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SEMI-AUTONOMOUS TELEOPERATION, GUIDANCE, AND OBSTACLE AVOIDANCE WITH PATH ADHERENCE

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ABSTRACT

Decreasing user effort and automating subtasks such as obstacle avoidance and user guidance has shown to increase the effectiveness and utility of teleoperation. Extending the capabilities of teleoperation remains a critical research topic for tasks that need to leverage user knowledge, or for unstructured environments that autonomous solutions are not robust enough to handle. Previous methods have focused individually on joint space tasks, regression or training based user intention recognition and intervention, or application specific solutions. To overcome the limitations of these methods, this paper proposes the use of path planning based gross motion assistance with a projection based user intention recognition method, for improving task execution in semi-autonomous teleoperation. The proposed solution synthesizes an assistive architecture that leverages the benefit of supervisory level task identification with semi-autonomous trajectory tracking. With the proposed method, continuous and more immersive teleoperation is achieved, as control states are user selected and task execution is informed from the operator's motion. The effectiveness of the proposed method is validated with a user study.

Keywords: Teleoperation, Semi-autonomous control, Shared control, Intention recognition, Motion planning

1 INTRODUCTION

The benefit of teleoperation stems from its ability to leverage operator knowledge to handle unstructured or complex remote tasks that fully autonomous systems are unable to overcome. To increase productivity and reduce user fatigue, some autonomous methods have been applied to augment teleoperation in shared or semi-autonomous control. With these methods the user and robot share or split control over the system states, where the level of control is often handled with confidence weighting. Recent work [1,2] demonstrates that shared control improves task completion time and is intuitive for users.

Current research focuses on how best to incorporate autonomy and identify user input by examining different frameworks and levels of assistance, as well as how to identify user intention. Typically, the frameworks are implemented in a supervisory manor where the user defines tasks and targets ahead of operation [3,4] or hierarchical task control as presented in [5], where the shared control executes sub-tasks autonomously and may or may not assist the main task. Sub task control for redundant manipulators has been well studied [2,6–8]. Typical tasks include monitoring and preventing joint limits, configuration singularities, guiding end-effector orientation, and obstacle avoidance. These are natural candidates for automation to reduce user effort, allowing more focus on the higher level objective. Other task assistive methods have been implemented in the form of haptic force reflection for guidance [9,10]. This is accomplished through impedance based guidance and collision avoidance by use of virtual force fields or a virtual spring and damper con-

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necting the task and end-effector. Impedance based guidance has also been widely used in obstacle avoidance for mobile robots controlled via teleoperation [11–13]. Many shared control approaches have been adapted from the field of mobile robotics for guidance and collision avoidance in the form of potential fields [14], some with enhanced capabilities of online vision based fixture generation as in [15]. Unfortunately, both impedance and potential fields approaches have drawbacks, as the impedance force can confine the pose by pulling to a task while being repelled by an obstacle, similar to how a potential field may cause the robot to be locked into a local minimum. Other methods have focused on assistance recognition for predicting user motion to move to a target or execute a task. Most often, this is accomplished with a Hidden Markov Model (HMM) [16, 17]. Some have also used Gaussian processes for implementing shared control from tasks learned by demonstration [18]. The major drawback of such approaches is that they require training, which can be a very time consuming.

Different approaches, like those in [19, 20], identify user intention from their trajectory using regression to form a line for the expected path and accumulating the distances to targets from the path up to a threshold to determine intention. However, this requires the user to travel along the path for a sufficient amount of time until a target is identified. This will slow down operation, particularly in the presence of obstacles where the path may need to change to avoid collisions. A simplified method is to project the current direction on to the vector from the current end-effector pose to a target. This was done in [21] with a set of heuristics to identify user intent for autonomous execution of grasp primitives. However, in their method, the robot pose had to be sufficiently close to the grasping target, making it's use case more suited for action recognition than target identification. Although autonomous execution of fine movements is beneficial in some applications, it removes some of the user knowledge that can be leveraged in teleoperation. Thus, shared control and autonomous assistance for gross motion can be of greater benefit for reducing user effort and task completion time, particularly where user skill can be used for direct teleoperation. With this control structure, path planning can be leveraged to execute the aforementioned gross motion while avoiding collisions, such as in [22].

Some of the aforementioned methods demonstrate great potential as options for decreasing user effort, but to the knowledge of the authors, they have not been synthesized for a holistic shared control or semi-autonomous framework. This paper proposes the use of path planning with user intention recognition for guidance and obstacle avoidance for semi-autonomous teleoperation. The novelty of this work is twofold. First, a projection based predictor for user intention recognition is implemented for target identification based on user motion. Second, a control architecture for gross motion automation with subtask execution is developed for assistive teleoperation based on an optimal trajectory from an assumed path planner. The target identification runs continuously allowing for target correction, with the user controlling shifting between direct teleoperation or assisted control. By focusing on the gross motion, there is no need to realign pose frames as in situations with auto grasping. Moreover, this takes greater advantage of the teleoperation paradigm by leveraging user knowledge to execute complex tasks in unstructured environments, while reducing the burden on the user with trivial motion execution. Sub tasks of bounding workspace locations and singularity avoidance are applied to the user as haptic feedback. A user study for a pick and place operations is conducted to evaluate the proposed method's performance and user perception.

2 CONTROL ARCHITECTURE

The work presented here focuses on applying the proposed semi-autonomous teleoperation scheme to a real workspace synchronization of a heterogeneous master slave system, with a non-redundant follower. The formulation given below is developed for the experiment, but is presented generally and can be scaled to other systems.

Figure 1 depicts the proposed architecture summarized above, where FK and IK refer to the forward and inverse kinematics respectively. User input to the master haptic device is sent to the follower where a supervisor governs whether to navigate to a target autonomously based on the user input (State 1), or whether the target location has been reached and the user is given direct control of the slave with haptic feedback (State 2). The user is able to switch between states at any given time with a button on the master device; this could alternatively be placed on the master side computer. In this architecture, the master position is sent to the slave (referred interchangeably as the follower), where a PID controller is used to control each joint of the manipulator. The follower side controller is formulated for a heterogeneous master-slave system where the master workspace is much smaller than the follower workspace. Thus, only a delta position is sent, such that the user can choose when the master and follower are linked in order to re-orient themselves and continue operation when they have reached the end of the master's workspace. To not interfere with the operator, virtually imposed haptic forces are reflected back on to the user only for the workspace bounding sub task.

2.1 User Intended Target Identification

To identify the target that the user is trying to move towards, the heuristic in Eqn. (1) is used. It is the maximization of the dot product between the master velocity and the vector from the slave end effector to each of the targets. It takes the form of

$$i = \arg\max_{i}(\vec{v}\cdot\vec{r}_{x,i}) \tag{1}$$

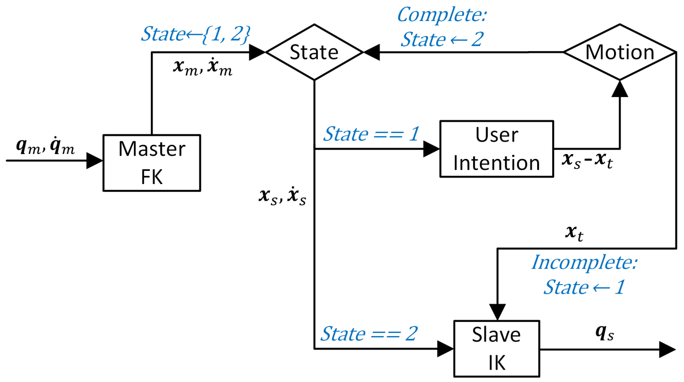

FIGURE 1: Semi-autonomous assistive architecture diagram with supervisory state based control for recognizing user intention and motion execution. Subscripts m, s, and t refer to the master, slave, and target respectively.

where i is the determined target, $\vec{v}$ is the velocity of the master, and $\vec{r}_{x,i}$ is the vector pointing from the slave end effector to the i^{th} target. To make the system agnostic to the magnitude of $\vec{v}$ and $\vec{r}_{x,i}$, each of them is normalized prior to the evaluation of the dot product. Assuming small sensor noise and a perfectly direct user heading, the above identifier would only fail to distinguish user intent in the case of exact symmetry such that the value of $\vec{v} \cdot \vec{r}_{x,i}$ is not unique. This extends to the case that the end effector and multiple targets are exactly in line with each other. Neither of these cases is highly likely and as such, the proposed identifier can be used to adequately determine user intent.

2.2 Master Side Haptic Forces

The master may be modeled as

$$M_m(q)\ddot{q} + C_m(q,\dot{q})\dot{q} + G_m(q) = \tau_m + \tau_h \tag{2}$$

where M is a positive definite and symmetric inertia matrix and C is a matrix of Coriolis and centrifugal effects. $(\dot{M} - 2C)$ is skew-symmetric, G is the gravity matrix, and $q \in \mathbb{R}^4$ is a vector of joint angles. τ_m is comprised of the master input torques based on the Cartesian space virtual forces F_H such that $\tau_m = J^T F_H$.

To ensure that the user does not crash the end effector into the ground, the virtual force is defined to be

$$F_H = \begin{cases} Ke + B\dot{e}, & \text{if } z_l > x_s > 0 \\ 0, & \text{if } z_l < x_s \end{cases} \tag{3}$$

where $e = z_l - x_s$ for the slave side position vector x_s, and z_l is the set lower workspace limit in the $\hat{k}$ direction.

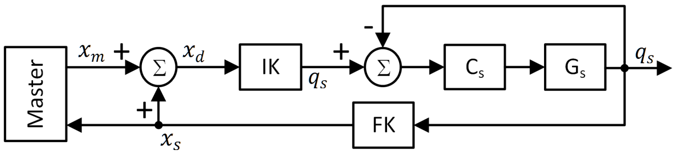

FIGURE 2: Slave side position controller for the workspace pose command. C_s and G_s are the slave low level controller and plant.

For workspace boundary singularities, the follower evaluates whether $|x_m| \leq L$, where x_m is a vector of the end effector pose, adjusted to be with respect to the manipulator's shoulder joint, and L is the workspace limit from joint q_2 such that

$$\sqrt{x^2 + y^2 + (z - L_1)^2} \leq L_2 + L_3 + L_4. \tag{4}$$

R is set to be the boundary radius for the virtually imposed haptic force. If $R < |x_m| < L$, the haptic force guides the user back towards inside the workspace, with the force asymptotically reaching infinity at the workspace boundary as

$$F_H = \frac{-\vec{r}\gamma}{(|\vec{r}| - R)^n}, \quad n = \text{even} \tag{5}$$

where γ is a tuning parameter to scale how quickly the force approaches the asymptote. This ensures that the user does not reach the workspace singularity. All of the haptic forces are limited to the output of the master haptic device, ensuring safe operation.

2.3 Follower Side Control

Although in non-delayed systems position-velocity and velocity-velocity control architectures are often used, they are known to lose transparency when time delay is present. For scaling to time delayed applications, the proposed control architecture mirrors a force position scheme where the follower tracks the master position command with haptic forces reflect onto the user from the haptic device. In the proposed method, the follower workspace is much larger than the master's, thus, a method must be employed to allow the user to reset the master position after running out of motion due to kinematic constraints. To accommodate this, a button is used to synchronize the master and follower, linking the end effectors and zeroing the current master position, such that only subsequent relative positions $x_m = \Delta x_h$ are sent.

On the follower side the assistive control architecture assumes a trajectory from a path planning algorithm. The trajectory is discretized into incremental desired pose commands sent to the follower. The desired slave manipulator pose, whether for direct teleoperation or autonomous trajectory following, is achieved by the position controller depicted in Fig. 2. The desired pose x_d is calculated from the current follower position and the delta sent from the master such that $x_d = x_m + x_s$. Joint control is implemented on the follower with a PID controller from the inverse kinematics of the pose. Because the follower robot is not kinematically redundant with the task space equal to the joint space $m = n, \in \mathbb{R}^3$ as the wrist is commanded independent of the end effector position, the inverse kinematics can be solved analytically from geometry instead of using a Jacobian pseudo-inverse. The actual robot position is then calculated based on the forward kinematics model to provide the correct desired pose for the master position command.

3 EXPERIMENTAL EVALUATION

To validate the proposed semi-autonomous control strategy, an experiment was conducted for a teleoperation task. Users completed a pick and place task with both the direct control of the system and the proposed assistive control scheme. Task completion time as well as user perceived effectiveness of the assisted control was evaluated. To compare with previous studies and provide a deeper analysis, the trajectory length and total angular displacement was also evaluated.

3.1 Experimental Setup

The experiment used a teleoperation system consisting of a Geomagic Touch [23] as the master haptic device, and a Kinova Mico arm [24] as the follower. The Mico arm is a four DOF manipulator with a two finger gripper attachment. The Geomagic Touch has six DOF but only the first three joints are active. The passive wrist has a stylus held by the user with two buttons for three button modes: top (1), bottom (2), and both buttons held simultaneously (3). The master and follower are implemented on separate computers using MATLAB/Simulink running at 500 Hz. Communication between the master and follower is performed across the network using a UDP protocol to increase communication speed. Although the communication delay is nonzero, it was negligible such that the system is assumed to be without time delay.

A pick and place teleoperation task was conducted that involved grasping an empty water bottle and placing it into one of three containers, while avoiding an obstacle as depicted in Fig. 3. The bottle was placed in a staging area on a metal block elevating it from the table. For both the direct and assisted trials, the follower started in a home position just above the obstacle in between the containers and the bottle. The user study was carried out with six participants with three trials for each container target for both operation modes, for a total of 18 trials per user. Half of the users had previous experience controlling a teleoperated system.

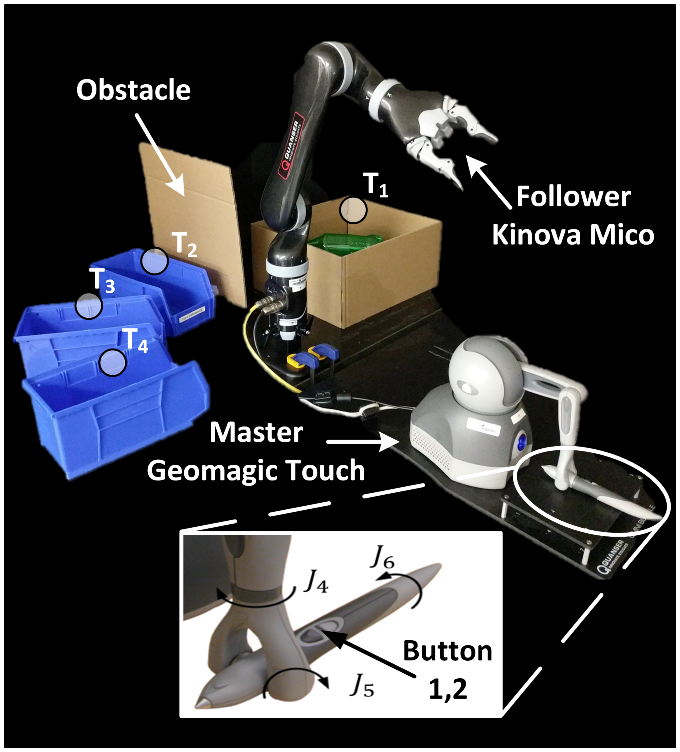

FIGURE 3: Experimental setup with indicated master and follower systems, environmental obstacles, and operational targets (T1-T4).

In the direct control mode, the Geomagic buttons were used to give the user control over more than just the end effector position. While holding Button 3, the end effectors are linked in the Cartesian space. While Button 1 is pressed, motion in the x-axis of the master opens and closes the follower gripper fingers. When Button 2 is held, motion along the y-axis turns the wrist. The previous pose of the follower is held while no buttons are engaged, allowing the user to reorient the stylus to make up for the disproportionate workspaces.

In the assisted mode, the user operated in different machine states. In State 1, the user inputs a motion for the intended target identification. Once a target is identified, the follower autonomously navigates to the target based on an assumed trajectory from a path planner. While the follower is executing the trajectory in State 1, the user can still give direction inputs to select another target. Once the follower has reached a target, the operator regains direct control of operation until switching back into the intention recognition state from any button double click. By employing this method, the user can select when they want the autonomous assistance. In the assisted mode, haptic forces are also generated in the direct control state for sub tasks of avoiding ground collision and staying within workspace boundaries,

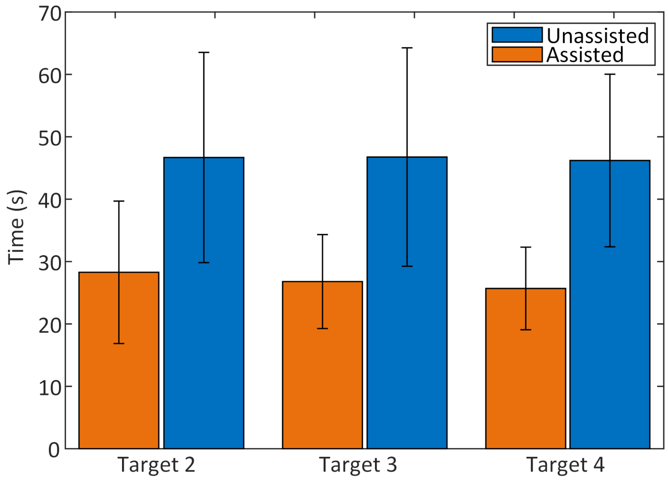

FIGURE 4: Task completion times for assisted and direct control teleoperation. The values of the bars are the mean values and the error bars indicate a single standard deviation.

as defined by Eqns. (3) & (5).

3.2 Results and Discussion

The experiment is evaluated by examining the completion time, trajectory length, total angular displacement, and the user's perceived effectiveness of the assisted control mode compared to the unassisted mode. The accuracy of the intention recognition method for predicting the target is also examined. Figure 4 shows the mean task completion times for each target for all the users, along with the standard deviation. The completion time was significantly shorter for the assisted mode, with no significant variation between targets. Overall, the assisted control scheme provided great benefit by automating the tedious task of gross manipulation. Traversing the obstacle was substantially accelerated by the assistive control. This method is particularly beneficial in the position based master-follower control scheme, since the user has to readjust when they reach the end of the master's workspace. Because of this, operator skill affected the spread of the data which can be seen in the variance of the completion times, particularly for the unassisted case.

In addition to operator skill, task learning throughout the trials also had an affect on the data. It was observed that users became more proficient in operating the system as trials progressed, resulting in an average completion time reduction of 23.8% for the unnassisted case and 35.6% for the assisted case, evaluated from the longest trial in each case for each user. The time reduction was also greater for novice users, with similar improvements between the unnassisted and assisted cases of 12.6% and 13.6% time improvement respectively.

TABLE 1: Trajectory length and angular displacement comparison

	Unassisted Length		**Assisted Length**	
	(m)	**(rad)**	**(m)**	**(rad)**
Target 2	2.838	17.622	2.706	14.258
Target 3	3.014	18.793	3.006	15.616
Target 4	3.402	20.781	3.261	16.323
Mean	3.085	19.066	2.991	15.399

The benefit of the proposed method is also evaluated using metrics of the user's motion. Based on the trajectory data in Table 1, the proposed method increases the efficiency in task execution by reducing total motion of the task. For all cases, the trajectory length was shorter for the assisted mode than the unassisted one. It should be noted however, that the distance to the target and amount of maneuvering about an obstacle affects the overall trajectory length. This can be seen by comparing the trajectory lengths between the different targets where Target 3 as well as the mean vary minimally. On the other hand, the total angular displacement of the joints had a more significant benefit in minimizing motion, which can lead to longer usability of the system by minimizing wear. Naturally, the method of generating the trajectory affects these metrics from the use of optimization and any imposed conditions for safe maneuvering. For instance, the defined trajectories for the experiment ensured that the end effector

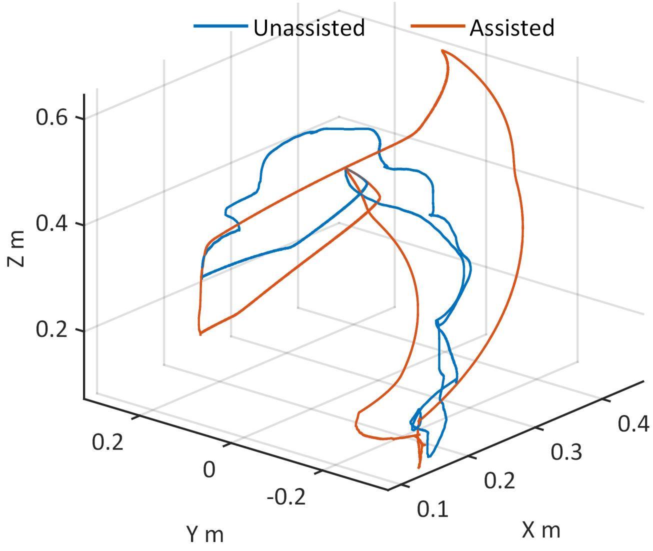

FIGURE 5: Trajectories for direct control and assisted teleoperation of a sample trial to Target 4

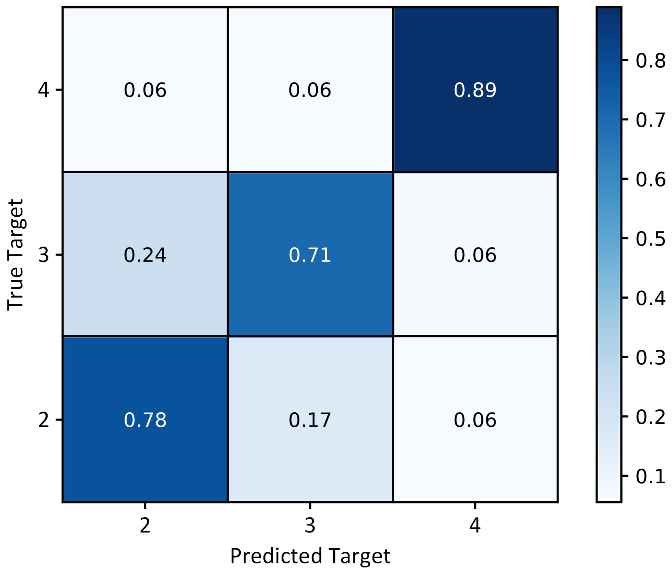

FIGURE 6: Confusion matrix of intended user target prediction.

could clear over the obstacle while maintaining the longitudinal orientation of the grasped bottle, resulting in a larger motion in the z-axis than most users, as depicted in Fig. 5.

The feasibility of this method is also supported by the effectiveness of the user intention recognition for target identification. A confusion matrix in Fig. 6 shows the accuracy of the method for each target. As expected, the outer targets had the greatest accuracy, as the path to the target has tighter margins to align to a target in between a group of other targets. Thus, the grouping of targets and their distribution can have an impact on the accuracy of the method because of how well users can align their motion. To better distinguish between tightly packed targets, a score can be used to accumulate confidence in the target with the method, however, this requires more movement along the path before a target is identified, which is a drawback seen in other user intention methods covered in the literature review above. Moreover, the proposed approach allows for selection correction, which was effectively implemented by the users in the study resulting in faster task completion times even if the initial target prediction was incorrect. This also allows for more immersive teleoperation as compared with a supervisory level target selection from the computer.

User perceived effectiveness of the assisted control scheme was also evaluated quantitatively with a standard 5 point Likert scale, as well as qualitatively from the users' comments. An average score of 4.67 was obtained from the users regarding whether they thought the assisted control scheme was more effective in task execution over direct control. All users reported perceiving the assisted control mode as beneficial for the task execution and non obstructive to operation. Additionally, the majority of users reported that the target selection was effective to speed up task execution, even in the few cases where the wrong target was initially selected. However, users did identify the button command on the stylus as difficult to operate at times.

4 CONCLUSION

This work presented a novel approach for assistive teleoperation with a control strategy that automates gross motion tasks with subtask execution, and incorporates path planing from an efficient user intention prediction method for target identification. A user study demonstrated the effectiveness of the proposed method as completion times for a pick and place task were significantly improved. Additionally, the user intention prediction proved to be accurate in target identification and a robust solution as it allows for online correction. User perception of the proposed method was positive, and all participants in the study identified the assistive mode to be effective in easing task execution.

This work was successful in demonstrating the practicality of the proposed semi-autonomous framework. As the method is based on path planning, future work is aimed at optimizing the trajectory planning for both static and moving obstacles. This provides an opportunity for increasing the efficiency and utility of semi-autonomous teleoperation. Moreover, this would provide a platform for extending these capabilities to time delayed teleoperation systems with important applications in remote tasks for telesurgery as well as space and hazardous area operations.

REFERENCES

[1] Amirshirzad, N., Kumru, A., and Oztop, E., 2019. "Human Adaptation to HumanRobot Shared Control". *IEEE Transactions on Human-Machine Systems*, ***PP***, pp. 1–11.

[2] Abi-Farraj, F., Pacchierotti, C., and Giordano, P. R., 2018. "User Evaluation of a Haptic-Enabled Shared-Control Approach for Robotic Telemanipulation". In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 1–9.

[3] Hambuchen, K., Bluethmann, W., Goza, M., Ambrose, R., Wheeler, K., and Rabe, K., 2006. "Towards Supervising Remote Dexterous Robots Across Time Delay".

[4] Landzettel, K., Brunner, B., Hirzinger, G., Lampariello, R., Schreiber, G., and Center, G. A., 2000. "A Unified Ground Control and Programming Methodology for Space Robotics Applications Demonstrations on ETS-VII". *Symposium A Quarterly Journal In Modern Foreign Literatures*.

[5] Stoyanov, T., Krug, R., Kiselev, A., Sun, D., and Loutfi, A., 2018. "Assisted Telemanipulation: A Stack-Of-Tasks Ap-

proach to Remote Manipulator Control". In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, pp. 1–9.

[6] Zhai, D.-H., and Xia, Y., 2017. "Adaptive Control of Semi-Autonomous Teleoperation System With Asymmetric Time-Varying Delays and Input Uncertainties". *IEEE Transactions on Cybernetics,* ***47***(11), 11, pp. 3621–3633.

[7] Wang, X., Yang, C., Ma, H., and Cheng, L., 2015. "Shared control for teleoperation enhanced by autonomous obstacle avoidance of robot manipulator". In 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vol. 2015-Decem, IEEE, pp. 4575–4580.

[8] Liu, Y.-C., and Chopra, N., 2013. "Control of semi-autonomous teleoperation system with time delays". *Automatica,* ***49***(6), 6, pp. 1553–1565.

[9] Smisek, J., van Paassen, M. M., and Schiele, A., 2015. "Haptic guidance in bilateral teleoperation: Effects of guidance inaccuracy". In 2015 IEEE World Haptics Conference (WHC), IEEE, pp. 500–505.

[10] Dong-Gu Kim, Sang-Kyun Kim, Jung-Tae Kim, Chong-won Lee, and Jong-Oh Park, 1998. "Active operator guidance using virtual environment in teleoperation". In Proceedings. 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems. Innovations in Theory, Practice and Applications (Cat. No.98CH36190), Vol. 2, IEEE, pp. 1084–1089.

[11] MA, Z., and Ben-Tzvi, P., 2015. "RML GloveAn Exoskeleton Glove Mechanism With Haptics Feedback". *IEEE/ASME Transactions on Mechatronics,* ***20***(2), 4, pp. 641–652.

[12] Janabi-Sharifi, F., and Hassanzadeh, I., 2011. "Experimental Analysis of Mobile-Robot Teleoperation via Shared Impedance Control". *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics),* ***41***(2), 4, pp. 591–606.

[13] Diolaiti, N., and Melchiorri, C., 2002. "Teleoperation of a mobile robot through haptic feedback". In IEEE International Workshop HAVE Haptic Virtual Environments and Their, no. June 2014, IEEE, pp. 67–72.

[14] Aigner, P., and McCarragher, B., 1997. "Human integration into robot control utilising potential fields". In Proceedings of International Conference on Robotics and Automation, Vol. 1, IEEE, pp. 291–296.

[15] Selvaggio, M., Chen, F., Gao, B., Notomista, G., Trapani, F., and Caldwell, D., 2016. "Vision based virtual fixture generation for teleoperated robotic manipulation". In 2016 International Conference on Advanced Robotics and Mechatronics (ICARM), IEEE, pp. 190–195.

[16] Stefanov, N., Passenberg, C., Peer, A., and Buss, M., 2013. "Design and Evaluation of a Haptic Computer-Assistant for Telemanipulation Tasks". *IEEE Transactions on Human-Machine Systems,* ***43***(4), 7, pp. 385–397.

[17] Aarno, D., and Kragic, D., 2008. "Motion intention recognition in robot assisted applications". *Robotics and Autonomous Systems,* ***56***(8), 8, pp. 692–705.

[18] Zeestraten, M. J. A., Havoutis, I., and Calinon, S., 2018. "Programming by Demonstration for Shared Control With an Application in Teleoperation". *IEEE Robotics and Automation Letters,* ***3***(3), 7, pp. 1848–1855.

[19] El-Hussieny, H., Assal, S. F. M., Abouelsoud, A. A., and Megahed, S. M., 2015. "A novel intention prediction strategy for a shared control tele-manipulation system in unknown environments". In 2015 IEEE International Conference on Mechatronics (ICM), IEEE, pp. 204–209.

[20] Chauhan, R. J., and Ben-Tzvi, P., 2018. "Latent Variable Grasp Prediction for Exoskeletal Glove Control". In Volume 1: Advances in Control Design Methods; Advances in Nonlinear Control; Advances in Robotics; Assistive and Rehabilitation Robotics; Automotive Dynamics and Emerging Powertrain Technologies; Automotive Systems; Bio Engineering Applications; Bio-Mecha, ASME, p. V001T07A002.

[21] Bohren, J., Papazov, C., Burschka, D., Krieger, K., Parusel, S., Haddadin, S., Shepherdson, W. L., Hager, G. D., and Whitcomb, L. L., 2013. "A pilot study in vision-based augmented telemanipulation for remote assembly over high-latency networks". In 2013 IEEE International Conference on Robotics and Automation, IEEE, pp. 3631–3638.

[22] Torres, L. G., Kuntz, A., Gilbert, H. B., Swaney, P. J., Hendrick, R. J., Webster, R. J., and Alterovitz, R., 2015. "A motion planning approach to automatic obstacle avoidance during concentric tube robot teleoperation". In 2015 IEEE International Conference on Robotics and Automation (ICRA), Vol. 2015-June, IEEE, pp. 2361–2367.

[23] 3D Systems Geomagic Touch Master Haptic Device. https://www.3dsystems.com/haptics-devices/touch.

[24] KINOVA Robotics MICO 4-DOF Manipulator. https://www.kinovarobotics.com/en/knowledge-hub/gen2-ultra-lightweight-robot.