Toward Immersive Teleoperation with Assistive Force Cues to Guide Users with Obstacle and Target Information

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***Abstract*—With advances in recent years, we now have several different possibilities for robot operations in complex environments. Scaling from direct teleoperation to fully autonomous planning and execution, the user may choose their level of involvement as called for by the task at hand. Direct teleoperation requires continuous user engagement, which can result in significant physical and mental workload. On the other hand, autonomous systems are frequently unreliable in unstructured or dynamic environments. Supervised autonomy bridges the gap between the two methods by automating some tasks while keeping the human in the loop and allowing them to intervene between autonomous stages. However, there is still a lack of access for intervention and course correction during each autonomous execution. The presented research introduces an assistive teleoperation approach on top of an autonomous system, where a human teleoperator can intervene, with a haptic user interface, in the robot's motion during autonomous task execution. Our proposed approach is divided into two stages. The first stage plans the entire trajectory using a motion planner. The second stage generates assistive force cues for the planned trajectory toward the target position while avoiding known obstacles. The robot is in full control of the task execution until the operator introduces conflicting inputs to the haptic device. This inherently allows the system to function autonomously till the operator notices an error and intervenes by providing haptic inputs.**

I. INTRODUCTION

The decision making authority for a robot to execute a task in a complex environment may vary across the autonomous spectrum [1]. One end of the spectrum contains direct teleoperation while the other end includes fully autonomous system. The key approach has always been to reduce the user involvement while assuring a safe execution of commands. This has been achieved over the years by shifting control between the robot and human operator as per the task. The level of arbitration shift is mostly achieved by establishing that the robot is assisting the human in completing the task. This is achieved by several methods like shared control strategies where the robot assists the user during teleoperation or supervised autonomy of the robot where the robot performs autonomous sub tasks while the human operator is in control of high level plans [2]. Over time as robotic systems are becoming more capable, the focus can be shifted from 'assisting the human operator' to 'assisting the robot' in completing the task. Such strategies are normally observed during autonomy level 3 or 4 in autonomous vehicles (AV) [3] [4], where the autonomous system can make decisions and execute them until the operator takes over. A similar strategy can be utilized for autonomous robots during manipulation tasks, where the robot can perform tasks autonomously but the operator must be present to take control if necessary. The necessity to take control can be based on operator judgment determined as per the task at hand and the action planned by the robot. Shared control strategies can then be applied to assist in the direct teleoperation if the human operator takes control. The current research focuses on a strategy to convey the robot's planned action to the user via a haptic device which in turn helps in guiding the user or monitoring the planned actions while allowing for autonomous execution of the manipulation task until taken over by the human operator as depicted in Fig.1.

II. RELATED WORK

Direct teleoperation of a robot in a complex environment with objects and obstacles can pose challenges in mental and physical workload to the user. The continuous user involvement was, previously, always considered necessary. Additional assistance from the robot was provided to the human operator to help alleviate the workload. Classical force reflection based telepresence methods convey contact forces to the teleoperator which gives the user an immer-

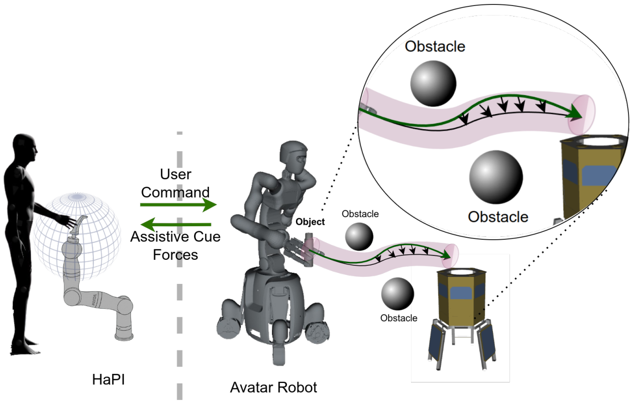

Fig. 1. The assistive teleoperation system overview. A joystick installed on HaPI (on the left) provides the user with a force-reflection UI to command the avatar robot (shown as the humanoid robot in the middle of the figure). The arrows emanating from the chosen path (shown in green) represent the assistive (attractive and repulsive) force cues. These assistive force cues help guide the teleoperator to complete the task of commanding the avatar robot to the target position via the suggested path (shown in black).

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sive experience of the avatar robot's environment [5] [6]. Going beyond this approach, the robot can also convey its situational awareness like its proximity to the objects and obstacles through assistive force cues in the form of virtual fixtures. Virtual fixtures were first introduced in [7] as the additional virtual sensory information that could be overlaid on actual sensor feedback from the robots. This concept was not restricted to force feedback alone but could also include auditory signals. Approaches with FRVF (Forbidden region virtual fixtures) as shown in [8] guide the user by restricting the robot workspace to a certain region. Various modifications in FRVF implementation are also possible based on whether the virtual fixtures are implemented in the robot workspace or on the haptic command workspace. On the other hand GVF (Guidance Virtual Fixture) assist the user by guiding them to the end goal. The GVFs first arrived in the form of pseudo-admittance control but could also be modified to include virtual fixtures that could guide the operator in case of structured tasks [9]. These strategies brought an additional layer of immersion to the human user and helped in teleoperation by being informed in a more natural way.

Other approaches focused on the control interface. It focused on assisting the user in controlling a muti DoF robot with a low bandwidth control interface. This is achieved in [10], by mapping user commands to a sequence of robot states belonging to a specific task. This sequence of states are termed as skills and are defined by using specific constraints and conditions for state transitions. This approach depends on the human operator to take action and provide assistance to the operator in completing the task. In this case the human operator has to be continuously engaged while performing the respective task.

Approaches to further reduce the workload by reducing engagement of the human operator include supervised autonomy. In this approach, the low level control is delegated to the robot. The robot uses its local intelligence, dexterity and reasoning ability to complete the task based on high level task commands from the human operator [2]. This approach is further extended to scalable autonomy in [11] [12], where the command modalities can be adjusted from direct teleoperation to supervised autonomy as per the task at hand. This gives the human operator a full range of command capabilities for a more intuitive and effective robot command.

All the previously stated approaches relied on the human operator to take action and assisted them in completing the task. The assistive system presented in this paper makes a suggestion in the form of force feedback to inform the user about the robot's intention and takes autonomous actions unless mid-trajectory interference is given by the user. Our approach creates virtual forces to reflect to the user to render on the Haptic Pilot/Personal interface (HaPI), but the robot is completely unrestricted in its movements due to soft guidance. This is similar to using Haptic shared control (HSC) where the user is completely aware of the assistance provided [13] but with a major distinction that the robot is still able to execute actions without the user being continuously engaged. Similar methodology was implemented in [14] but with a distinction, that a set of pre-recorded trajectories were used as reference to make realtime decisions.

III. METHODOLOGY

The proposed approach is an end-to-end implementation of the assistive teleoperation system. The manipulator performs tasks which involves interaction with the environment during teleoperation. In order to accommodate the interaction forces and include the necessary compliance during teleoperation, the manipulator is using an impedance controller [15].

A. *Teleoperation Strategy*

The teleoperation strategy is intended to achieve the capability to intervene whenever necessary during autonomous task execution. To achieve this the system has three major levels: a control framework for the haptic interface, a control framework for the robot and the assistive teleoperation system. The control frameworks on the haptic interface side and the robot side interpret the control signals given by the assistive teleoperation system. The assistive teleoperation system calculates the trajectory to the desired goal and simultaneously also waits for the user intent before sending the signals to the robot controller. Similarly it calculates the guiding force (attractive and repulsive forces) and conveys it to the operator via the haptic interface. Fig. 2 depicts the control signals between the three major levels described and the LWR (Light Weight Robot) represents the avatar robot used in the current experimental setup [16].

B. *Assistive Guidance*

The task to be completed by the avatar robot is provided by the user. The global planner generates the trajectory to complete the task. The trajectory is generated offline and then passed on to the assistive teleoperation system. The assistive teleoperation system breaks down the trajectory into individual goal points for the impedance controller to follow and also converts them as haptic guidance forces for the haptic interface. The user receives these forces as a suggested path via the haptic interface, but the magnitude of these forces are tuned such that it can be easily overcome by the user. This lets the user to either follow the suggested path or dismiss the suggestion. The user's intention is calculated based on the comparison between the guidance forces transmitted and the movement of the haptic interface as described in the

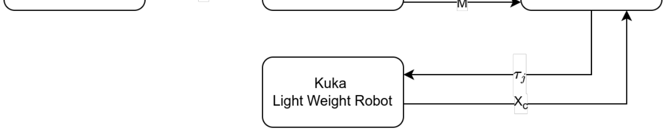

Fig. 2. Teleoperation strategy that decides the seamless switch between autonomous task execution and teleoperation based on user intent from the operator side [16]

section IV-B. These forces are filtered to avoid any rapid non-perceivable changes in direction and magnitude on the haptic interface. As long as the haptic interface, controlled by the user, follows the guidance force, the robot is commanded to follow the path. But as soon as the user deviates from the suggested path, the robot shifts to direct teleoperation [16]. In direct teleoperation, if the user is within the influence region of the trajectory (virtual tunnel around the trajectory), the user feels a haptic guidance force pulling the robot to align with the trajectory. The guidance force is a combination of attractive force from the trajectory and repulsive force from the boundary of the influence region.

C. *Haptic Interface*

The haptic device used for this research is called HaPI. The Haptic Personal/Pilot Interface, or HaPI is an interchangeable hand interface mounted on top of a Kuka LWR4+ 7-DoF robotic arm [17]. HaPI is a versatile input system that can be used for various applications. It has multiple degrees of freedom with the ability of force detection from the user and also force reflection from the avatar robot. Based on the requirement single or multiple DoFs for HaPI could be blocked to mimic the appropriate input device. The interchangeable interface can be attached with any form of input devices for the user's hand. They can be in conventional formats such as joysticks and steering wheels, or novel designs such as the Motion CANVAAS (Motion Console Application for Novel Virtual, Augmented and Avatar System) [18], and hand exoskeleton named Exodex Adam as shown in Fig. 3. Motion CANVAAS uses a touchscreen with ergonomic handles attached to the sides of the screen as the interface. This helps in incorporating touchscreen based as well as haptic based teleoperation capabilities in a single interface [18]. On the other hand, Exodex Adam [19] is a reconfigurable, dexterous whole-hand haptic input device. The Exodex interface along with HaPI acts as a grounded exoskeleton that helps in seamlessly perceiving the robot environment while , at the same time, commanding the robot [19][20]. In our approach, HaPI is used with a joystick and is set to a center sprung mode. Upon release, the haptic interface returns to the center causing the robot to stop moving, which acts similar to a dead-man/enable switch. The center sprung mechanism also makes it necessary to set the entire teleoperation system in a position-velocity controlled mode. This reduces the workspace of the haptic interface by a significant amount, thus making it suitable for constrained spaces for teleoperation. It further reduces the need for re-indexing the haptic interface every time it reaches the workspace limit. The area around the haptic interface is also divided into two virtual spherical region as shown in Fig. 4. The inner sphere marks the dead-zone and makes sure that minor accidental misalignment in the return position of the haptic interface does not cause unwanted teleoperation movement on the manipulator end. The outer spherical region marks the outer limit of motion and indirectly limits the maximum possible velocity that can be achieved by the avatar robot.

IV. SYSTEM IMPLEMENTATION

The avatar arm and HaPI should be compliant to external interactions like the obstacles in the environment and the user input respectively. The avatar robot arm has Cartesian and joint impedance controller [15] which calculates the appropriate torque for each joint based on the specific input. The input is received from the assistive module described in section IV-A. The total torque on each joint is a sum of the torque due to impedance controller and the torque required for gravity compensation.

A. *Assistive Module*

In this case a customized implementation of RRT that uses information from previous solutions to efficiently plan is used as a global planner [9]. This trajectory serves two purposes, the first being used to command the impedance controller on the robotic arm and the second being used to provide the assistive forces on HaPI (described in IV-B). The trajectory is given as input to the impedance controller of the avatar robotic arm.

On the other hand the task of converting the Cartesian poses from the trajectory as force feedback on HaPI is not as straight forward. Initial trials were conducted by directly converting the distance and direction, from one point in the trajectory to the next point, into force. The magnitude of the force was derived from the distance component of the trajectory and the direction was directly derived from the direction of the subsequent point on the trajectory. However, this led to incoherent forces perceived as random vibrations by the person using HaPI. Ernst Weber, an experimental psychologist, discovered that the minimum deviation from the previous signal, required for the user to recognize a perceivable change is from 5 to 15 %. Human haptic perception also generally follows Weber's law. However, deviations can occur mostly due to the type of stimulus and also the body

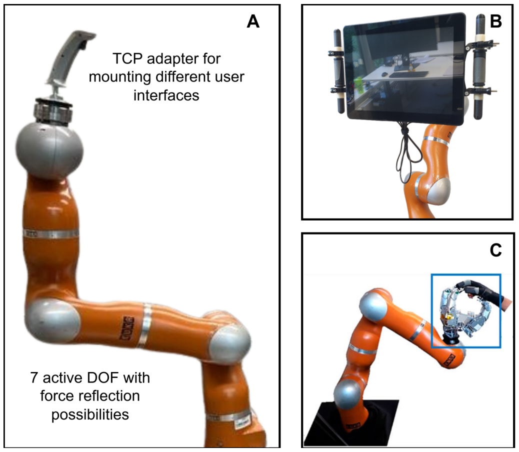

Fig. 3. HaPI, the *Haptic Personal/Pilot Interface*, and some possible UI implementations: Image A: Utilizing a Kuka LWR with joint and Cartesian controls designed for human interactions, we can mount different UI end effectors to mimic classical UI and render novel ones. Some of the different novel UI formats that can be realized on HaPI are the Motion CANVAAS [18] (Image B) and Exodex Adam [19] (Image C)

part where the stimulus is applied. Nevertheless, Weber's law can effectively act as a baseline for tuning the magnitude of the force feedback [21].

In addition to the previously mentioned input data, the assistive module also receives the parameters K and M from HaPI to allow the robot to seamlessly switch between assisted to direct teleoperation as described in III-A. The calculation of the parameters K and M is explained in detail in section IV-B. The equation 1 uses the parameter along with the information like the planned trajectory and the current robot pose to command the avatar implementation.

$$\tau_{joint} = M\left[K \cdot \tau_{j-imp}(Q_p) + (1-K) \cdot \tau_{c-imp}(X_c + X_{ti})\right] \quad (1)$$

with

$$K \in \{0,1\} \; and \; M \in \{0,1\}$$

X represents the Cartesian pose and Q represents the joint angles given as inputs to the impedance controllers. τ_{j-imp} and τ_{c-imp} represent the joint and Cartesian impedance control functions that take joint angles and cartesian poses as respective inputs. The subscripts p, c and ti represent the planned trajectory, current pose of the robot and the incremental pose for direct teleoperation respectively[16].

B. Haptic Interface Implementation

The current haptic setup brings in benefits, in context of its DoF and its capacity to simulate a wide range of scenarios for haptic feedback. But on the other hand, it also brings in disadvantage like the volume of workspace required to operate HaPI is large. The implementation of a static position, P_{hr}, as input to the impedance controller renders the arm as a center sprung joystick. P_{hc} denotes the current position of the haptic interface. Two virtual concentric spheres are defined around the joystick, to mark the boundary of the inner dead zone with radius represented by R_r and the maximum threshold of the active region (outer dead zone) represented by R_b as shown in Fig.4. The region between inner dead zone and outer dead zone is called the active region. The region within the inner dead zone is the inactive region. Any movement of the joystick made by the user within this region should not cause any movement on the avatar robotic arm. This is made sure by the parameter M, introduced in equation 2, which switches its value from 0 to 1. The value of M is 0 when the joystick is within this area and it is 1 when the joystick is outside the inner dead zone (within the active region) as defined in equation 4.

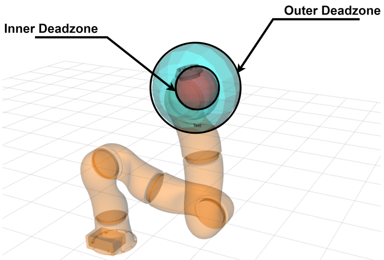

Fig. 4. Dual dead zone on HaPI. Inner dead zone accounts for the centering errors during teleoperation and outer dead zone limits the active workspace to prevent any rapid movements of the robot arm [16]

$$M = \begin{cases} 1, & \text{if } d >= R_r \text{ and } d <= R_b \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where d is the distance between points P_{hr} and P_{hc}

The parameter K defines the mode of teleoperation. The mode is direct teleoperation when the value of K is zero and it is assistive teleoperation when the value is one. The value of K is chosen as per the equation

$$\theta = \cos^{-1}(\hat{F}_a . \hat{F}_u) \quad (3)$$

$$K = \begin{cases} 1, & \text{if } \theta <= threshold \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where $\hat{F}_u$ is the unit vector of the force applied on HaPI by the user and $\hat{F}_a$ is the unit vector in the direction of the assistive force, provided by the assistive module, on HaPI. The threshold was set to a static value of 20 degrees based on user feedback.

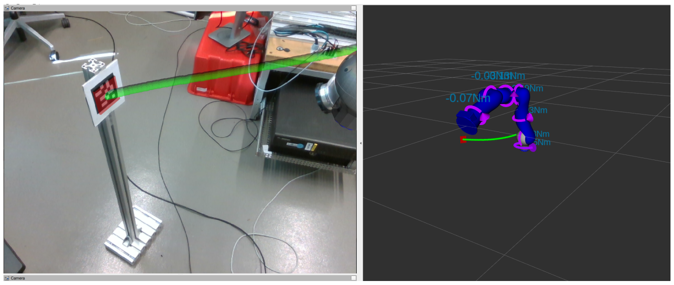

Fig. 5. User Interface with live video stream, virtual twin and planned trajectory overlay [16]

In our experimental setup, the user is instructed to teleoperate the robot to the goal position indicated by the marker. To check whether the features implemented in this paper has any specific effect on the mental workload of the user, the implementation of the framework was divided into three categories for the experiments, which are direct teleoperation, assistive teleoperation with visual overlay as shown in Fig. 5 and assistive teleoperation with force feedback along with visual overlay.

V. RESULTS AND DISCUSSION

As shown in Fig. 6, a sample trajectory is generated during a task execution and the corresponding guidance forces. The guidance forces generated during the assistive teleoperation setup are smoothed out by maintaining a fixed magnitude and direction until a noticeable change in direction or magnitude on the robot task execution trajectory is required.

A pilot study was conducted with 5 participants and NASA Task Load Index (TLX) was used to evaluate the experiments along with the accuracy and time required to

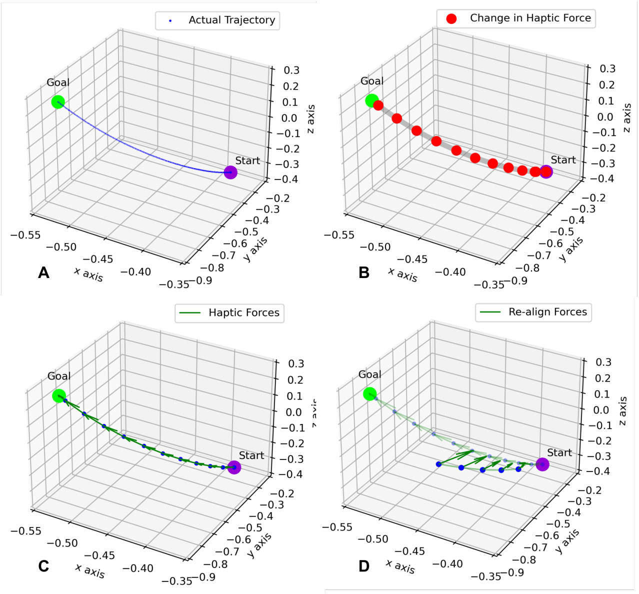

Fig. 6. Plot denoting the actual robot trajectory in blue (A), the waypoints on the trajctory where the change in haptic force is perceived by the user (B) and shown by red points ; the haptic forces denoted by the quiver shown in green (C); In case of accidental deviation of the robot from the proposed trajectory a re aliging force guides the user back on to the actual path (D)

complete the task. Fig. 7 shows a sample trajectory and the corresponding path chosen by the user during one of the experiments. It denotes a visible deviation in path due to lack of depth information for the user. Fig. 8 shows the six parameters measured during the NASA Task Load Index in the form of grouped bar plots along with respective error bars. The three groups indicate the different teleoperation modes. The ratings are adjusted according to the importance of each parameter based on the user's perception of how much each parameter contributes to their mental workload. Lower ratings for the parameters mental demand, physical demand, temporal demand, effort, frustration while a higher rating for performance indicate a better system as indicated by the arrows at the bottom of the Fig. 8.

Based on the results from the NASA TLX, the assistive teleoperation system performs better than direct teleoperation in all categories except in case of temporal demand, where it performs at the same level. In comparison to the visual projection based teleoperation it performs better in all categories except performance, where the performance of the visual projection based method is better than the assistive framework by a small margin. The mental demand for assistive teleoperation was the lowest as the user had continuous force feedback guiding them to the goal point. Direct teleoperation required the user to navigate any potential obstacles and required constant attention to monitor the state of the robot. The visual projection based method lead to a higher mental demand as the user felt a constant need to follow the projected path along with constant monitoring of the surrounding obstacles and the goal point. This also led to a constant course correction so that the robot stays on track leading to higher physical demand, which indirectly also affects the perceived effort and temporal demand by the user. This additional cognitive load for the visual projection method could have resulted due to the fact that the users were made aware early on in the experiment that the projected path could be wrong and at any point the user can and should take control in case of any unnoticed obstacle. This created an additional cognitive load which has been reflected in the adjusted ratings on the TLX.

In our implementation, the haptic device used for teleoperation in the current setup, is constrained to have a smaller workspace than the actual avatar arm. The current strategy of having a center sprung mechanism attempts to command the robot using a haptic device with constrained workspace and without re-indexing the device. In case of direct teleoperation using a haptic device, the capability to enable and disable teleoperation mode is generally implemented using a different interface like a physical switch, a button on the user interface or a physical button on the haptic device. These are either operated before the start of the teleoperation or are sometimes continuously operated during teleoperation. But the need of an additional interface to enable and disable teleoperation could be avoided with a center sprung mechanism. The haptic devices inherently have inertia effects, on the interface, based on their respective geometry and dynamics. The effect of inertia on HaPI was large, however, the center sprung mechanism helped constrain the workspace and reduce the inertia effect.

VI. CONCLUSION

The presented approach combines the strength of autonomous task execution and the user judgment, to efficiently execute a task where the individual reliability of both autonomous execution and direct teleoperation is low. The method demonstrated positive results during the pilot study but a more detailed and extensive study in future would help

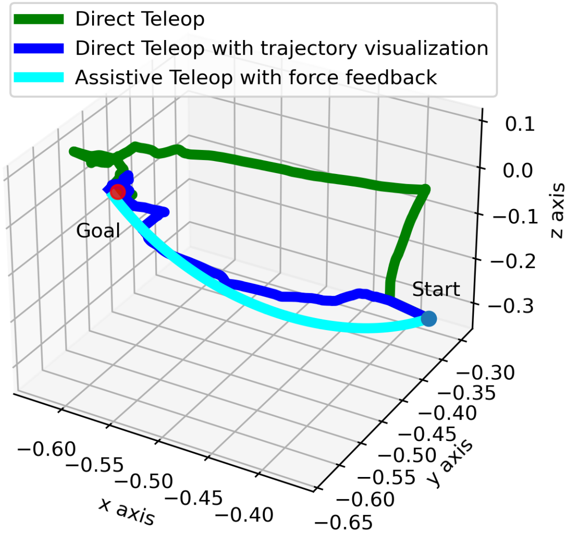

Fig. 7. The trajectory of the end effector for a particular task with direct teleoperation, visual assistive guidance and the optimal trajectory using force feedback calculated by the autonomous system.

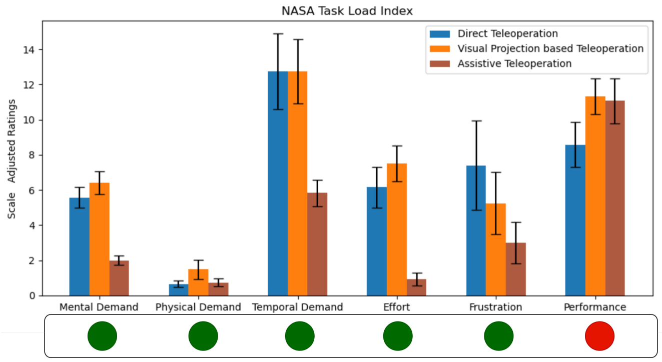

Fig. 8. Parameters measured for NASA TLX depicted above in the form of grouped bar plots with error bars representing standard deviation. The green circular marker at the bottom of the graph depicts that lower value of the measured parameter is better while the red marker depicts that higher value of the measured parameter is better.

in determining additional advantages and drawbacks. The assistive force cues are a valuable addition to realizing the intents of both the user and the robot and eventually helps in combining user and robot knowledge on the task at hand. We are now putting two brains (real and artificial) to work together to achieve a goal. This form of haptic assistance during autonomy and the capability to intervene represents a level of Scalable Autonomy [22], which can be further integrated into a fully scalable UI approach that enables the user to intuitively slide from direct control all the way to full task delegation of Supervised Autonomy or even full autonomy.

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