Plugfest 2009: Global Interoperability in Telerobotics and Telemedicine

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Abstract— **Despite the great diversity of teleoperator designs and applications, their underlying control systems have many similarities. These similarities can be exploited to enable interoperability between heterogeneous systems. We have developed a network data specification that can be used for Internet based control of a wide range of teleoperators.**

In this work we explore Internet based interoperable telerobotics, focusing on the telesurgery application domain. Fourteen globally dispersed telerobotic master and slave systems were connected in thirty trials in one twenty four hour period. Users performed common manipulation tasks to demonstrate effective master-slave operation. With twenty eight (93%) successful, unique connections the results show a high potential for standardizing telerobotic operation. Furthermore, new paradigms for telesurgical operation and training are presented, including a networked surgery trainer and exoskeleton control of micro-manipulators.

I. INTRODUCTION

Many telemanipulation systems have a great deal in common.

The robots usually includes one or more master manipulators, and one or more remote manipulators. The manipulators have up to six degrees of freedom in Cartesian position and orientation while kinematics functions translate between Cartesian information and the robots' control workspace. Furthermore, the communication architecture for Internet based teleoperation is often a Internet protocol (IP) network socket with a well defined data interface to transmit control data using a fixed binary packet. Despite these commonalities there has been no accepted framework for interconnecting such systems, and network interfaces are currently described arbitrarily by individual research groups. In the same way that Internet standards have connected heterogeneous computing systems, we predict robot communication standards will speed research and development of interoperable teleoperated robots.

To explore the development of interoperability in teleoperation, we carried out an experiment interconnecting numerous teleoperation research groups using a common data interface. In this experiment we demonstrate fluid interconnectivity between heterogeneous, independently developed teleoperation systems, focusing on one teleoperation domain: telesurgery. The goal of this work is to demonstrate that a large number of globally dispersed research groups can interoperate a variety of teleoperation systems using a common data interface. The interface, called the Interoperable Teleoperation Protocol or ITP, is intended as a starting point for development of a robust and practical standard for Internet robotic teleoperation. Each participant already had master / slave teleoperation capability, and it is these existing systems that were connected, not new robots designed with interoperability in mind.

Long distance telesurgery has been demonstrated in successful operation using dedicated point-to-point network links [1], [2]. Furthermore, Internet-based robotic teleoperation has been explored in many experiments using co-developed master and slave systems (e.g. [3], [4])) and network characterizations have shown that under normal circumstances Internet can be used for teleoperation with force feedback [5]. Meanwhile, work by by the Tachi Lab at the University of Tokyo sought to create a very general protocol for telerobotics by describing the unique capabilities of each robot [6].

The current work is a new direction, exploiting similarities among teleoperation systems to develop standards, simplify software architecture and improve interoperability. The developed protocol is operable over public Internet offering a flexible, effective and easy to implement way of interconnecting widely dispersed teleoperation robots with different designs and control architectures.

It should be further noted that several communications architectures and open-source software packages are available for robotic operation over the Internet (e.g. [7]–[10]). However, these are often designed for mobile robots, and are unsuitable for the high packet rates and extreme delay sensitivity particular to telemanipulators and telesurgery systems.

II. INTEROPERABLE TELEROBOTICS

To demonstrate interoperable telerobotics over the global Internet, fourteen unique telerobotic master and slave systems were connected by nine groups in five countries. In the context of surgical telerobotics, the master manipulator is operated by the surgeon in order to control the motions of the slave, or patient-side robot. All the connected systems used the same network facing data interface, which we call the Interoperable Teleoperation Protocol or ITP.

A. *Interoperable Teleoperation Protocol*

ITP is a stateless data description representing commands between the master to the slave robot. To make cooperation as simple as possible, the first data interface for the ITP is a low-overhead binary UDP packet structure. The small size makes it suitable for high packet rates.

The ideal protocol is robust enough to work with any new teleoperators independently of their design, and flexible to accommodate any new data transforms or teleoperation architectures. Therefore, a mechanism is built in for designating new, numbered data specifications, extending the protocol to new innovations. Listing 1 below shows the data interface that was used in the experiments described in this paper. The "pactyp" (packet type) and "version" fields indicate the data type in use. For these experiments packet type one was used, and the version was 0.43 or 43 as an integer.

The ITP requires a common reference frame. From the users perspective, facing the workstation, the right-handed frame has: the positive Y-axis pointing right, the positive X-axis pointing away, and the positive Z-axis pointing down. Each master and slave implement transformations to convert their own coordinate systems to the common reference frame.

There are many ways to describe movement commands from master to slave. For networked teleoperation it is important that the system be robust to arbitrary network delays and packet loss. In particular, the commanded movement should be free from major discontinuities, and should act "safely" when recovering from a period of delay. In the current experiment, motion commands for two arms are encoded as position increments in three Cartesian dimensions (delx, dely, delz) and orientation increments in roll, pitch and yaw (delroll, delpitch, delyaw). Position is in units of integer microns and orientations are in integer micro-radian units. The choice of integers sidesteps the complexity of floating point specifications. Increments of position and orientation were calculated as follows:

$$
\begin{aligned}
\Delta X_k &= X_k - X_{k-1} && (1)\\
\Delta R_k &= R_k - R_{k-1} &&\\
X &= [x, y, z]^T && (2)\\
R &= [roll, pitch, yaw]^T &&
\end{aligned}
$$

In this representation there is no explicit notion of a time-step, making the scheme more robust to varying network delay and packet rate compared to velocity coding schemes. In response to packet loss, the result is position drift, compared with absolute motion commands which would entail step discontinuities in commanded position. With small packet loss the drift is minor and easily accommodated by the user through indexing.

Indexing is a common feature among teleoperation systems and allows the user to change the master configuration without moving the slave. Two states, "engaged" and "disengaged", are defined to coordinate indexing between master and slave robot and are indicated in the "surgeon_mode" field of Listing 1. While in the disengaged state, the slave robot should ignore any motion commands until the engaged state is requested. The incremental motion scheme simplifies indexing, since absolute position agreement is not required between master and slave.

```
#pragma pack
#define SURGEON_DISENGAGED 0
#define SURGEON_ENGAGED 1
struct M2S_data {
        unsigned int sequence;
        unsigned int pactyp;
        unsigned int version;
        int delx[2];
        int dely[2];
        int delz[2];
        int delyaw[2];
        int delpitch[2];
        int delroll[2];
        int buttonstate[2];
        int grasp[2];
        int surgeon_mode;
        int checksum;
};
```

Listing 1. C implementation of the binary packet structure sent from master to slave robot.

Endianness and data types were chosen to conform to 32-bit x86 architecture.

Motion scaling is another common feature among teleoperators. The scale factor is not explicitly encoded by the ITP. Instead motion scaling is controlled by the master side and is implicit in the scaled motion commands.

The lightweight UDP datagram protocol is used, since it does not require the additional overhead of the more common TCP protocol. UDP does not guarantee data integrity, but does provide the lowest possible latency. A sequence number is important for tracking out-of-sequence or lost packets, and corrupt packets are detected by the checksum and discarded. Lost incremental motion packets contribute to position drift. With a high packet rate each lost packet contributes only a small amount of drift that can be easily accommodated by the user through indexing. Most importantly, lost incremental motion packets will not lead to unpredictable or unsafe motion of the slave manipulator.

The ITP does not specify a packet rate. These experiments used packet rates from 10Hz up to 1kHz. 1kHz packet rates are exceptionally high compared to average Internet usage. However, there were no problems reported in our experiments due to the high rate, a result that agrees with [5].

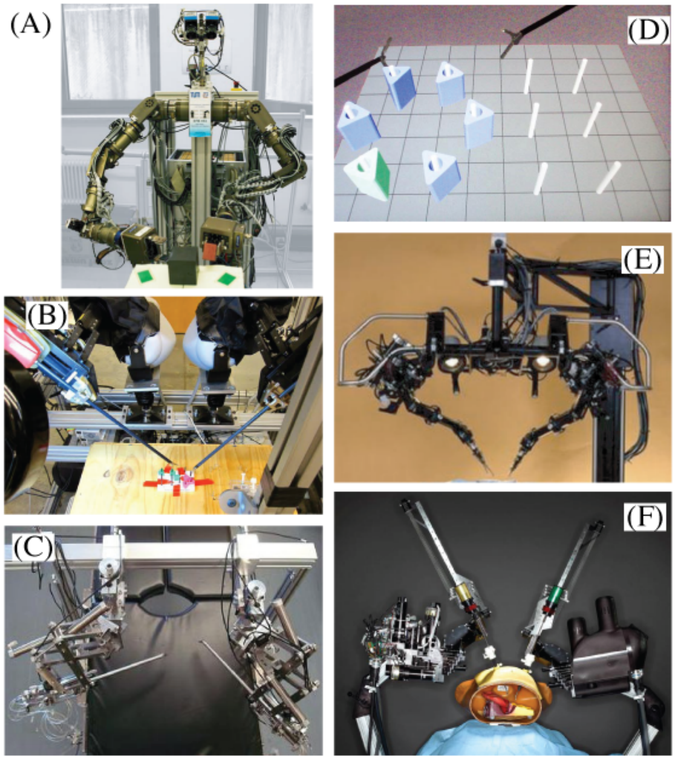

Fig. 1. (A) TUM general purpose Telerobot. (B) Patient-side robot of the JHU custom version of the da Vinci. (C) TokyoTech IBIS IV surgical robot. (D) RPI VBLaST^{TM}. (E) SRI M7 surgical robot. (F) UW Raven surgical robot.

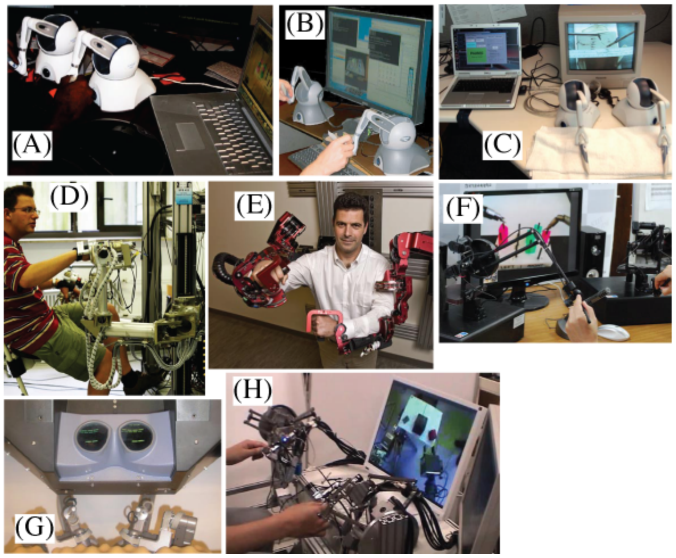

Fig. 2. (A, B, C) Phantom Omni control station with free software at RPI, ICL and UW respectively. (D) TUM ViSHaRD7. (E) UCSC Exoskeleton. (F) Phantom Premium with custom software at KUT. (G) Master console of the JHU custom version of the da Vinci. (H) TokyoTech delta master.

B. Connected Slave Systems

The six slave systems used in the experiment are described here and shown in figure 1. All systems had two arms and were operated via UDP/IP using ITP.

The Raven surgical system developed at the University of Washington, Seattle (UW, Seattle, WA, USA) is a six degree of freedom (DoF) capable cable-driven research robot for remotely operated minimally invasive surgery (MIS). It has a unique spherical mechanism for MIS operation around the trocar point [11].

Located at the Tokyo Institute of Technology, Suzukakedai Campus (TokyoTech, Yokohama, Japan) the IBIS IV system is a pneumatically actuated MIS research robot with 6 DoF plus a gripper [12]. The IBIS IV detects environmental contact force without the use of a force sensor by inference from the pneumatic pressure.

Johns Hopkins University (JHU, Baltimore, MD, USA) connected a commercial MIS robot, the JHU Custom daVinci. The robot hardware is from Intuitive Surgical Inc., Sunnyvale, CA, USA, with custom control software and electronics by Johns Hopkins. The daVinci represents the state of the art in commercial surgical robotics [13].

The M7 surgical research robot was connected at SRI International (SRI, Menlo Park, CA, USA). The M7 is a 6+ DoF robot designed for open telesurgery with battlefield and trauma applications [14].

The VBLaST^{TM}laparoscopic training simulator was connected at the Rensselaer Polytechnic Institute (RPI, Troy, NY,USA). It is a virtual reality based bimanual trainer with haptics that is designed to replicate the FLS tasks. Two virtual MIS tools follow the motion of a physical tool connected to the interface, or may be teleoperated via the built-in network support.

Technische Universität München (TUM, Munich, Germany) connected a general purpose, redundant 7 DoF telemanipulator with a relatively large grasper. The two anthropomorphic arms were designed for general, large-scale manipulation tasks. [15]

This diverse group of slave systems demonstrates the wide variety of robotic capabilities that would be available to surgeons in a standardized, networked surgery world.

C. Connected Master Systems

Eight master systems, shown in figure 2, were used in the experiments. The master systems transmitted ITP data at up to 1kHz via UDP/IP. Although many of the systems are haptic devices capable of force-feedback, the function was not used in thses experients.

Three of the master systems at UW, RPI and Imperial College London (ICL, London, UK) comprised two 6DoF Phantom Omni (SensAble Inc, Woburn, MA, USA) haptic devices and surgical console software from UW [16].

Korea University of Technology and Education (KUT, Cheonan, South Korea) used the Phantom Premium (also SensAble Inc.) with their own ITP compatible software.

A commercial daVinci surgeon console (also by Intuitive Surgical, Inc.) with custom controller and software was used at JHU [13].

At the University of California, Santa Cruz (UCSC, Santa Cruz, CA, USA) an upper-limb powered exoskeleton was used, allowing whole-arm motions to scale down to surgery scale tasks [17]. One-arm operation was performed with this system, so tasks were simplified to one arm.

At TUM, ViSHaRD7, a custom designed, general-purpose master with 7 DoF was incorporated [18]. The arms are mounted on a mobile platform to form a mobile haptic interface, but in this experiment the mobile base was not activated.

Finally TokyoTech developed a master system based on a delta motion platform specifically for control of MIS assistant robots [19].

III. EXPERIMENTAL METHODS

A. *Telerobotic FLS*

Most participants in this experiment each performed the Telerobotic Fundamentals of Laparoscopic Surgery (TFLS) block transfer task, modified for time constraints. Exceptions were made for some robots as described below. TFLS was adapted by Lum [20] from a proprietary scoring method invented by the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) to evaluate surgeons' laparoscopic proficiency [21]. The test can be seen in Figure 3.

The TFLS Block Transfer task is essentially a pick-and-place task. Six plastic blocks approimatelys one cm^3 are first arranged on the left half of an array of pegs. Subjects grasp each numbered block in order with the left hand, lift it from the peg, transfer the block to the right hand tool, and place the block on a numbered peg on the right side of the board. In this experiment, participants transferred as many blocks as possible in ten minutes.

Due to particular robot configurations, task modifications were necessary in a few cases. The TUM Telerobot slave was designed for manipulating larger objects, so a substitute, bi-manual, pick-and-place task was performed. Users transferred a 4x4x5 cm cube 20 cm from the right to left side of an 8x8x8 cm obstacle, switching hands in the process.

The UCSC Exoskeleton was operated in one-arm mode, so the FLS block transfer was done without the hand-to-hand switch.

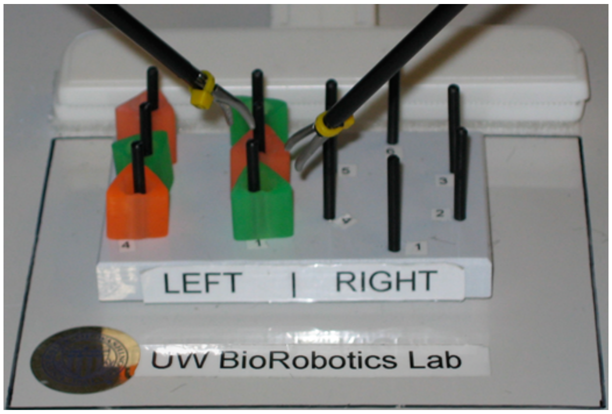

Fig. 3. The Telerobotic FLS block transfer task.

B. *Plugfest event*

Nine groups from North America, Asia and Europe participated in this experiment testing interoperability among their systems. In one 24-hour period on July 30, 2009 participating groups connected over the Internet to control each others robots recording success or failure of the connection and performance on a simple task.

With eight masters and six slaves, forty-eight connections were possible. However, labs did not connect their own master-slave combinations, and, to keep the operating schedule within reasonable hours, only global regions separated by less than nine hours were connected. With these constraints thirty two connections were possible. Thirty were attempted, and two were not attempted due to time limitations.

Feedback to the user was visual only and did not include haptics. The focus of this research is on teleoperation rather than video technologies, so Skype video was selected due to its ubiquity, easy of use and cross-platform compatibility. The type and location of the camera, PC specification, and video display configuration were not controlled in the experiment.

In each connection the ten minute block transfer task was performed one to three times and the number of transferred blocks was recorded. Network time delay was measured and recorded in each connection using round trip "ping" times. In addition, users were asked to qualitatively judge the ease of use of each master/slave connection compared with their own master-slave and past experiences with teleoperators.

IV. RESULTS

Thirty trials were conducted to connect the various master and slave systems across the Internet. Of those, 29 resulted in successful task completion, 20 bimanual TFLS, 5 one-handed TFLS block transfer, and three bimanual gross manipulation tasks.

Figure 4 shows the number of blocks transferred and ping times for each master-slave connection. The average number of blocks transferred in the 20 successful bimanual TFLS trials was 7.4. The average number of blocks transferred one-handed was 11.6. The average time for block transfer in the gross manipulation trials was 8.2 minutes. The most blocks transferred in ten minutes with bi-manual operation was 16. 30 blocks were transferred using the upper-limb exoskeleton to control the MIS robot at Ttech, IBIS, in the one-handed mode of operation. The highest average blocks transferred per connection for any slave robot was on the UW slave system with an average of 9.5 blocks per 10 minute connection.

There were two unsuccessful trials. In one case a slow packet rate of 10Hz was incompatible with a slave-side controller that assumed 1kHz updates for accurate velocity estimation. The resulting behaviour triggered a slave-side safety system which harmlessly shut down the robot. For unknown reasons, the behavior was asymmetrical; the right arm moved fine, while the left one caused the fault. In the second unsuccessful case, the orientation mapping between

	Slave Systems					
Master Systems	UW	JHU	RPI	SRI	TOK	TUM**
UW	▨	▨	(*)12	(34) 14	(133) 15	▨
ICL	▨	(112) 11	(*)6	▨	(288) 5	(183) 7
JHU	(73) 9	▨	(*)7	X	▨	X
KUT	(180) 6	▨	(*)6	(175) 4	(224) 6	(305) 13
RPI	(*) 8	(*) 13	▨	(*) 2	▨	▨
TOK	(135) 16	▨	▨	(*) 12	▨	(302) 4.5
TUM	▨	(115) 1	(*)4	▨	(295) 2	▨
UCSC†	(21) 13	(83) 4	(*)5	(22) 9	(155) 30	▨

Fig. 4. Number of blocks transferred in each master-slave trial, and ping response times in parenthesis. *Ping times not taken. **Block transfer task completion time. †One-handed operation only.

master and slave was too confusing, and the user did not complete the task.

V. DISCUSSION

The task performance given in the table of Figure 4 demonstrates that all but two of the thirty master/slave pairings were capable of performing the task. However, the numerical results do not necessarily reflect the usefulness of a given system. The number of blocks transferred in a given connection is highly influenced by variation in user experience, familiarity with the robot systems and a differences in video quality and delay. That being said, the number of successful trials was quite high.

In addition, the thirty experiments allowed a globally dispersed robot and human operator population to interoperate in a time-critical fashion. In many cases the slave system was "hot-swapped"- operated by several different masters in rapid succession without restarting. Smooth interoperability like this will improve collaborative telerobotic action, for example, a patient is handed off from one surgical specialist to another.

Furthermore, several interesting telesurgical technologies were explored in this experiment. A virtual reality surgical simulator was controlled in the exact same way as the physical slave systems, demonstrating how surgeons around the world may train on an advanced simulation platform without requiring local installation of simulation software.. Also, several types of surgical master and slave systems were connected, exploring different modes for action and control. The UCSC Exoskeleton, for example, showed how a surgeon's full range of upper limb motion could be scaled down to control minimally invasive surgical manipulators. In the future surgeons, may be able to select among many workstation designs to best suit their operating requirements.

Twenty-eight out of thirty attempted connections resulted in some degree of task completion. However, even among these there were some difficulties. In many instances, orientation mapping from master to slave was unnatural or incorrect, in that rotation of the master did not produce the desired rotation of the slave. In at least four cases this was severe enough that orientation degrees of freedom were disabled and robots were operated in three DoF Cartesian space. At the same time, the method of using orientation increments to represent the the roll, pitch and yaw leaves open the problem of RPY singularities and the jump discontinuities associated therewith. This will have to be fully addressed in future work, possibly by changing the orientation representation.

Regarding video feedback, Skype was easy to use across platforms and was effective in all thirty connections. At the same time, many users complained about video quality and video delay. Another common complaint was the lack of stereoscopic imaging and depth perception. Combined, the poor quality of visual feedback degraded task performance. Future experiments should use a teleconferencing application with higher quality, lower latency and stereo capabilities.

Future work should also address security and session negotiation. For example, in one connection UCSC and UW sent packets simultaneously to RPI VBLaSTł resulting in erratic action. To resolve this, a system for logging into a robot may be necessary. Also the UDP data structure is in the public domain so others could send packets by scanning the opened ports.

VI. CONCLUSIONS AND FUTURE WORK

In this work we have shown the feasibility of interconnecting a large number of heterogeneous teleoperation systems using a common protocol, the Interoperable Teleoperation Protocol. This demonstration has used a simple teleoperation data interface that does not require device-specific negotiation. The great simplicity of the ITP makes it easy to incorporate into telerobotic systems. Although this experiment focused on the application of telesurgery, these results indicate that the developed architecture is generalizable to a wide range of telerobotics applications.

This experiment used only unilateral teleoperation, while bilateral operation is very interesting. This will be explored in future experiments, as well as further additions to the ITP. We predict that increased collaboration will result from these experiments and expect interesting synergistic results.

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