROBOTICS AND COMPUTER ASSISTED SURGERY
Int J Med Robotics Comput Assist Surg 2006; **2**: 216–224.
Published online in Wiley InterScience (www.interscience.wiley.com). **DOI:** 10.1002/rcs.99

ORIGINAL ARTICLE

Long-distance robotic telesurgery: a feasibility study for care in remote environments†

R. Rayman[1,2]*
K. Croome[1]
N. Galbraith[1]
R. McClure[1]
R. Morady[1]
S. Peterson[1]
S. Smith[1]
V. Subotic[1]
A. Van Wynsberghe[1]
S. Primak[1]

[1]*Canadian Surgical Technologies and Advanced Robotics (CSTAR), London Health Sciences Centre, London, Ontario, Canada*

[2]*Department of Medical Biophysics, The University of Western Ontario, London, Ontario, Canada*

*Correspondence to: R. Rayman, London Health Sciences Centre, Division of Cardiac Surgery, 339 Windermere Road, London, Ontario, Canada N6A 5A5. E-mail: raymanr@aol.com

†No conflict of interest was declared.

Accepted: 7 July 2006

Abstract

Background Basic telesurgical manoeuvres were conducted with signal delays.

Methods Eight test subjects conducted four manoeuvres. Time delays of 0–1000 ms were investigated. Time to task completion and error rate were recorded in sequential delays of 0–600 ms. Additionally, blinded random delays of 0–1000 ms were studied.

Results In the sequential trials (0–600 ms), there were no significant differences in average task time compared to zero latency. The error rate remained low despite increasing time delay, and was significantly less at 500 ms ($p < 0.05$). In the random trials, task time was significantly greater at delays of 500, 600, 800 and 1000 ms ($p < 0.05$). There were no significant differences in error rates ($p = 0.252$).

Conclusions Operators are capable of performing surgical exercises at significant delays. Latent video feedback is difficult for telesurgery. Visual or virtual reality cues should be implemented to aid the operator in a high-cadence telesurgery environment. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords robotics; surgery; telesurgery; internet; remote care

Introduction

The use of robots in surgery is increasing, as the technology allows intricate procedures through port access incisions. For the past five years, surgeons have used robots to perform single coronary artery bypass, prostatectomy and gastric fundoplication with 5–10 mm incisions. Surgical robots will continue to be used in more procedures as more powerful technologies are introduced.

Long-distance robotic telesurgery is defined as the performance of surgery using a robot platform over a communication link. The remote surgeon sits at a central console and performs surgery on a patient, using a slave robot at a different location.

Robotic telesurgery has the potential to significantly improve health care in remote communities and provide cost-effective services. Surgical care in remote or non-terrestrial environments will require sophisticated instruments, apparatus and communications networks. In order to provide timely care, an expert surgeon could provide therapy to a patient thousands of miles away. Populations in remote environments may encounter variable surgical problems, and a variety of surgeons might be called upon to provide treatment or training to local medical crews.

The ability of the operator to overcome significant delays during surgery is unknown. Long-distance surgery represents one of the most demanding multimedia applications to date, with little room for compromises in quality of service or audiovisual fidelity. Additionally, the robotic platform would need to be highly ergonomic and provide the surgeon with complete awareness of the patient's status.

Although teleoperation has been incrementally studied over the past 15 years (8,19), the field of robotic telesurgery is quite new. There is only one telesurgery-capable, three-armed robotic system worldwide. This system allows full robotic instrument and camera manipulation from the console, and places realistic surgical demands on the operator and the communications network. It is the only clinical-grade, telesurgical robot in existence.

Our research group has now been provided with this telesurgery platform. We are testing the platform in a stepwise process of discovery, with a focus on defining what can and cannot be done, especially with respect to limitations of latency, bandwidth and platform architecture.

Using this platform, Butner and Ghoudoussi (4) gave qualitative insight into how much latency was comfortable for the surgeon. While 330 ms was the maximum latency recommended, they did not provide stepwise, quantitative information of telesurgical performance.

The work of Marescaux *et al*. (16) provided the first proof of concept that the system was capable of live patient surgery. Their trans-Atlantic case on a female patient was conducted with latency of 155 ms, but they could not ethically perform varying latency experiments during this human procedure.

Anvari *et al*. (1) reported quantitative data of the impact of latency on performance of telesurgery for the first time. The group showed that operators using the telesurgery system required significantly more time to complete tasks as latencies approached 500 ms, with an associated increase in error rates. Similar results have been demonstrated with less sophisticated platforms (5,21).

Human and technical limitations during telesurgery need to be defined. Moving forward, telesurgery could be applied to several scenarios, all with differing human resources, IT assets, and medical situations. Isolated environments, such as Canadian or other remote communities, non-terrestrial missions or hostile (battleground) situations are all instances where telesurgery would provide valuable patient care. A basic set of rules should be applied to all scenarios based on these limits.

Our initial experiments were designed to test the feasibility of typical manoeuvres during telesurgery. We used a novice group of operators to both test effectiveness at varying latencies and record any adaptation or learning which could occur. Additionally, the reliability and flexibility of prototype telesurgery and IT equipment was tested. Based on these results, a set of recommendations for the advancement of telesurgery equipment has been derived.

Materials and methods

Our group tested the feasibility of performing surgical manoeuvres at varying time latencies. In remote environments, the latency of commands would be a significant and rate-limiting factor in telesurgery. The perceived latency is the time difference between the surgical input by the operator at the console and the viewed manipulation (output) transmitted to the operator via a remote camera.

In a communications network consisting of analogue-to-digital encoding, network transmission and human reaction, the perceived time latency (T_P) is defined as:

$$T_P = T_{en} + T_t + T_r$$

where T_{en} is the time for encoding/decoding, T_t is the time for network transmission and T_r is the operator's reaction time to the output.

In a complex set of manoeuvres meant to complete a task, the time to complete a manoeuvre (T_M) consists of the perceived time latency (T_P) plus the time for the manoeuvre displacement (T_{move}) and the time to interpret and plan the next input (T_{plan}):

$$T_M = T_{en} + T_t + T_r + T_{move} + T_{plan}$$

An overall task consists of many such manoeuvres, each involving times for encoding, transmission, reaction, movement and planning:

$$\begin{aligned} \text{Task} &= T_{M1} + T_{M2} + T_{M3} + \cdots \\ &= (T_{en1} + T_{t1} + T_{r1} + T_{move1} + T_{plan1}) \\ &\quad + (T_{en2} + T_{t2} + T_{r2} + T_{move2} + T_{plan2}) + \cdots \\ &= {}^{n}\sum_{1} (T_{en} + T_t + T_r + T_{move} + T_{plan}) \qquad (1) \end{aligned}$$

where n is the total number of manoeuvres required to complete the task. These parameters are interrelated, have effects on one another, and are affected by the performance of the system used and by the human operator (e.g. a decrease in communications bandwidth would affect both transmission and interpretation and planning times). The implications and optimization of such a system will be discussed later.

We modelled surgical manoeuvres using the following exercises. For each exercise, the task completion times and error rates were recorded.

Surgical exercises

The robotic exercises were designed to simulate typical surgical manoeuvres. These involved object grasping and

DOI: 10.1002/rcs

precise placement, object steering and curved needle manipulation. We did not simulate more complex tasks, such as knot tying or precise suture placement (Figure 1). Our experiments were designed to determine whether even the simplest surgical tasks were feasible with signal delays. The experimental exercises were:

a) Pick up the orange cone with the left hand and place in circle. Then replace to the original position with right hand. Pass back and forth six times.
b) Pick up a rod with left hand. Pass the rod through three hoops without touching the hoop. Pass back and forth through the hoops four times.
c) Pick up the orange ring with left hand, grasping the ring at the black line. Manoeuvre the ring with both hands so that right hand only holds it at the black line. Do not drop or ground the ring during manoeuvring. Repeat back and forth four times.
d) Pick up a 6-0 needle with the right hand. Pass needle to enter right dot and exit left dot. Retrieve exiting needle with left hand. Reload needle back to right hand and repeat six times (dexterity hand may be reversed for left-handed people).

Eight test subjects from were assigned to complete the surgical exercises. Seven had no previous experience on the Zeus or other robotic systems. All subjects had access to the robotic system regularly. The group had a 1 week familiarization period and then performed the surgical exercises at transfer latencies (T_t) of 0–600 ms, in increments of 100 ms. Over 1700 exercises were conducted in the sequential trials.

Additionally, a core group of four subjects performed the exercises with random delays between 0 and 1000 ms. These subjects had been exposed to the platform 5 days/week over a period of approximately 4 months. Therefore, they continuously experienced the rigours of the system and latency demands and had the opportunity to learn or adapt. Approximately 200 exercises were conducted in the random trials.

Task time to completion and error rate were recorded for all exercises.

Robotic platform

The Zeus robotic platform (Intuitive Surgical Inc.) was designed with master–slave architecture consisting of a surgeon's-side console and patient-side robotic arms. Each side could be connected via multiple methods, including UDP Internet protocol, satellite or communications software. Our configuration of the NetDisturb software (22) could emulate variations in latency, packet loss or other transmission characteristics.

At the console, the surgeon sat with instrument controls in both hands and a video screen showing the surgical view directly in front (Figure 2a, b). The remote surgical

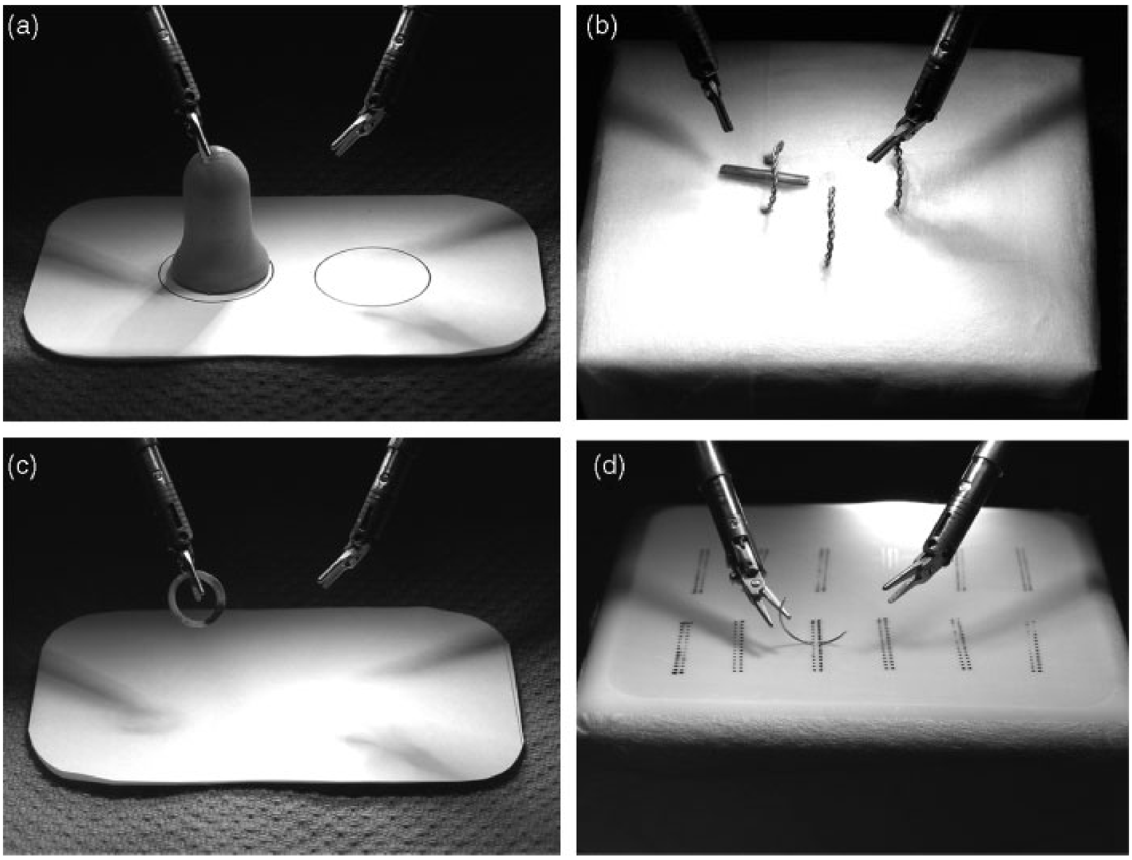

Figure 1. The four exercises (a–d) used in the experiments. These represented typical manoeuvres during surgery. Predefined errors during the tasks were recorded by an observer

DOI: 10.1002/rcs

endoscope camera was moved left, right, up, down, etc. using a mouse control interface. Both the live surgical and operating room views were provided. The surgeon also communicated with the remote surgical team via live audio exchange, using an in-room camera (Polycom Inc.).

At the patient side, three robotic instrument arms were used to perform surgery. One arm held a camera scope to provide the surgical view, while the others manipulated interchangeable instruments. The surgical arms had five degrees of freedom, with basic axis movements plus an additional wrist joint at the instrument end. A complete technical description of the prototype can be found in Butner and Goudoussi (4).

Telecommunications simulation

We had access to a transcontinental Internet private network (IP-VPNe), live partitioned satellite feed and telecom simulation software. The network architecture was designed to be fully redundant, with the possibility of human surgery in mind. The VPNe architecture had dual encoders, switches and routers, and the satellite transmission could act as a back-up if the VPNe failed (Figure 3). Both networks were high quality, 10 Mbps connections with minimal packet loss.

Figure 2. The robotic telesurgery laboratory set-up. The operator sits at a console (a) and has the surgical site video directly ahead on screen. Additionally, a remote room view is provided with live audiovisual connection (b)

For these experiments, the effects of varying latencies on performance and learning were investigated. We simulated latencies from 0 to 600 ms sequentially in 100 ms increments using NetDisturb software. Additionally, random delays between 0 and 1000 ms were tested. These latencies were chosen to simulate those expected in 'real-world' communications networks. Delays from 60 to more than 500 ms are characteristic in our communications test bed during ground-based IP or satellite transmissions (Table 1).

Results

There were no major technical issues with the robotic platform or communications network. Overall, the system worked well and all participants were able to complete the tasks over all latencies. Participants found the exercises to be challenging, and reported some fatigue in performing the tasks at higher latencies.

Sequential trials

The summarized results of all exercises in the sequential trials are shown in Figures 4, 5. Task times decreased for latencies up to 300 ms and then increased moderately. There were no significant time differences for any of the latencies compared to zero (repeated measures ANOVA, overall $p = 0.012$; Dunnett's t-test). Paradoxically, the error rate during the trials decreased with increasing delays. This trend was significant when comparing zero delay to 500 ms (overall $p = 0.002$; Dunnett's t-test).

Between individual trials, a spike in task time was observed as participants first encountered a higher latency. Trials subsequent to this at the same latency were performed with lower times. This trend seemed to be even more pronounced at higher latencies (Figure 6).

Random trials

During the random trials, participants were unaware of the latency they were to experience during an exercise. In a summary of all exercises, task times gradually increased with increasing latencies. The times were significantly higher than zero delay at latencies of 500 ms and above ($p < 0.001$; Figure 4). Despite the high latencies, there

Table 1. Laboratory communications test bed

	Transmission type	Bandwidth (Mb/s)	Approximate distance round trip (km)	Latency (T_t ms)
NetDisturb software	Emulated	Emulated	0	User-defined
Internet protocol (private partition)	UDP/IP	10	4150	65
Satellite	Ku band	10	71 000	600

DOI: 10.1002/rcs

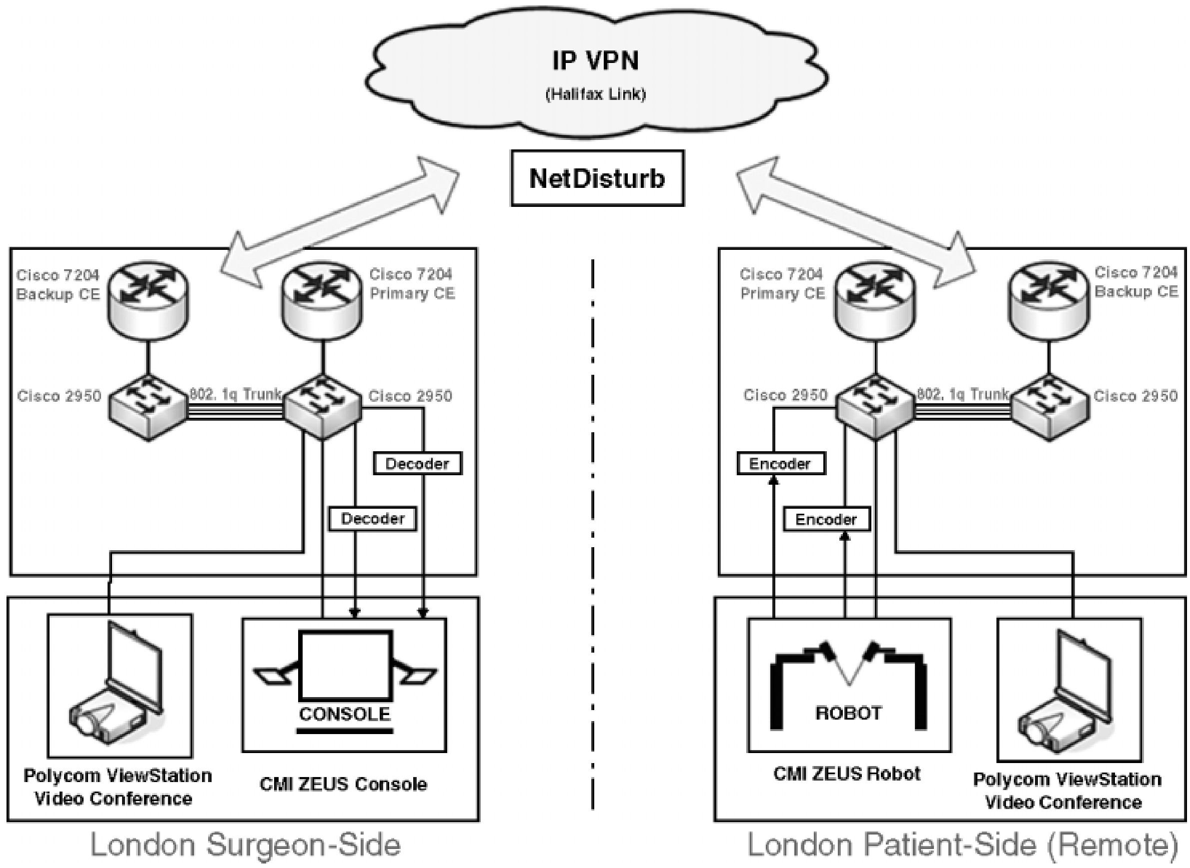

Figure 3. Communications test bed for the experiments. Signals from all devices were collected and multiplexed by a switch, creating a single data stream directed by a router. The networking hardware was fully redundant on both sides. The system automatically chose the most reliable link. Routers on each side could be connected in different ways to emulate different modalities of deployment. These were NetDisturb software (current experiments), long-distance UDP/IP or Ku band satellite

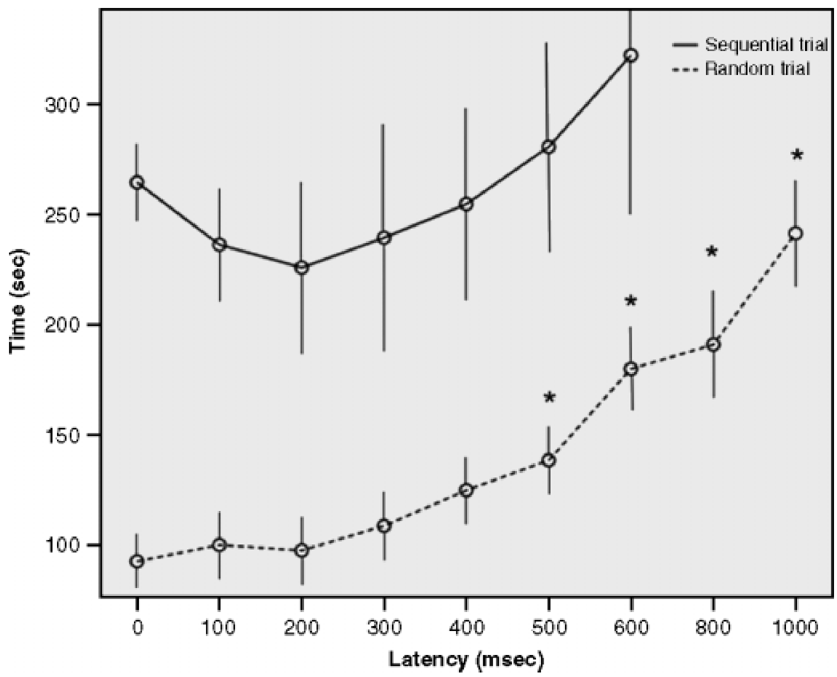

Figure 4. Overall time for task completion for the sequential and random delay trials at differing latencies. Random trial times were significantly greater compared to zero latency at 500 ms and beyond (repeated measures ANOVA, $p < 0.001$)

DOI: 10.1002/rcs

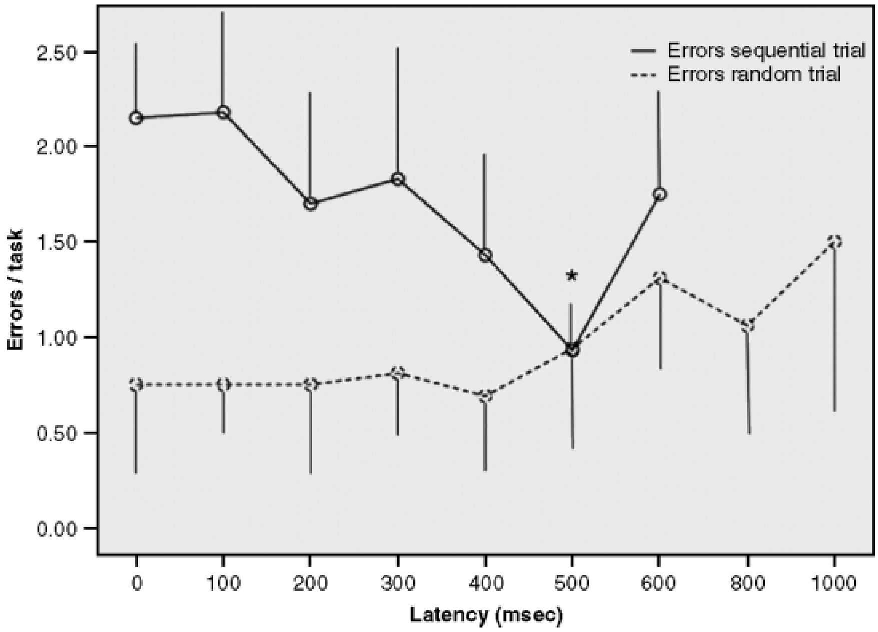

Figure 5. Error rates vs. latency for the sequential and random delay trials. There were no significant differences in error rate compared to zero latency except at 500 ms during the sequential trials ($p = 0.002$)

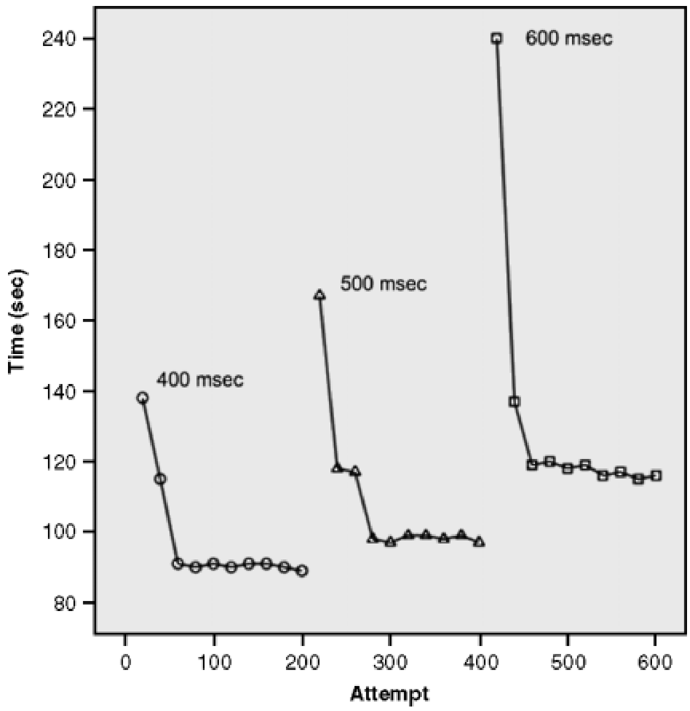

Figure 6. A typical example of task times during attempts at higher latencies during a particular exercise. Short-term learning occurred as the operator encountered a higher latency, then adapted to it during subsequent attempts. Latencies of 400, 500 and 600 ms are shown

were no significant differences in error rates compared to those experienced with zero latency (overall $p = 0.252$; Figure 5).

Discussion

The results of our study highlighted different strategies employed to overcome high latencies. Slowing of operator movements and 'move-and-wait' techniques were observed at higher time delays. In reference to equation 1:

$$\text{Task} = {}^{n}\sum_{1}(T_{\text{en}} + T_{\text{t}} + T_{\text{r}} + T_{\text{move}} + T_{\text{plan}})$$

the parameters under the control of the operator were the velocity of movement (T_{move}), the total number of moves

DOI: 10.1002/rcs

required for the task (n) and the planning time between manoeuvres (T_{plan}). Slowing the velocity of the movement would increase the time for any particular manoeuvre to occur (increased T_{move}). Employing a move-and-wait strategy would break smooth movements into a number of broken, staccato manoeuvres (thereby increasing n). Similar techniques have been reported by operators using latent systems both in surgical and aerospace applications (9,13). In both cases, although the task time increases, the error rate is decreased by increasing accuracy and simplifying the planning process.

The time and pressure added by recovering from an expected error, resetting instruments and planning of a new set of manoeuvres seemed to be more important for overall performance. Our test subjects worked to keep error rates low despite increasing latency (Figure 5). However, whether this type of strategy could be employed within real surgical scenarios is unknown. The cadence of surgery is often predicated by clinical urgency. An operator with only the 'raw data' of latent video feedback could find urgent manoeuvres quite difficult.

Both short- and long-term learning were observed within the experimental set. Short-term learning can be seen clearly in Figure 6, where the operator's time for task completion spiked with each newly encountered latency and then decreased as accommodation occurred.

In the sequential trials, our results showed a trend of decreasing task times up to 300 ms and error rates up to 500 ms (Figures 4, 5). We have associated this decrease with the effect we call 'long-term learning'. This type of learning is associated with improving performance through repeating a task a number of times. During this period, the operators were continuously gaining experience on the system beyond the 1 week familiarization period. The effect of long-term learning remained with the participant over the whole period of experiments (just over 4 months). The figures also indicate that the minimum amount of training needed to properly perform simple tasks can be achieved over relatively short periods of time, equivalent to a training period consisting of 3–4 weeks of 1h/day, three times a week.

During the random trials a similar trend was not observed, as most learning benefits had likely occurred by the 4 month mark. Overall task times and error rates were lower than the sequential trials, even beyond 500 ms. The participants likely demonstrated task proficiency and strategies derived from the previous 4 month experience. Latencies beyond 500 ms are likely to be experienced using satellite networks, and have not been previously studied (1).

What type of automation is appropriate for telesurgery?

Having only the raw data of latent video feedback in a real surgical scenario could be quite difficult for the operator. Unstable patients or challenging tissue manipulation would be incongruent with slowing of movements to overcome latency. Additionally, the duration of surgery could introduce significant fatigue for the operator. The question of user-predictive or other automation for use in telesurgery should be addressed.

In predictive displays, the operator is shown what will be expected to happen over the next interval of time, given the current system inputs. The prediction is usually shown on the operator's screen. This type of technology has been used on pilots' displays, ships, submarines and air traffic control displays for several years. In robotic telesurgery, a predictive display would show the surgeon where instruments would end up, given their current input and the latency. The surgeon could then 'lead' the actual process and perform larger manoeuvres with confidence.

For operator delays greater than 300 ms, Held et al. (12) has shown that sensory motor adaptation is impossible, and that subjects dissociate their own hand movements from those of the telerobot at these delays. The simplest predictive displays would show the operator a computer-generated screen cursor which is extrapolated forward in time. Given the current conditions of the system, a predictive model can be run many times faster than the actual process (Figure 7). An expected final point is shown if 'all conditions are kept the same as present', and could indicate where tools will stop with the given latency. Even these simple displays improve the performance of the operator (3). More sophisticated predictive technology could provide a virtual representation of the robot and its environment. In any movement, the virtual display can be used to understand how the robot will react, given the current network (15,18). Leading the actual process and performing larger manoeuvres can decrease task time by as much as 50% (20).

Whether higher levels of command are appropriate for telesurgery is unknown. In supervisory control, the operator commands the robot to perform a set of manoeuvres and monitors how they are performed. By doing so, the operator is removed from the control loop. The robot would need to possess sensory or other analytical capability in order to carry out the instruction set. This could be quite difficult in a three-dimensional space with variations in tissue elasticity and homogeneity. Current robots can perform complex, autonomous tasks in predictable, 'object-stable' environments (7,11,14). However, even the best visual and force sensing available would probably not suffice for autonomous tissue dissection or manipulation.

Finally, much work has been done in the area of wave transformation techniques to synchronize multiple users experiencing different latencies. Time-based algorithms can predict the next steps of multiple operators and compute and represent a pertinent state to all participants. This has been used extensively in on-line gaming (2,6,10,17). Although this is not directly applicable to telesurgery, the network architecture

Int J Med Robotics Comput Assist Surg 2006; 2: 216–224.
DOI: 10.1002/rcs

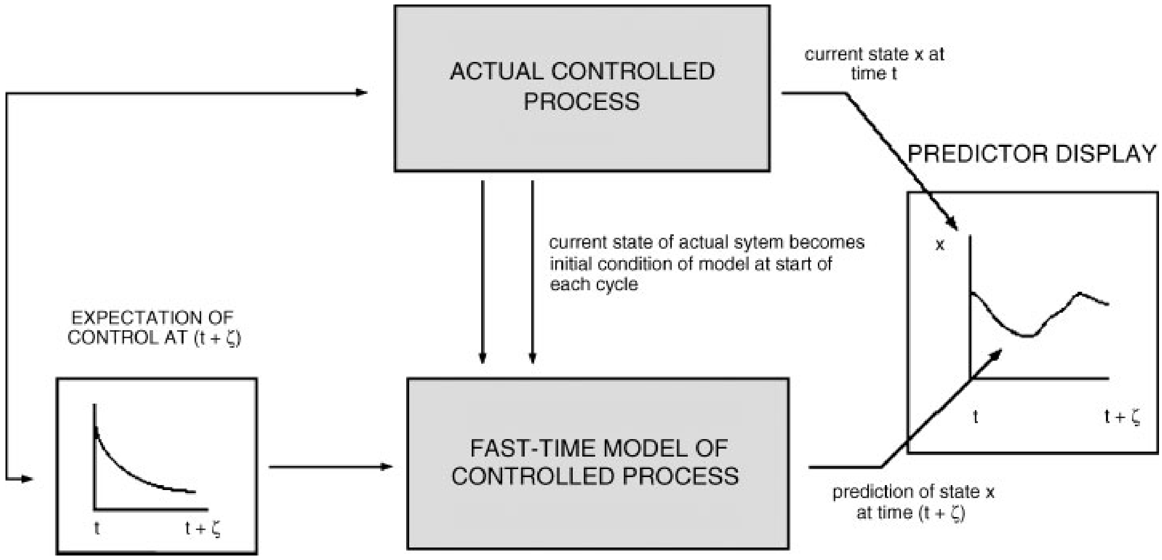

Figure 7. The Ziebolz and Paynter technique for latent systems prediction. The predictor model is run many times faster than the actual operating process. Therefore, prediction is based on the current inputs of the operator and constantly updated for accuracy

underlying such systems may be useful. The surgeon's 'next move' probably cannot be predicted because of variations in anatomy, which are unknown until exposed by dissection. However, more advanced server–client architectures interposed between operator and slave surgical robots may help minimize the effects of long latencies.

In conclusion, we have shown that operators are capable of performing surgical exercises at significant transmission delays. The surgical platform studied has been used effectively for small latencies (300 ms or less). For delays greater than 500 ms, slowing of movements minimized errors and simplified task planning. However, such strategies are not optimal for the cadence of surgery. Further platform modifications, such as visual or virtual reality cues, are required to provide the operator with more reliable predictors during high latencies.

Acknowledgements

The authors wish to thank the entire CSTAR telesurgery team, which included senior members of the Departments of Surgery and Electrical Engineering at The University of Western Ontario. This team was instrumental to the project.

This study was supported by the Canada Foundation for Innovation and The Ontario Research and Development Challenge Fund. The authors wish to acknowledge Bell Canada and Telesat Canada for their technical and facilities contributions. The authors do not have any conflicts to report which could affect the research.

References

1. Anvari M, Broderick T, Stein H, *et al*. The impact of latency on surgical precision and task completion during robotic-assisted remote telepresence surgery. *Comput Aid Surg* 2005; **10**(2): 93–99.
2. Arcara P, Melchiorri C. Control schemes for teleoperation with time delay: a comparative study. *Robotics Autonom Sys* 2002; **38**: 49–64.
3. Bejczy A, Kim W. Predictive displays and shared compliance control for time-delayed manipulation. Proceedings of the IEEE International Workshop on Intelligent Robot Systems (IROS) 1990; 407–412.
4. Butner S, Ghodoussi M. Transforming a surgical robot for human telesurgery. *IEEE Trans Robot Autom* 2003; **19**(5): 818–824.
5. Chong N, Kotoku T, Kohtaro O, *et al*. Remote coordinated controls in multiple robot cooperation. Proceedings of the IEEE International Conference on Robot Automation 2000; 3138–3143.
6. Cronin E, Kurc A, Filstrup B, Jamin S. An efficient synchronization mechanism for mirrored game architectures. *Multimedia Tools Apps* 2004; **23**(1): 7–30.
7. DeSouza G, Kak A. A subsumptive, hierarchical, and distributed vision-based architecture for smart robotics. *IEEE Trans Sys Man Cyber* 2004; **34**(5): 1988–2002.
8. Fabrizio M, Lee B, Chan D, *et al*. Effect of time delay on surgical performance during telesurgical manipulation. *J Endourol* 2000; **14**(2): 133–138.
9. Ferrell W. Remote manipulation with transmission delay. *IEEE Trans Human Factors Electron* 1965; Human Factors Electron 6, no. 1.
10. Feretti S. Interactive maintenance for event synchronization in massive multiplayer online games. Technical Report Univ of Bologna Dept of Comp Sci 2005–05; 1–202.
11. Galbraith J, Kenyon G, Ziolkowski R. Time-to-collision estimation from motion based on primate visual processing. *IEEE Trans Pat Anal Mach Intellig* 2005; **27**(8): 1279–1291.
12. Held R, Durlach N. Telepresence, time delay and adaptation. In *Pictorial Communication in Virtual and Real Environments*, Ellis SR (ed.). Taylor and Francis: London, 1991; 232–246.
13. Kim T, Zimmerman P, Wade M, Weiss C. The effect of delay visual feedback on telerobotic surgery. *Surg Endosc* 2005; **19**: 683–686.
14. Kondo N, Monta M, Fujiura T. Fruit harvesting robots in Japan. *Adv Space R* 1996; **18**(1): 181–184.
15. Lane J, Carignan C, Akin D. Advanced operator interface design for complex space telerobots. *Auton Robot* 2001; **11**: 49–58.
16. Marescaux J, Leroy J, Gagner M, *et al*. Transatlantic robot-assisted telesurgery. *Nature* 2001; **413**: 379–380.
17. Munir S, Book W. Internet-based teleoperation using wave variables with prediction. *IEEE/ASME Trans Mechatron* 2002; **7**(2): 124–133.
18. Sayers C, Paul R. Coping with delays: controlling robot manipulators under water. *Indust Robot* 1994; **21**(5): 24–26.
19. Sheridan T. Teleoperation, telerobotics and telepresence: a progress report. *Control Eng Practice* 1995; **3**(2): 205–214.

20. Sheridan T. Space teleoperation through time delay: review and prognosis. *IEEE Trans Robot Automat* 1993; **9**(5): 592–606.
21. Thompson J, Ottensmeyer M, Sheridan T. Human factors in tele-inspection and tele-surgery: cooperative manipulation under asynchronous video and control feedback. *Medical Image Computing & Computer Assisted Intervention* 1998; 368–376.
22. ZTI-Telecom NetDisturb; http://www.zti-telecom.com/fr/pages/netdisturb.htm.