31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Teleoperation in Surgical Robotics – Network Latency Effects on Surgical Performance

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Abstract—**A teleoperated surgical robotic system allows surgical procedures to be conducted across long distances while utilizing wired and wireless communication with a wide spectrum of performance that may affect the outcome. An open architecture portable surgical robotic system (Raven) was developed for both open and minimally invasive surgery. The system has been the subject of an intensive telesurgical experimental protocol aimed at exploring the boundaries of the system and surgeon performance during a series of field experiments in extreme environments (desert and underwater) teleportation between US, Europe, and Japan as well as lab experiments under synthetic fixed time delay. One standard task (block transfer emulating tissue manipulation) of the Fundamentals of Laparoscopic Surgery (FLS) training kit was used for the experimental protocol. Network characterization indicated a typical time delay in the range of 16-172 ms in field experiments. The results of the lab experiments showed that the completion time of the task as well as the length of the tool tip trajectory significantly increased ($\alpha < 0.02$) as time delay increased in the range of 0-0.5 sec increased. For teleoperation with a time delay of 0.25s and 0.5s the task completion time was lengthened by a factor of 1.45 and 2.04 with respect to no time delay, whereas the length of the tools' trajectory was increased by a factor of 1.28 and 1.53 with respect to no time delay. There were no statistical differences between experienced surgeons and non-surgeons in the number of errors (block drooping) as well as the completion time and the tool tip path length at different time delays.**

I. INTRODUCTION

THE core capability of telemedicine is to deliver rapid and high quality healthcare across large distances. Diagnosis, consultation, and medical intervention in remote sites can save patient lives in, combat situations, areas of natural disaster, and underserved sites. Teleoperation is a mode of operation in which the remote human operator becomes an integral part of the system. This mode of operation makes it possible for surgical procedures to be conducted across long distances while utilizing wired and wireless communication with a wide spectrum of performance that may affect the outcome. Although the majority of the surgical robotic systems [1-4] utilize teleoperation as fundamental mode of operation even if the master (surgeon console) and the slave (surgical robot) are located the same room, physically separating the two sub-systems introduces time delays that affect the surgeon's performance and ultimately the outcome of the surgical procedure. The latency associated with sending information across the network between the master and the slave of the telerobotic system is bounded from one end of the spectrum by the speed of light and from the other by bandwidth of the physical system defined by its infrastructure and traffic. The goal of this research effort is to study the affect of time delay on surgical skills performance utilizing a surgical robot in teleoperation mode.

II. METHODS

A. Rational

The methodology of this study is divided into two sections: field experiments and lab experiments performed with Raven [5-9]. The field experiments were used in part to define latencies associated with different configurations of network architectures. Based on this information discrete and fixed time delays were selected and emulated in controlled lab experiments.

B. Flied Experiments

Seven field experiments were conducted with Raven with various network architectures (wired and wireless) and a wide spectrum of physical distances (Table 1). In experiment 1 (HAPs/MRT) the system was deployed in two remote sites in desert-like conditions in Simi Valley, CA, while utilizing an Unmanned Aerial Vehicle (UAV) as a wireless node between the sites. In experiments 2, (Imperial College London - ECL), 6 (Surgical Robot Course) and 7 (Tokyo Tech), the surgical robot located in Seattle, WA was teleoperated from different sites around the world using commercial internet link. In experiments 4 and 5 the surgical robot was deployed in Aquarius – an undersea habitat, located 3.5 km off-shore in the Florida Keys, and teleoperated from Seattle, WA as well as the National Undersea Research Center, at Key Largo, FL using a combination of wired and wireless communication as part of

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978-1-4244-3296-7/09/$25.00 ©2009 IEEE

TABLE I
FIELD EXPERIMENT - RAVEN

No.	Experiment (Acronym)	Patient Site (Slave) Surgical Robot	Surgeon Site (Master) Surgical Console	Communication Layer Video	Communication Layer Network Architecture	Time Delay [msec] (*)	Distance [Km]
1	HAPs/MRT	Field – Simi Valley, CA	Field – Simi Valley, CA	HaiVision, Hai560	Wireless via UAV	16	0.5
2	*ICL*	Seattle , WA	London, UK	iChat / Skype	Commercial Internet	172	7700
3	*Animal Lab*	Seattle , WA	Seattle , WA	Direct S- Video	LAN	1	0
4	*NEEMO 12 - Aquarius*	Aquarius (underwater), Key Largo, FL	Seattle , WA	HaiVision, Hai1000	Commercial Internet – Seattle WA to Key Largo, FL Microwave Comm. - Key Largo, FL to Aquarius	76	4500
5	*NEEMO 12 - NURC*	NURC (land), Key Largo, FL	Seattle , WA	HaiVision, Hai200	Commercial Internet	75	4500
6	*Surgical Robot - Course*	Seattle , WA	Montpellier, France	*iChat/Skype*	*Commercial Internet*	170	8500
7	*Tokyo Tech*	Seattle , WA	Tokyo, Japan	iChat/Skype	Commercial Internet	131	7600

(*) Note: The time delay refers to the latcnacy in sending position commands between the muster and the salve. The latency regarding the video transmission, compression and decompression was not recorded.

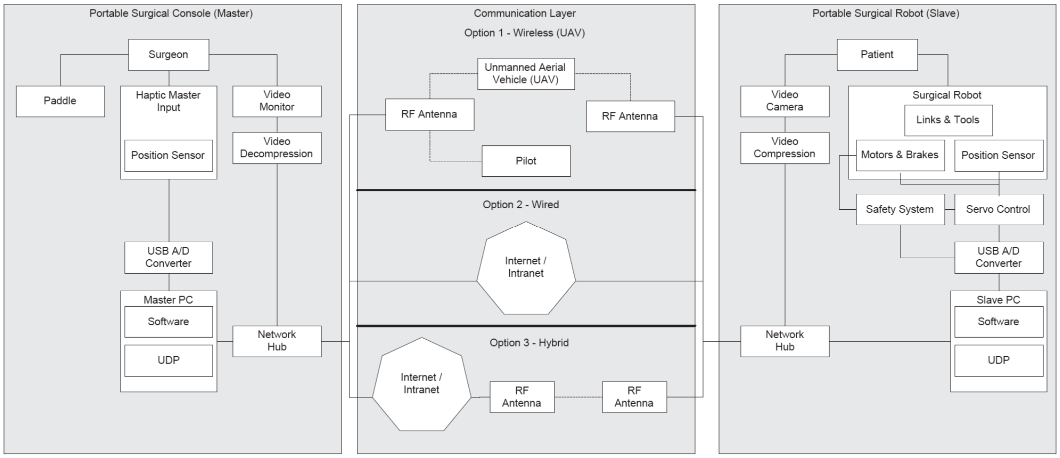

Fig. 1. RAVEN functional block diagram with different optional communication layers utilized in the field experiments

NASA's NEEMO XII mission (NASA Extreme Environment Mission Operations).

C. Lab Experiments

1) System Setup

In a real teleoperation, physical distance and a real network separate the patient and surgeon's sites with time varying delays. When a surgeon makes a gesture using the master device, motion information is sent through the network to the Patient Site with a network time delay (T_n). The manipulator moves and the audio/video (a/v) device observes the motion. Digital a/v is compressed (T_c), sent from the Patient Site to the Surgeon Site through the network (T_n), then decompressed (T_d) and observed by the surgeon. The surgeon has experienced a total delay $T = 2T_n + T_c + T_d$, from the time (s)he made the gesture to the time that action was observed. In the simulated teleoperation the Surgeon and Patient sites are not separated by physical distance but are connected through a Linux PC with two network cards running NISTNET that emulates a real network. This emulator allows the experimenter to adjust the average packet delay between the Surgeon and Patient sites [12]. The a/v feed is connected directly from the camera at the Patient Site to the monitor at the Surgeon Site through S-video eliminating any delay due to compression/decompression. The surgeon experiences a total delay, T_e due to the emulator, from the time (s)he made the gesture to the time that action was observed.

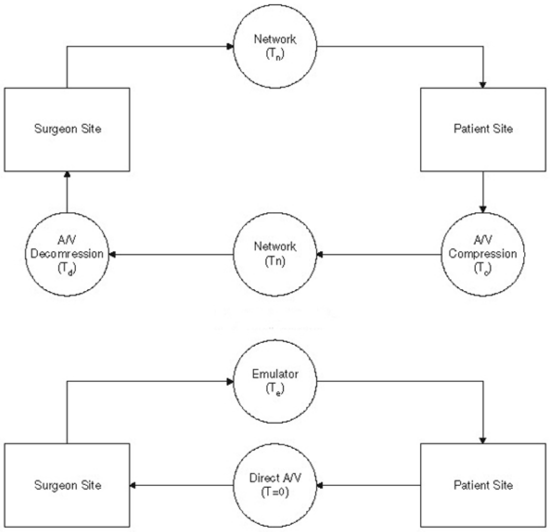

Fig. 2. Simplified teleoperation communication flow. Real teleopetaion in the field experiments (top) – Detailed diagram is depicted in Fig. 1 .A setup for the lab experiments with emulated time delay (bottom).

2) Experimental Design

The Society of American Gastrointestinal and Endoscopic Surgeons (SAGES), one of the major professional surgical organizations, has developed a curriculum for teaching minimally invasive surgical skills termed the Fundamentals of Laparoscopic Surgery (FLS) which includes both cognitive and psychomotor skills. The skills assessment consists of five tasks. The FLS skills tasks have been validated to show significant correlation between score and postgraduate year [10,11] and are considered by many to be the "gold standard" in minimally invasive surgical skill assessment. The Block Transfer is one of the five tasks which emulates tissue handling and manipulation.

The experimental task consists of moving six blocks, one at a time, from the left side of the FLS peg board (Fig. 3 right) to the right side and back to the original position in a sequential predefined order under video guidance (a total of 12 transfers). In our experiment, the completion time as well as the tool tip trajectory were recorded. The three treatments of the experiment included emulated delays of 0, 250 and 500 ms presented to the subjects in randomized order. Each experimental treatment was conducted three times by each subject (nine times total) in a randomized order.

The subjects performed the training tasks first with no delay then with 250ms delay in order to learn how to teleoperate the RAVEN and minimize the learning effects during the execution of the experimental protocol. Within one week from the start of their training, they returned to perform the time delayed block transfer experiment.

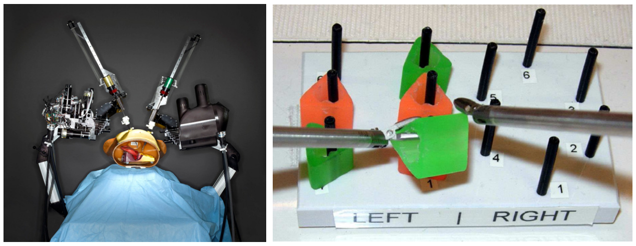

Figure 3: Experimental setup: The Raven surgical robot (Left) The SAGES FLS Block Transfer task board (Right)

3) *Subjects – Definition of the Population*

Fourteen subjects, five surgeon and nine non-surgeons, ages ranging from 18 to 43, participated in this study under University of Washington Human Subjects Approval Number 01-825-E/B07.

III. RESULTS

1) *Field Experiments*

Given the stochastic nature of the network there is a specific distribution of packet delay. Fig. 4 depicts the distribution of the delay during the NEEMO experiments given a transmission rate of 1 kHz. The distribution of the latency is in the range of 63-95 ms with a peak at 78 ms. Table 1 defines the average latencies during all the field experiments. One should note that these latencies represent only the delay in sending position command from the master to the slave (T_n). The latency due to the digital a/v compressed (T_c) and decompressed (T_d) which is usually larger and hardware/software dependent and is estimated to be in the range of 200 ms (hardware compression / decompression) during HAPs/MRT and about 1s for commercial internet (software compression / decompression).

Fig. 5 summarizes the mean completion time for a single expert surgeon (E1) who participated in multiple field and lab experiments performing the block transfer task. In each of the first three weeks of training, E1 performed three repetitions of the Block Transfer in the lab environment with effectively no delay. There is a learning effect as E1's mean time improved from week to week. During the NEEMO XII mission, E1 completed a single repetition of the task with the RAVEN in Aquarius and another single repetition with it on-shore at NURC Key Largo, FL. For comparison, E1, who uses a daVinci clinically was able to complete the block transfer task in about one minute using the da Vinci, taking only slightly longer with the stereo capability disabled.

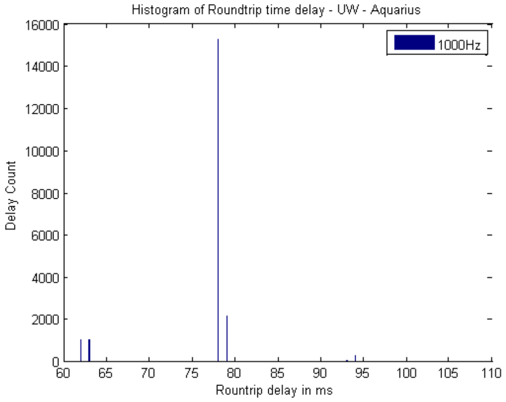

Fig. 4. Histogram of number of packets with respect to delay between Seattle WA and Aquarius, Key Largo, FL at a transmission/receiving frequency of 1K.

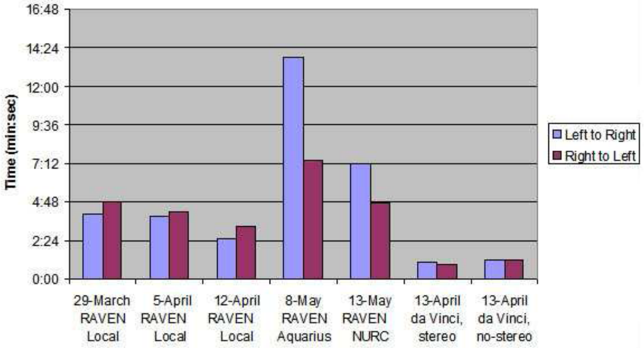

Figure 5: Average block transfer completion times of a single expert surgeon during local training on the RAVEN as well as during the NEEMO mission. Completion times using an ISI daVinci are included for comparison.

2) *Lab Experiments*

A two-way analysis of variance (ANOVA) was used to determine the effect of the time delays (0, 250, 500 ms) and the subject group (surgeon, non-surgeons) on the three performance parameters: (1) block transfer completion time, (2) the number of errors (dropping the block - recovered and unrecovered); (3) tool tip path length as the response variables (time delays and group type). In general both the completion time and the tool tip trajectory length monotonically increased as the time delay increased (Fig. 6). The ANOVA analysis indicated that the difference in mean block transfer time as well as the tool tip path length between each of the three treatments (0ms, 250ms, and 500ms delay) are statistically significant ($\alpha < 0.02$). While the stated objective of the task was to minimize errors some errors occurred but the number of errors in response to delay effect and surgeon effect were not significant. It is possible that if the task was more technically challenging, the frequency or severity of errors would start to differentiate between subjects with more and less skill. The difference in mean block transfer completion time between surgeons and non-surgeons was not statistically significant.

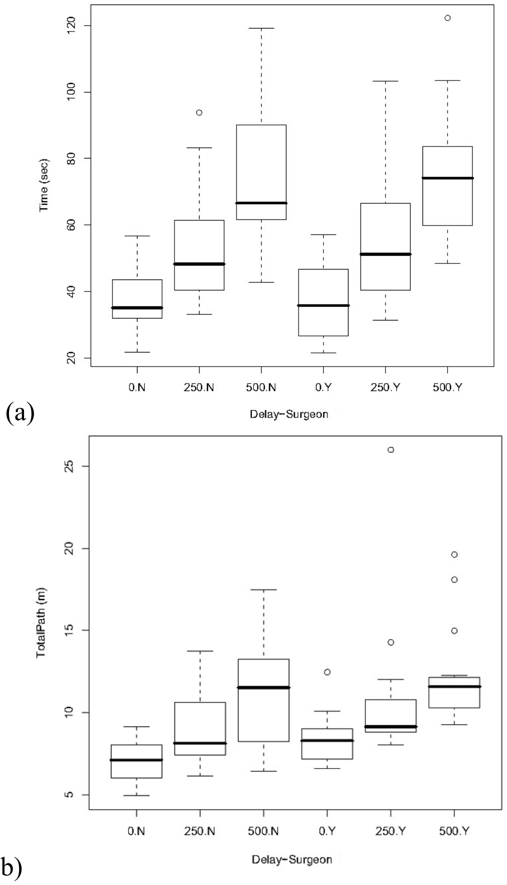

Figure 6: The effect of the block transfer completion time (a) and the tool tip path (b) are significantly different $(\alpha < 0.02)$ for the three time delays (0, 250, 500 ms), for both the surgeon (Y) and the non-surgeon (N). For teleoperation with a time delay of 0.25s and 0.5s the task completion time was lengthened by a factor of 1.45 and 2.04 with respect to no time delay, whereas the length of the tools' trajectory was increased by a factor of 1.28 and 1.53 with respect to no time delay.

IV. CONCLUSION

The development of the TeleRobotic Fundamentals of Laparoscopic Surgery (FLS) tasks has established a standard means by which other investigators working in the area surgical robotics can conduct performance testing. The FLS is already a standard in all surgical residency training programs in the US. Time delay is an embedded characteristic of any network. As indicated in the field experiments, the latency related to the compression/and decompression of the audio/video (a/v) is significantly larger then the latency related to the transmission of position commands between the master and the slave. As such the a/v transmission latency is the limiting factor that determines the overall performance of the system. The results acquired in the lab experiments indicated degradation of teleoperation performance as a function of an increasing time delay using the completion time and the tool path length as the performance measures. Potential solutions for this degradation of teleoperation performance include semi autonomous operation. In the context of tissue manipulation the surgeon may point to the target position and the robot will execute the command autonomously given constraints regarding obstacle avoidance and stress thresholds.

ACKNOWLEDGMENT

Development of the RAVEN was supported by the US Army, MRMC, grant number DAMD17-1-0202. The HAPs/MRT project was supported by the US Army TATRC, grant number W81XWH-05-2-0080. The authors would like to thank the HAPs/MRT collaborators at the University of Cincinnati, AeroVironment, and HaiVision as well as our collaborators in London at Imperial College and at Tokyo Tech. The NEEMO XII participation has been supported by the US Army TATRC grant number W81XWH-07-2-0039. The authors would like to thank the NEEMO collaborators from University of North Carolina at Wilmington, US Navy, National Undersea Research Center, National Oceanographic and Atmospheric Administration, NASA, and in particular, Dr. Timothy Broderick, Charles Doarn, and Brett Harnett from the University of Cincinnati.

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