A Trust-Based Mixed-Initiative Teleoperation Scheme for the Shared Control of Mobile Robotic Systems

Hamed Saeidi
Department of Mechanical Engineering
Clemson University, Clemson, SC 29634
Email: hsaeidi@g.clemson.edu

Yue Wang
Department of Mechanical Engineering
Clemson University, Clemson, SC 29634
Email: yue6@clemson.edu

***Abstract*—In this work, a trust-based mixed-initiative scheme for teleoperation of multiple mobile robots is developed. In the proposed scheme, the task of controlling the robots is shared between a human operator and autonomous controllers of the mobile robots. The control inputs from human and the autonomous robot controllers are dynamically blended via a computational human-to-robot trust model. Meanwhile, the haptic force feedbacks provided to the operators are also adjusted dynamically with a function of computational robot-to-human trust in order to improve human performance. The results of a preliminary study on one human-robot pair indicate that the proposed scheme can improve task performance by 31% and reduce operator workload by 23.9% compared to the pure bilateral teleoperation.**

I. Introduction

In a mixed-initiative control scheme, control commands of a human operator and an in-situ autonomous controller are dynamically blended in order to integrate human inputs with autonomous control and achieve higher performance [4]. In a bilateral haptic teleoperation scheme, a human operator controls a robot remotely via a control device while receiving haptic force feedback cues that help the operator to control the robot more effectively [1]. In this work, we take advantage of both schemes and develop a trust-based mixed-initiative bilateral teleoperation scheme for mobile robotic systems, where human-to-robot trust mediates the blending between manual and autonomous control and robot-to-human trust adjusts the intensity of the haptic force feedback.

In teleoperation, human performance may suffer from teleoperation delays [4]. On the other hand, robot performance will deteriorate under exclusively autonomous control due to its limited sensing and processing capabilities. Human factors research indicates that human trust in a robot is a major factor that determines the use of autonomous controllers of the robot and is dynamic and highly dependent on robot performance [2]. Built on the literature, we develop computational models of human-to-robot trust and robot-to-human trust. We utilize objective measures to compute the human-to-robot trust such that we provide a human-like, however unbiased control allocation method to improve the overall task performance. The robot-to-human trust is used to adjust the level of haptic feedback provided to the operator for reduced workload.

In the remaining parts of this paper, first we introduce the proposed control scheme for one human-robot pair [3] in Section II and the results of a case study are presented in Section III. Then, an extension to multi-robot system is provided in Section IV.

II. Trust Based Mixed-Initiative Teleoperation

Our proposed trust-based mixed-initiative bilateral haptic teleoperation scheme for a target tracking example is shown in Fig. 1. The mixed-initiative control integrates manual commands with autonomous control commands using variable allocation scales $\alpha(t) \in (0,1]$ and $1-\alpha(t)$, respectively. Another variable scale $\beta(t)$ scales force feedback cues in order to provide various levels of assistance to the operator. We define the trust-based variable scaling parameters in the following range $0 < \underline{\alpha} \leq \alpha(t) \leq \overline{\alpha} \leq 1, \quad 0 < \underline{\beta} \leq \beta(t) \leq \overline{\beta}$, where the positive constants $\underline{\alpha}, \overline{\alpha}, \underline{\beta}, \overline{\beta}$ are task-based choices determining the lower and upper bounds on $\alpha(t)$ and $\beta(t)$. Here, we define $\alpha(t)$ and $\beta(t)$ as a function of human-to-robot trust (denoted as $T_{hr}(t)$) and robot-to-human trust (denoted as $T_{rh}(t)$) respectively as shown in Fig. 1. The functions indicate that whenever human trust in robot is lower, $\alpha(t)$ takes a higher value such that the autonomous controller has a smaller contribution and vice versa. Similarly, lower levels of robot-to-human trust lead to higher values of $\beta(t)$ which makes the human operator receive larger force feedback cues for performance improvement and vice versa.

We propose the performance-centric computational models of human-to-robot trust $T_{hr}(t)$ and robot-to-human trust $T_{rh}(t)$ according to the following:

$$\dot{T}_{hr}(t) = -a_{hr}\frac{T_{hr}(t) - \underline{T}_{hr}}{\overline{T}_{hr} - \underline{T}_{hr}} + b_{hr}\frac{P_r(t) - \underline{P}_r}{\overline{P}_r - \underline{P}_r} \qquad (1)$$

$$\dot{T}_{rh}(t) = -a_{rh}\frac{T_{rh}(t) - \underline{T}_{rh}}{\overline{T}_{rh} - \underline{T}_{rh}} + b_{rh}\frac{P_h(t) - \underline{P}_h}{\overline{P}_h - \underline{P}_h} \qquad (2)$$

where the constants $\{a_{hr}, b_{hr}, a_{rh}, b_{rh}\} \in (0,1]$ are some sensitivity parameters. Using these trust models, when the performances are bounded in $P_r(t) \in [\underline{P}_r, \overline{P}_r]$ and $P_h(t) \in [\underline{P}_h, \overline{P}_h]$, $T_{hr}(t)$ and $T_{rh(t)}$ are bounded as well, i.e. $T_{hr}(t) \in$

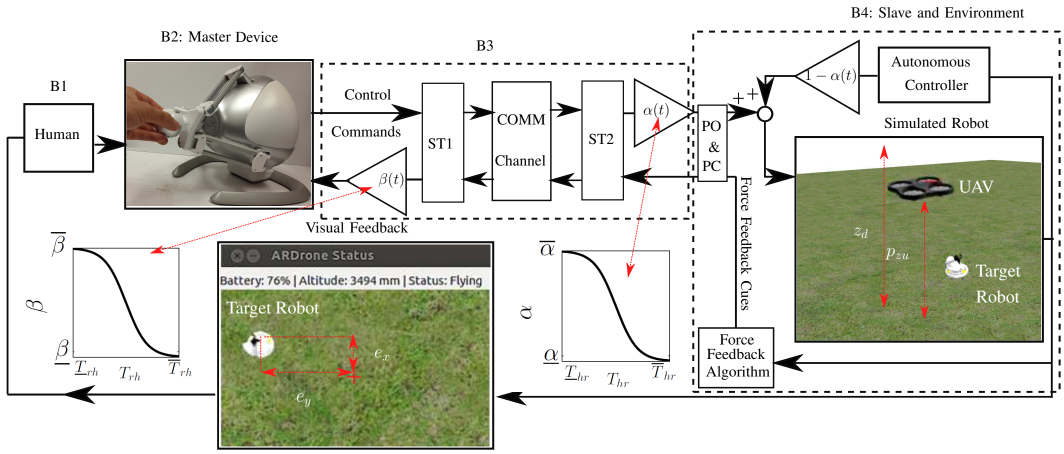

Fig. 1: Block diagram of an experiment testbed for the trust-based mixed-initiative bilateral teleoperation: a Falcon® master device, an A.R. Drone® UAV and a Robotino® UGV in the Gazebo simulator integrated via Robot Operating System (ROS).

TABLE I: Comparison of the control schemes.

Control Scheme	Err(m)		Pref (1-5)		TLX (0-100)	
	μ	σ	μ	σ	μ	σ
M	3.79	2.2	3.07	0.83	54.12	17.05
MI	16.76	20.9	2.91	0.69	52.42	29.87
MMI	2.73	1.76	3.63	0.48	40.46	16.8
TMI	2.63	1.59	3.82	0.45	30.21	16.15

$[\underline{T}_{hr}, \overline{T}_{hr}]$ and $T_{rh}(t) \in [\underline{T}_{rh}, \overline{T}_{rh}]$. These bounds determine the acceptable range of trust to avoid either human-robot over-reliance or under-reliance. These trust values can be easily computed by the robot via the models (1)-(2) and the values of real-time performance metrics. Consequently, a proper shared-control allocation as well as force feedback scaling can be carried out on the slave and master sides.

In [3], we guarantee the stability of the entire scheme of Fig. 1 via different passivity-based techniques. More specifically, we develop wave/scattering transformations for the block B3 (i.e. ST1 and ST2 in the communication channel) to guarantee the passivity of the communication channel in the presence of time-varying power scaling (i.e. $\alpha(t)$ and $\beta(t)$) and communication delays (i.e. $T_1(t)$ and $T_2(t)$). We also utilize a passivity observer (PO) and a passivity controller (PC) to guarantee the passivity of the slave robot. In this case, the PO tracks the energy of the slave and activates the PC that modifies the force feedbacks in order to dissipate the active energy created by slave.

III. Results

We conducted an experiment via the testbed shown in Fig. 1 to evaluate the performance of the proposed trust-based mixed initiative bilateral haptic teleoperation scheme. In this test, the goal is to control a UAV to track a target ground robot at a desired altitude (here $z_d = 4$). The UAV can be both teleoperated by a human operator and autonomously controlled with an outer-loop PID controller to hover over the target. Here, we evaluate the human performance P_h and robot performance P_r in real-time according to their share (i.e. $\alpha(t)$ and $1-\alpha(t)$) in average tracking error $\mathbf{e}(t)$ of the UAV in last 10 seconds.

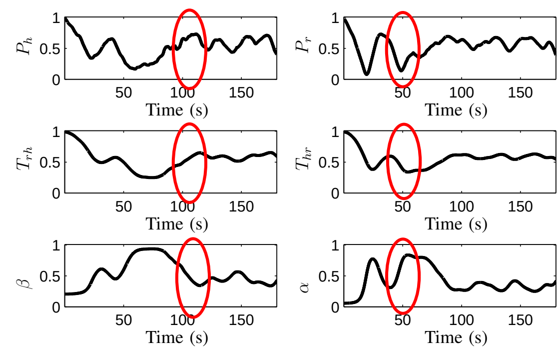

Fig. 2: Evolution of performance, trust, and scaling parameters of participant 2 in the TMI scheme.

A set of experiments were conducted for 8 participants via three mixed-initiative control schemes and an exclusively manual teleoperation scheme according to the following:

- **M**: Pure manual teleoperation + haptic feedback,
- **TMI**: Automated trust-based mixed-initiative teleoperation + haptic feedback using the scheme in Fig. 1,
- **MMI**: Manually adjusted mixed-initiative teleoperation + haptic feedback (MMI),
- **MI**: Automated trust-based mixed-initiative teleoperation + no haptic feedback.

The subjective evaluation of workload via NASA TLX in addition to the operators' preference towards each control scheme were assessed. Table I shows the mean values (μ) and standard deviations (σ) of these metrics along with the objective tracking error criterion (i.e. "Err" in meters). According to this table, the proposed TMI scheme leads to the smallest tracking error, lowest workload, and highest preference of the participants on average. Compared to the pure manual mode M, TMI improves the performance by

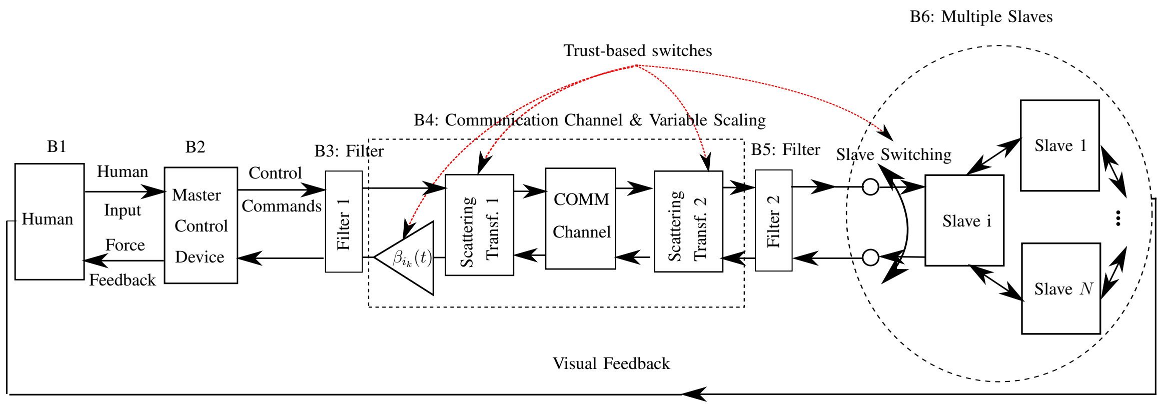

Fig. 3: Block diagram for the trust-based bilateral teleoperation of multi-robot team.

31% and reduces the workload by 23.9%. An example of the evolution of the performances $P_h(t)$ and $P_r(t)$, trust functions $T_{hr}(t)$ and $T_{rh}(t)$, as well as the allocation functions $\alpha(t)$ and $\beta(t)$ in the TMI scheme is shown in Fig. 2. In this example, we can see that when $P_h(t)$ stays at a high level (e.g. between 100-120 seconds), $T_{rh}(t)$ increases and results in a lower level of $\beta(t)$ and hence less force feedback. Similarly, when $P_r(t)$ plummets (e.g. between 40-60 seconds), $T_{hr}(t)$ decreases which results in a higher level of $\alpha(t)$ and hence less contribution from the autonomous controller.

IV. Extension to Multi-Robot Systems

In this section, we extend the proposed scheme to the multi-robot systems as shown in Fig. 3 which is suitable for applications such as platooning or formation control [1]. In this case, the human-to-robot trust $T_{hr_i}(t)$ and robot-to-human trust $T_{rh_i}(t)$ can be calculated for each robot i according the models (1) and (2), where $i \in \{1, 2, \cdots, N\}$ determines a specific robot in the team consisting of N robots, and $P_{r_i}(t)$ is the performance of robot i. In the multi-robot scheme shown in Fig. 3, human-to-robot trust $T_{hr_i}(t)$ will be used to decide which specific leader robot should be teleoperated by human during a specific time period while the other robots are under a pure local autonomous control. An example of such a trust-based leader selection policies can be always collaborating with the robot that has the highest trust for improved overall task performance.

In the new multi-robot scheme, we utilize robot-to-human trust $T_{rh_i}(t)$ as a criteria to scale the force feedback cues such that whenever robot i is chosen as the teleoperated leader in the time period $(t_k, t_{k+1}]$, the force feedbacks will be scaled with a variable scale $\beta_{i_k}(t) = g_{rh_i}(T_{rh_i}(t))$, depending on the trust of the current leader to human, i.e. $T_{rh_i}(t)$. The function $g_{rh_i}(\cdot)$ should follow the same logic as $\beta(t)$ in the single robot case in Section II.

However, development and utilization of such a scheme requires non-trivial extensions to the scattering transformations to handle the switches between different configurations of team whenever a new leader is chosen. The corresponding new theoretical extensions are parts of an ongoing research in which a novel switched scattering transformation is developed via switched-system passivity techniques. Moreover, switches between the leader robots cause discontinuous force feedback which can be problematic and confusing for the operator. Therefore, another major block that is developed in the new scheme is a passive and stable first-order filtering method to smoothen the transitions between the leader changes (i.e. blocks Filter 1 and Filter 2 in Fig. 3). Finally, the position synchronization and convergence of the team of robots is guaranteed using the proposed scheme.

V. Conclusion

In this work, a stable trust-based mixed-initiative teleoperation scheme for mobile robots was developed. A preliminary experiment with human-in-the-loop indicates that the proposed scheme with computational two-way models of trust can improve the task performance and reduce human workload compared to exclusively manual teleoperation. Extensions to multi-robot systems are also discussion.

Acknowledgments

This research was supported by the National Science Foundation under grant No. CMMI-1454139.

References

[1] A. Franchi, C. Secchi, M. Ryll, H. H. Bülthoff, and P. R. Giordano. Shared control: Balancing autonomy and human assistance with a group of quadrotor uavs. *Robotics & Automation Magazine, IEEE*, 19(3):57–68, 2012.

[2] J. Lee and N. Moray. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35(10):1243–1270, 1992.

[3] H. Saeidi, F. McLane, B. Sadrfaridpour, E. Sand, S. Fu, J. Rodriguez, J. R. Wagner, and Y. Wang. Trust-based mixed-initiative bilateral teleoperation of mobile robotic systems. *accepted for presentation in American Control Conf.*, 2016.

[4] R. Wegner and J. Anderson. Agent-based support for balancing teleoperation and autonomy in urban search and rescue. *Int. J. of Robotics & Automation*, 21(2):120, 2006.