Shared Control For Teleoperation With Time Delay

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***Abstract*—Even after more than 50 years of research, improving teleoperation systems that have communication time delay remains a challenging human factors problem. We propose that a teleoperation system combining a predictive display with shared control will improve time-delayed teleoperation. In this paper we discuss our motivation and initial implementation of the system. We additionally propose a user study that will investigate the merits of this system.**

I. Introduction

In a letter dated July 10, 1806, Thomas Jefferson refers to the Hawkins and Peale polygraph as "the finest invention of the present age" [16]. In what could be considered the first teleoperation device, the polygraph mechanically linked two writing utensils so that the *slave* utensil produced an identical copy of the document prepared by an author writing with the *master* utensil. Nearly one hundred and fifty years later in the late 1940s, Raymond C. Goertz created what is widely considered the first teleoperator, which allowed scientists to safely conduct experiments with nuclear material [11]. Shortly thereafter, the field of robotics began to flourish in ernest, exemplified by General Motors' introduction of the first industrial robot, Unimate, into its production lines in 1961 [14].

Given the relative maturity of the field of teleoperation, especially when compared to other robotic domains, it is perhaps surprising that creating intuitive teleoperation interfaces that allow an operator to perform complex tasks in a remote environment is not yet a solved research problem. While it is true that excellent teleoperation systems exist, i.e. the da Vinci surgical system [12], many of the best teleoperators are suitable for use in a narrow slice of applications.

For example, the da Vinci surgical system provides surgeons a good understanding of the remote environment via an immersive 3-dimensional stereo display. However, in many applications the operator must maintain a high level of situational awareness in his or her local environment. It would not be safe to disallow a search-and-rescue worker to directly view the local disaster field in order to provide him or her with a full 3-dimensional view of the remote robot's surroundings [6]. Second, the da Vinci robot always works in a configuration that is far from its kinematic limits. Unfortunately, achieving this desired result requires a large robotic manipulator to achieve a relatively small workspace, which is acceptable in robotic surgery, but not in any application that requires a mobile manipulator. Furthermore, the da Vinci surgical system costs between 0.6 and 2.5 million U.S. dollars [15] and is too cost prohibitive for many applications. Finally, with the exception of a few notable cases, e.g. Ghodoussi et al. [10], the master console and slave manipulator are always colocated in the same room during robotic surgery, so that the communication time delay between the master and slave robot is negligible.

Creating systems to extend teleoperation beyond what is achievable by expensive systems with fully-immersive master interfaces that control a remote robot with full manipulability under negligible time delay has been a consistently active field of research. In this paper we choose to focus on improving the usability of teleoperation systems that operate under significant communication time delays between the master interface and the slave manipulator. We note that time delay is a challenge that will never disappear with improved technology because communication speeds are fundamentally limited by the speed of light for earth-to-space and earth-to-earth applications and by the the speed of sound traveling in water for subsea robotic applications [23, 21]. We propose that combining a predictive display with shared control can greatly improve the usability of teleoperation systems with time delay.

In this paper, we first discuss relevant background information in Section II. Next, Section III provides details of our proposed system and the initial implementation. Finally, we leave the reader with our plans to conduct a human subject experiment to interrogate the merits of our proposed system in Section IV.

II. Background

Overcoming difficulties presented by time delay in teleoperation is one of the most challenging and well investigated research areas related to teleoperation. In 1993, Sheridan [23] published a review paper on the 30-year history of research aimed to mitigate negative effects of time delay. In 2016, over 50 years after research began in this area, Sheridan [22] still cites communication delay as one of the two major human-factors challenges facing teleoperation. We note that although a significant amount of research in this area aims to create better controllers to improve stability of teleoperators with time delay [1], this paper focuses solely on the human factors challenges that remain in a stable system with communication delay between the master and the slave robot.

One major human factors approach to improving teleoperation with time delay has focused on creating predictive displays that immediately inform the user of the expected state to the robot and the robot's environment based on his or her control input e.g. [2, 13]. Hirzinger et al. [13] showed that such a predictive display allowed a ground operator to execute a task with a robot in space without relying on an elemental-move-then-wait strategy, which is employed by operators working under time delay. Both Brunner et al. [5] and Funda et al. [9] extended predictive displays to a teleprogramming framework. Teleprogramming is particularly valuable in applications with both time delay and limited communication bandwidths, such as subsea manipulation tasks [21]. In the teleprogramming

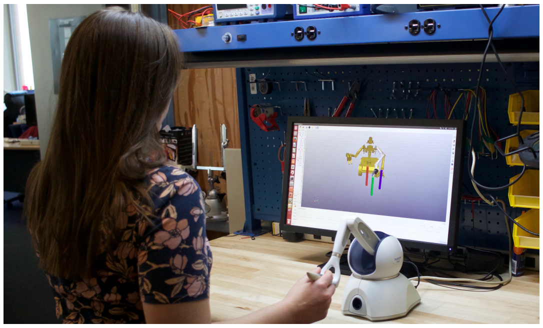

Fig. 1. The system's operator interface consists of a PHANToM Omni and a predictive visual display.

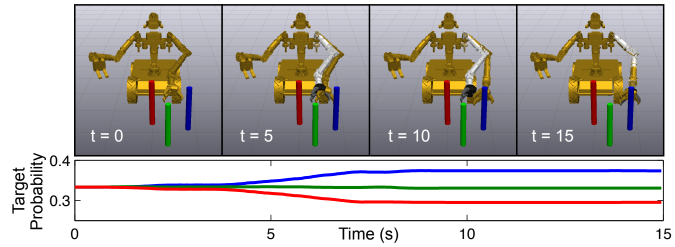

Fig. 2. A sample reach-and-grasp task was performed with our system. As an operator completes the task, he or she is shown both the predicted state of the robot (gold) and the last returned real state of the robot (silver). The robot had no prior knowledge of the user's intent and used the methods developed by Dragan and Srinivasa [7] to predict that the operator was attempting to grasp the blue target. The bottom plot shows the probability assigned to the red, green, and blue targets as a function of time.

paradigm, the operator interacts with a simulated robot, just as he or she would interact with a simulated robot in a predictive display. However, in teleprogramming batched commands are sent to the remote robot, as opposed to being continuously streamed. The commands are either sent as determined by the operator, i.e. after he or she is satisfied with a motion plan created in the simulated environment, or as dictated by the teleprogramming system, i.e. batched commands are sent at a rate of 2 Hz. A team of researchers at MIT recently created a teleprogramming interface, called the Director, as their master interface for the DARPA Robotics Challenge [8].

The Director also incorporates shared autonomy by having the operator specify a goal pose and having the robot autonomously plan its motion trajectory. Shared autonomy, along with supervised autonomy, is a second vein of work that many researchers have focused on to improve teleoperation with time delay [20]. In shared autonomy, both the user and the robot take separate and active roles to work together to execute the task. In supervised autonomy, the human operator generates high level commands that the robot executes autonomously. Most recently Bohren et al. [3], created a semi-autonomous teleoperation system in which the remote robot autonomously executes a task segment after it recognizes the operator's intent. Bohren et al. [4] validated this approach in a simulated teleoperator with 4 seconds of communication delay. While we are encouraged by the success of this work, we note that their approach requires the robot to have a complete task plan in order to predict the user's intent confidently enough to assume control. While providing the robot with a full task plan is acceptable for several applications, such as preplanned assembly tasks, many domains require the completion of tasks with a sequence of actions that cannot be predetermined, such as a search and recover task.

To extend this line of work to applications where the robot does not have prior knowledge of the task plan, we have created a system that combines a predictive display with a shared control framework. In shared control, the human operator and the robot work together to complete the mission in the remote environment [19].

III. Teleoperator

We have implemented the shared control frame work developed by Dragan and Srinivasa [7], which was more recently implemented by Muelling et al. [18]. Importantly, in this implementation operators always have the power to override the shared control system and *breakaway* from a path leading the robot towards an incorrectly predicted goal. We have combined shared control with a predictive display, to give the operator immediate feedback of the robot's commanded state.

A. Hardware

The master interface of our teleoperator is show in Fig. 1. The operator uses a PHANToM Omni [17] to control the motion of the remote robot. The operator views both the predicted state of the robot, displayed immediately to the operator, and the real state of the robot using the MIT Director interface [8]. The real state of the robot corresponds to the predicted state after a time period equal to the 2-way communication delay, so the real robot state can be thought of as approximately trailing the predicted robot state.

The slave robot used in this experiment is a custom robot, named Optimus. Optimus has an RE^2 Robotics 16-degree-of-freedom manipulator, comprised of two 7-degree-of-freedom arms and a 2-degree-of-freedom torso. We are currently using a virtual version of this robot, simulated using the Drake toolbox [24], and will use the real robot in the future.

B. Shared Control Implementation and Predictive Display

Fig 2 illustrates our implementation of the shared control policy developed by Dragan and Srinivasa [7]. In this framework, the robot is aware of a set of possible goal states that the operator may be trying to achieve. The robot then uses a cost function and the operator's commands to determine which of the possible goal states is most likely to be the operator's intended goal state. The robot then plans a path to the predicted goal and moves to a state that is a weighted combination of the operator's commanded state and the robot's predicted state. In this work, the goal states correspond to a set of simulated graspable objects, such as those shown in Fig. 2. The cost function is the Cartesian distance to each goal.

As seen in Figs. 1 and 2, the operator views two robot models: the predicted state of the robot (gold) and last known actual state of the robot (silver). The predictive model shows the robot's desired state immediately after the shared control policy blends the operator's commands with the robot's predicted command. Simultaneously, this desired state is commanded to the robot. After a two-way time delay, the display will show the robot's actual state after it attempted to achieve the desired pose.

The visual display also displays information about the remote robot's environment. In the current simulated system, the operator views virtual objects directly. In the future system, the operator will view data collected by visual sensors on the real robot. We also plan to dynamically model objects in the robot's environment and show a prediction of how their motion would evolve given the commanded state of the robot.

IV. Proposed User Study

We plan to run a user study in the very near future to see how shared control affects teleoperation with time delay. We will implement a 2x2 within subject experimental design. Subjects will test the system both with and without the predictive display and with and without shared control. We will analyze task performance and subjective ratings to determine the relative merits of each component of the system.

References

[1] Paolo Arcara and Claudio Melchiorri. Control schemes for teleoperation with time delay: A comparative study. *Robotics and Autonomous Systems*, 38(1):49–64, 2002.

[2] Antal K Bejczy, Steven Venema, and Won S Kim. Role of computer graphics in space telerobotics: Preview and predictive displays. In *Fibers*, pages 365–377. International Society for Optics and Photonics, 1991.

[3] Jonathan Bohren, Chavdar Papazov, Darius Burschka, Kai Krieger, Sven Parusel, Sami Haddadin, William L Shepherdson, Gregory D Hager, and Louis L Whitcomb. A pilot study in vision-based augmented telemanipulation for remote assembly over high-latency networks. In *Proc. International Conference on Robotics and Automation*, pages 3631–3638. IEEE, 2013.

[4] Jonathan Bohren, Chris Paxton, Ryan Howarth, Gregory D Hager, and Louis L Whitcomb. Semi-autonomous telerobotic assembly over high-latency networks. In *Proc. International Conference on Human Robot Interaction*, pages 149–156. IEEE Press, 2016.

[5] B Brunner, K Zettel, B Steinmetz, and G Hirzinger. Tele-sensor-programming: A task-directed programming approach for sensor-based space robot. 1995.

[6] J. Casper and R.R. Murphy. Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center. *Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, 33 (3):367–385, June 2003.

[7] Anca D Dragan and Siddhartha S Srinivasa. A policy-blending formalism for shared control. *The International Journal of Robotics Research*, 32(7):790–805, 2013.

[8] Maurice Fallon, Scott Kuindersma, Sisir Karumanchi, Matthew Antone, Toby Schneider, Hongkai Dai, Claudia Pérez D'Arpino, Robin Deits, Matt DiCicco, Dehann Fourie, et al. An architecture for online affordance-based perception and whole-body planning. *Journal of Field Robotics*, 32(2):229–254, 2015.

[9] Janez Funda, Thomas S Lindsay, and Richard P Paul. Teleprogramming: Toward delay-invariant remote manipulation. *Presence: Teleoperators & Virtual Environments*, 1(1):29–44, 1992.

[10] Moji Ghodoussi, Yulun Wang, et al. Robotic surgery-the transatlantic case. In *Proc. IEEE International Conference on Robotics and Automation*, volume 2, pages 1882–1888. IEEE, 2002.

[11] Raymond C Goertz. Fundamentals of general purpose remote manipulators. *Nucleonics*, 10(11):36–42, 1952.

[12] Gary Guthart and John Kenneth Salisbury Jr. The intuitive telesurgery system: Overview and application. In *Proc. IEEE International Conference on Robotics and Automation*, pages 618–621. IEEE, 2000.

[13] Gerd Hirzinger, Bernhard Brunner, Johannes Dietrich, and Johann Heindl. Rotex-the first remotely controlled robot in space. In *Proc. on International Conference on Robotics and Automation*, pages 2604–2611. IEEE, 1994.

[14] NG Hockstein, CG Gourin, RA Faust, and David J Terris. A history of robots: from science fiction to surgical robotics. *Journal of Robotic Surgery*, 1(2):113–118, 2007.

[15] Intuitive Surgical Inc. Investor presentation, 2016. URL http://investor.intuitivesurgical.com/phoenix.zhtml?c=122359&p=irol-IRHome.

[16] Thomas Jefferson. Thomas Jefferson to James Bowdoin July 10, 1806, Retrieved from the library of congress. *https://www.loc.gov/item/mtjbib016296*.

[17] Thomas H Massie and J Kenneth Salisbury. The phantom haptic interface: A device for probing virtual objects. In *Proc. Symposium on Haptic Interfaces*.

[18] Katharina Muelling, Arun Venkatraman, Jean-Sebastien Valois, John Downey, Jeffrey Weiss, Shervin Javdani, Martial Hebert, Andrew B Schwartz, Jennifer L Collinger, and J Andrew Bagnell. Autonomy infused teleoperation with application to bci manipulation. *Proc. Robotics: Science and Systems*, 2015.

[19] Günter Niemeyer, Carsten Preusche, and Gerd Hirzinger. Telerobotics. In *Handbook of Robotics*, pages 741–757. Springer, 2008.

[20] Carl F Ruoff. *Teleoperation and Robotics in Space*, volume 161. AIAA, 1994.

[21] Craig P Sayers, Richard P Paul, Louis L Whitcomb, and Dana R Yoerger. Teleprogramming for subsea teleoperation using acoustic communication. *Oceanic Engineering*, 23(1):60–71, 1998.

[22] TB Sheridan. Human-robot interaction: Status and challenges. *Human factors*, 2016.

[23] Thomas B Sheridan. Space teleoperation through time delay: review and prognosis. *Transactions on Robotics and Automation*, 9(5):592–606, 1993.

[24] Russ Tedrake. Drake: A planning, control, and analysis toolbox for nonlinear dynamical systems, 2014. URL http://drake.mit.edu.