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Addressing Operator Physical Ergonomics in Teleoperation with Multi-modal Dynamic Workspace Re-indexing

Thijs Exterkate[1], Nicky Mol[1], David A. Abbink[1,2], J. Micah Prendergast[1], and Luka Peternel[1]

***Abstract*— This paper presents a multi-modal dynamic workspace re-indexing method for addressing operator ergonomics and workspace limitations. The proposed method has two interactive modes: pose-to-pose mode, which is active when the operator is within an ergonomic workspace of comfortable arm postures, and ergonomic workspace drift mode, which activates after the operator makes an excursion beyond the boundaries of the ergonomic workspace when trying to reach more distant targets with the remote robot. In the ergonomic workspace drift mode, the operator temporarily stays slightly outside these boundaries, while the offset between the local and remote workspace drifts with a velocity proportional to the excursion distance. This dynamically re-indexes the remote workspace toward the distant target, and the operator can remain in a comfortable posture while the remote robot moves toward the intended target where the task is. To construct the ergonomic workspace, we employed the Rapid Upper Limb Assessment method. To validate the proposed method, we conducted experiments on a teleoperation setup involving a Force Dimension Sigma7 haptic device controlling a Kuka LBR iiwa robotic arm. The results show that the proposed controller successfully addresses workspace limitations by dynamically re-indexing the follower's workspace towards target objects, while maintaining good operator ergonomics.**

I. INTRODUCTION

Humanoid robots that possess capabilities similar to humans are increasingly deployed for tasks in environments that are unsafe or inaccessible for humans, such as inspection & maintenance and disaster response [1], [2]. Nevertheless, these robots currently fall short of human adaptability and cognitive capabilities, resulting in a necessity for human-in-the-loop control. Teleoperation addresses this need by enabling human operators to remotely control these robots [3], [4].

Teleoperation can be done through various interfaces, such as motion capture systems [5]–[7], data gloves [8], 3D mice [9], [10], joysticks/scroll wheels [11], mixed-reality [12], and haptic devices [13]–[15], which register operator actions and translate them to the remote robot. The benefit of haptic devices lies in their ability to transmit force feedback from the remote robot to the operator, enhancing the performance in tasks involving complex physical interactions [16]. Nevertheless, haptic devices are often limited in their workspace. This poses a challenge when the target/task requires the robot to move beyond the workspace of the haptic device, requiring alternative strategies to extend the robot's reach.

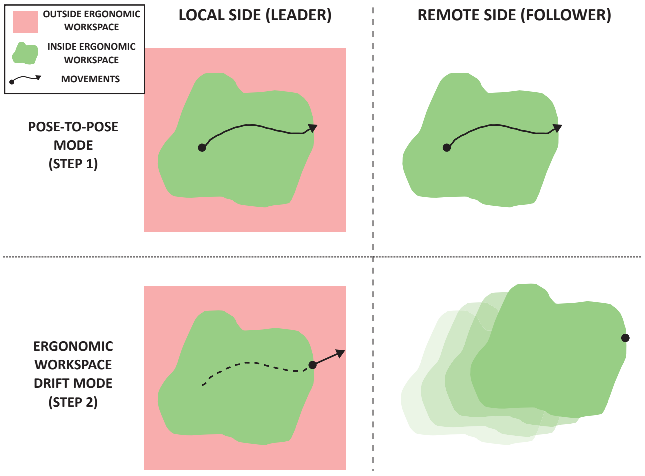

Fig. 1: The proposed multi-modal dynamic workspace re-indexing method for addressing operator ergonomics and workspace limitations. Local (left) and remote (right) perspectives are shown. The green zone represents the operator's ergonomic workspace, while the red zone represents the actual physical workspace of the haptic device. Movements are shown with a black line, where the dot indicates the earlier point (or being stationary) and the arrow indicates the later point. Top row: pose-to-pose mode inside the ergonomic workspace, where operator movement is directly mirrored by the remote robot. Bottom row: ergonomic workspace drift mode outside the ergonomic workspace, where the workspace offset between local and remote pose drifts with the velocity proportional to the distance outside of the ergonomic zone.

Existing approaches attempt to overcome the workspace limitations of haptic devices. Scaling operator movements expands the remote robot's workspace but reduces resolution, making precise manipulation harder [17], [18]. Static workspace re-indexing (or decoupling/clutching) [19]–[21], allows the operator to shift the workspace offset during the decoupled phase, much like repositioning a computer mouse by lifting it. However, like lifting a mouse, teleoperation is paused during the decoupled phase. Dynamic workspace re-indexing offers a continuous alternative that avoids pausing by gradually drifting the workspace offset [17]. While this eliminates the need to pause the teleoperation, the positional drift may interrupt the task execution.

Beyond device limitations, physical ergonomics of the operator presents another critical concern, specifically the risk of discomfort and muscle fatigue from maintaining awkward arm postures over periods of prolonged work. This can lead to work-related musculoskeletal disorders (WMSDs) [22]. Ergonomics of teleoperation interfaces can

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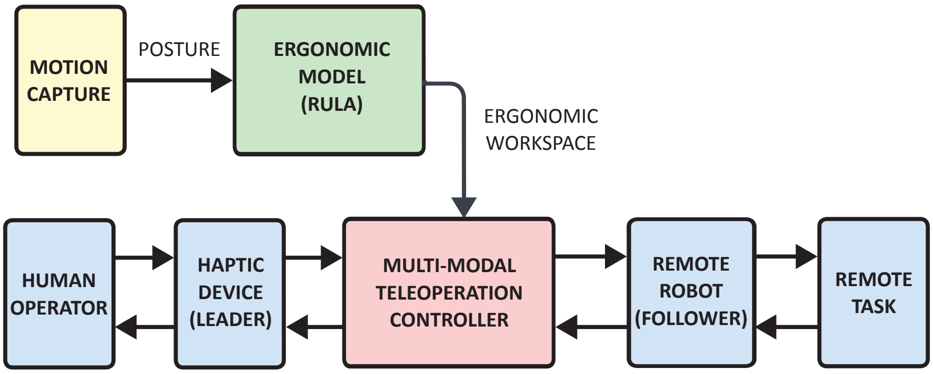


Fig. 2: Block diagram of the proposed ergonomic teleoperation approach. Light blue blocks indicate the standard elements of a 4-channel teleoperation system. Motion capture (yellow) measures the operator's posture and informs the ergonomic model (green) that generates the ergonomic workspace map. The ergonomic workspace feeds into the multi-modal teleoperation controller (red), enabling it to interactively switch between pose-to-pose and workspace drift modes.

be evaluated offline using various metrics, such as joint usage, range of motion comfort, center of mass divergence, and posture comfort [23]. Efforts to address ergonomics online include shared control algorithms that aim at reducing physical effort by taking over some of the required task force from the operator [24]. However, poor design of shared control may achieve the opposite [25]. Another approach is the use of virtual fixtures and constraints to guide the operator based on ergonomic look-up tables [26]. Alternatively, high-fidelity musculoskeletal models can be used to assess operator ergonomics in real-time and correct the human arm posture to reduce muscle fatigue by temporarily pausing the teleoperation to adjust the haptic device for better posture [27]. Nevertheless, a unified approach that dynamically addresses both workspace limitations and operator ergonomics is missing.

To address this gap, we propose a multi-modal dynamic workspace re-indexing method for addressing operator ergonomics and workspace limitations during teleoperation using a haptic device (see Fig. 1). The proposed method has two interactive modes: pose-to-pose mode, which is active when the operator is within an ergonomic workspace of comfortable arm postures, and ergonomic workspace drift mode, which activates after the operator makes an excursion beyond the ergonomic workspace when trying to reach more distant targets with the remote robot. In the ergonomic workspace drift mode, the operator temporarily stays only slightly outside of the ergonomic workspace, while the offset between the local and remote workspace drifts with a velocity proportional to the excursion to dynamically re-index them toward the distant target. That way, the operator can remain in a comfortable posture while the remote robot moves toward the intended target where the task is.

After re-indexing, when the offset is moved at the remote robot side, the control is switched back to pose-to-pose mode, allowing the operator to work on the task within the same ergonomic postures at the local side. It is important to note that the pose-to-pose mode, where the operator works within the ergonomic zone, is active most of the time (i.e., doing the task), while the drift mode is active for relatively short periods when re-indexing is needed. We validate the proposed method with experiments on a teleoperation setup involving a Force Dimension Sigma7 haptic device controlling a Kuka LBR iiwa robotic arm. The results show that the proposed controller successfully addresses workspace limitations by dynamically re-indexing the follower's workspace towards target objects, while maintaining good operator ergonomics.

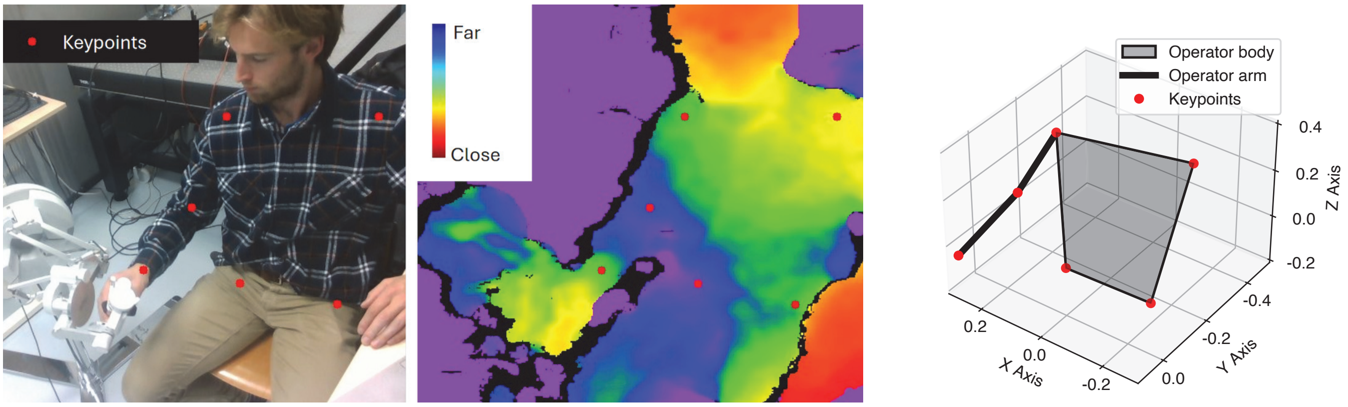
II. METHODS

Figure 2 illustrates the block scheme of the proposed ergonomic teleoperation approach. The human operator manipulates a haptic device (leader) that measures the pose and can render force feedback. The pose commands are translated to the remote robot (follower) via a multi-modal teleoperation controller. This controller dynamically manages operator ergonomics and workspace limitations by switching between two modes: a direct pose-to-pose mapping when the operator is within the ergonomic workspace, and a workspace drift mode for re-indexing when ergonomic boundaries are exceeded. The multi-modal controller is supplied with the ergonomic workspace that is defined by an ergonomic model, which processes real-time operator posture measurements from a motion capture system.

A. Motion Capture

To inform the ergonomic model about the posture of the operator in real time, a motion capture system is necessary. While several motion capture technologies exist–such as marker-based optical systems, inertial measurement units, and depth cameras–each presents different tradeoffs in practicality, affordability, complexity, and precision. For this study, we selected a depth camera due to its affordability and ability to function without requiring the operator to wear sensors.

We employed an RGB depth camera to capture both RGB and depth image streams. The RGB stream was processed using the pose detection model MMPose [28] to extract 2D pixel coordinates for body keypoints, including the nose, shoulders, elbows, wrists, and hips (see Fig. 3a). These 2D keypoints were then projected into 3D space by leveraging



(a) Visual data (RGB image on the left and corresponding depth image on the right) captured using the RealSense D435 while the operator is operating the Force Dimension Sigma7 haptic device. Body keypoints (red dots) were determined using the pose estimation model MMPose [28].

(b) 3D stick model obtained based on the keypoints generated from the camera data that corresponds to the images in Fig. 3a. The axes show the positions in Cartesian space.

Fig. 3: Motion capture data processing pipeline.

depth information. Finally, a virtual stick model of the operator (illustrated in Fig. 3b) was constructed by connecting these 3D keypoints. This virtual stick model served as the input for the real-time ergonomic scoring.

B. Ergonomic Model

We assessed the ergonomics of the operator's posture by using Rapid Upper Limb Assessment (RULA) [29]. RULA assigns a score ranking postures from 1 (minimal injury risk) to 9 (high injury risk). While the complete RULA method assesses the arm, hand, neck, and torso, this study focused on the ergonomic score of the operator's arm since it involved tele-manipulation tasks. We defined an ergonomic workspace as the subset of operator arm postures with a RULA score of 1. We divided the ergonomic workspace into a translational component and a rotational component.

1) Translational Ergonomic Workspace: To determine the translational component of the ergonomic workspace, we calculated all possible wrist positions by iterating over the three shoulder DoFs and the elbow DoF. Each arm configuration is assigned a RULA score. This generates a database of ergonomic scores for all possible arm configurations. We filtered all arm configurations with a RULA score of 1 to form a 3D point cloud and used its envelope to define the translational ergonomic workspace. To maintain an ergonomic posture, the operator must remain within this translational ergonomic workspace envelope, which is shown in Fig. 4.

2) Rotational Ergonomic Workspace: To determine the rotational component of the ergonomic workspace, we identified wrist angles of $[-15, 15]$ degrees for pitch, roll, or yaw, as specified by RULA for rotations. These angles define the envelope of the rotational ergonomic workspace and were measured by the haptic device.

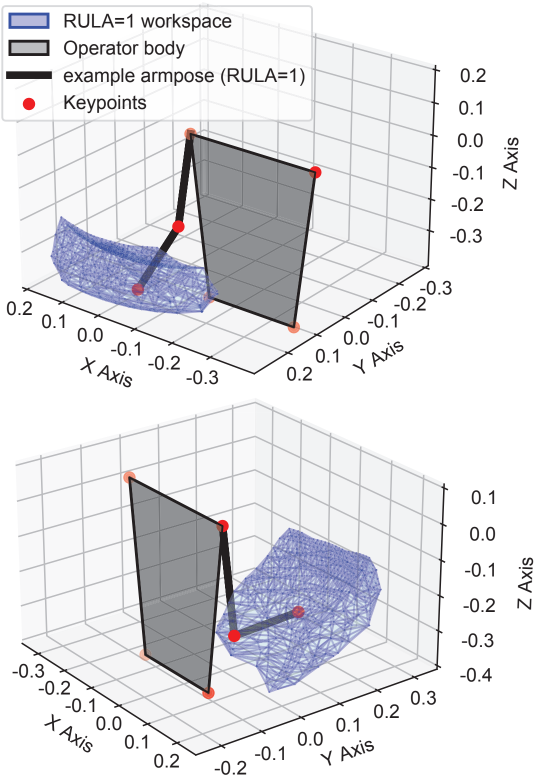


Fig. 4: The 3D stick model of the operator's body with a translational ergonomic workspace presented from two different viewpoint angles. In this example, the translational ergonomic workspace was derived from the arm configurations with RULA=1 scores. The axes show the positions in Cartesian space.

C. Multi-modal Teleoperation Controller

The proposed controller switches between two main control modes (see Fig. 1 for illustration). In the pose-pose mode, the pose as measured by the haptic device is used as a commanded reference pose to be translated to the remote robot. This control mode is activated when the leader handle is located within the ergonomic workspace on the local side, either within the ergonomic workspace boundaries shown in Fig. 4 or within the rotational limits of $[-15, 15]$ degrees. The remote robot is controlled by a Cartesian impedance controller at the joint-torque levels. The interaction force/torque in Cartesian space was defined as:

$$\boldsymbol{f} = \boldsymbol{K}(\boldsymbol{x}_\mathrm{r} - \boldsymbol{x}) + \boldsymbol{D}(\dot{\boldsymbol{x}}_\mathrm{r} - \dot{\boldsymbol{x}}), \tag{1}$$

$$\boldsymbol{x}_\mathrm{r} = \boldsymbol{S}_\mathrm{ff}\boldsymbol{x}_\mathrm{h}, \tag{2}$$

where $\boldsymbol{f} \in \mathbb{R}^6$ is the commanded interaction force/torque between the remote robot and a remote environment, $\boldsymbol{x}_r \in \mathbb{R}^6$ and $\boldsymbol{x} \in \mathbb{R}^6$ are the commanded reference pose and the actual pose of the remote robot, respectively, while $\boldsymbol{K} \in \mathbb{R}^{6\times6}$ and $\boldsymbol{D} \in \mathbb{R}^{6\times6}$ are stiffness and damping matrix, respectively. The commanded reference pose $\boldsymbol{x}_\mathrm{r} \in \mathbb{R}^6$ is derived from the measured haptic device pose $\boldsymbol{x}_\mathrm{h} \in \mathbb{R}^6$ using a feed-forward scaling diagonal matrix $\boldsymbol{S}_\mathrm{ff} \in \mathbb{R}^{6\times6}$. While in the general case, the elements of the $\boldsymbol{S}_\mathrm{ff}$ matrix can be set to different values if different scaling is needed in different axes, in this study, we wanted equal scaling in all axes; thus, we set all elements to 1. In this mode, the measured force $\boldsymbol{f} \in \mathbb{R}^6$ at the remote robot can also be used as a force feedback rendered at the local side by the haptic device.

In ergonomic workspace drift mode, the distance outside of the ergonomic zone (excursion) at the local side dictates the velocity with which the offset drifts on the remote side. While the operator can stay roughly in the same ergonomic workspace at the local side, the drift on the remote side enables reaching areas that were previously outside of the ergonomic workspace. The ergonomic workspace drift mode control is defined as:

$$\boldsymbol{f}_\mathrm{ew} = \boldsymbol{K}_\mathrm{ew}(\Delta\boldsymbol{x}_\mathrm{ew}), \tag{3}$$

$$\dot{\boldsymbol{x}}_\mathrm{offset} = \boldsymbol{B}_\mathrm{ew}\boldsymbol{f}_\mathrm{ew}, \tag{4}$$

where $\Delta\boldsymbol{x}_\mathrm{ew} \in \mathbb{R}^6$ is the distance outside of the ergonomic workspace (excursion) on the local side, $\boldsymbol{f}_\mathrm{ew} \in \mathbb{R}^6$ is the drift force/torque that is used to move the offset on the remote side, and $\boldsymbol{K}_\mathrm{ew} \in \mathbb{R}^{6\times6}$ is a drift stiffness matrix that maps the excursion distance to the drift force/torque. The drift force/torque is used to determine the offset drift velocity $\dot{\boldsymbol{x}}_\mathrm{offset} \in \mathbb{R}^6$ based on the diagonal matrix $\boldsymbol{B}_\mathrm{ew} \in \mathbb{R}^{6\times6}$ that represents a drift admittance.

Increasing $\boldsymbol{K}_\mathrm{ew}$ increases the sensitivity of the drift force/torque to the amount of excursion distance, which intuitively means more drift in the direction of the excursion. Increasing $\boldsymbol{B}_\mathrm{ew}$ increases the sensitivity of the drift velocity to the amount of drift force/torque, which intuitively means more drift in the direction of the force/torque. While both gains act similarly, we decided to use two equations to provide a proper physical representation, with the first, i.e., (3), representing impedance and the second, i.e., (4), representing admittance. This formulation also allows us to use the intermediate force/torque $\boldsymbol{K}_\mathrm{ew}$ as a cue to the operator by applying it as force feedback on the haptic device during the drift mode.

During drift mode, regular force feedback is temporarily replaced with a drift force $\boldsymbol{f}_\mathrm{ew}$ that is rendered by the haptic device to give the operator a clue about the velocity of the offset drift at the remote side and to indicate/guide the operator back inside the ergonomic workspace at the local side. When the operator resists the haptic forces, the remote robot workspace offset drifts with a translational and/or rotational velocity proportional to the force/torque exerted by the operator according to (3)-(4). By commanding a constant offset velocity while maintaining a relatively fixed leader pose, the remote robot workspace is dynamically re-indexed to a new location. For instance, to interact with a target object located outside the ergonomic workspace, the operator can temporarily leverage drift mode to move the remote robot while the haptic device remains stationary. When the remote robot's workspace is re-indexed toward the vicinity of the target, the operator can then interact with the object within the ergonomic workspace boundaries using pose-to-pose mode.

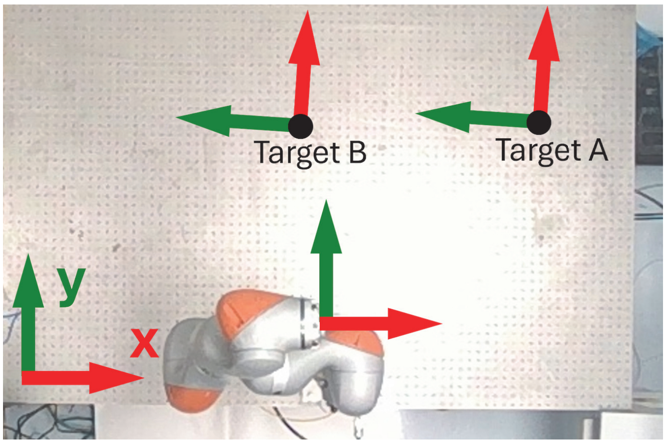


Fig. 5: Remote robot side of the experimental setup. The task target frames A and B with respect to the initial pose. The remote robot frame is initially aligned with the global frame, but the targets are rotated, and thus rotational movements are also required.

III. EXPERIMENTAL VALIDATION

To validate the key features of the proposed ergonomic teleoperation method, we conducted experiments using an experimental setup including a Sigma7 (Force Dimension, Nyon, Switzerland) haptic device as the leader and a 7-DOF KUKA LBR iiwa 14 R820 (KUKA AG, Augsburg, Germany) robotic manipulator as the follower (see Fig. 5). Our motion capture setup utilised an Intel RealSense D435 depth camera. The controllers were implemented using ROS. During the drift mode, force feedback at the haptic device was repurposed to give the operator a spatial awareness of how far outside of the ergonomic workspace they are, and consequently, how fast the offset drifts.

During the experimental validation, the operator remained seated upright, using only their arm to manipulate the haptic device without upper-body movement. The experimental task, as can be seen in Fig. 5, required the operator to sequentially reach two predefined target poses starting from an initial pose. To accomplish this, the ergonomic workspace drift mode had to be used when the target was outside of the ergonomic workspace, thereby shifting the remote robot's workspace offset towards the target's vicinity. When within reach of the desired target, pose-to-pose mode could be used to have intuitive and precise control of the remote robot to reach it. The task sequence comprised the following steps:

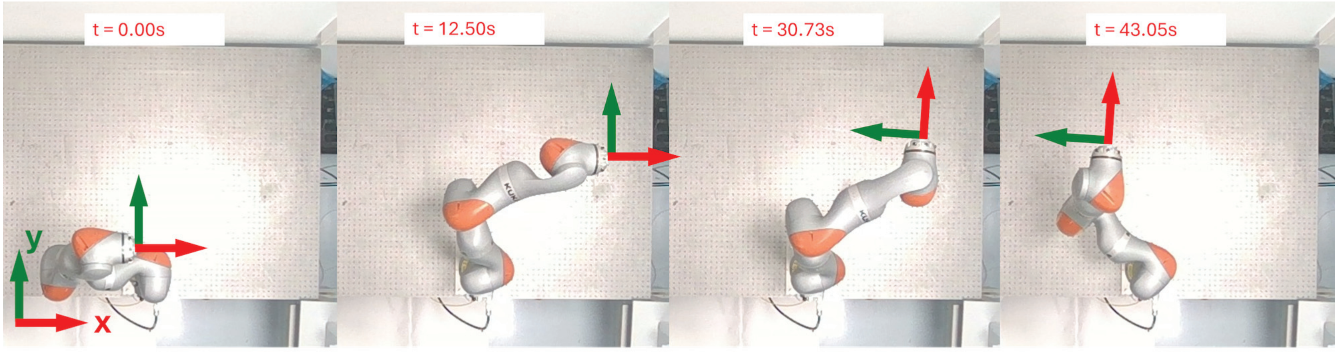


Fig. 6: Storyboard of remote robot states at timestamps corresponding to Fig. 7.

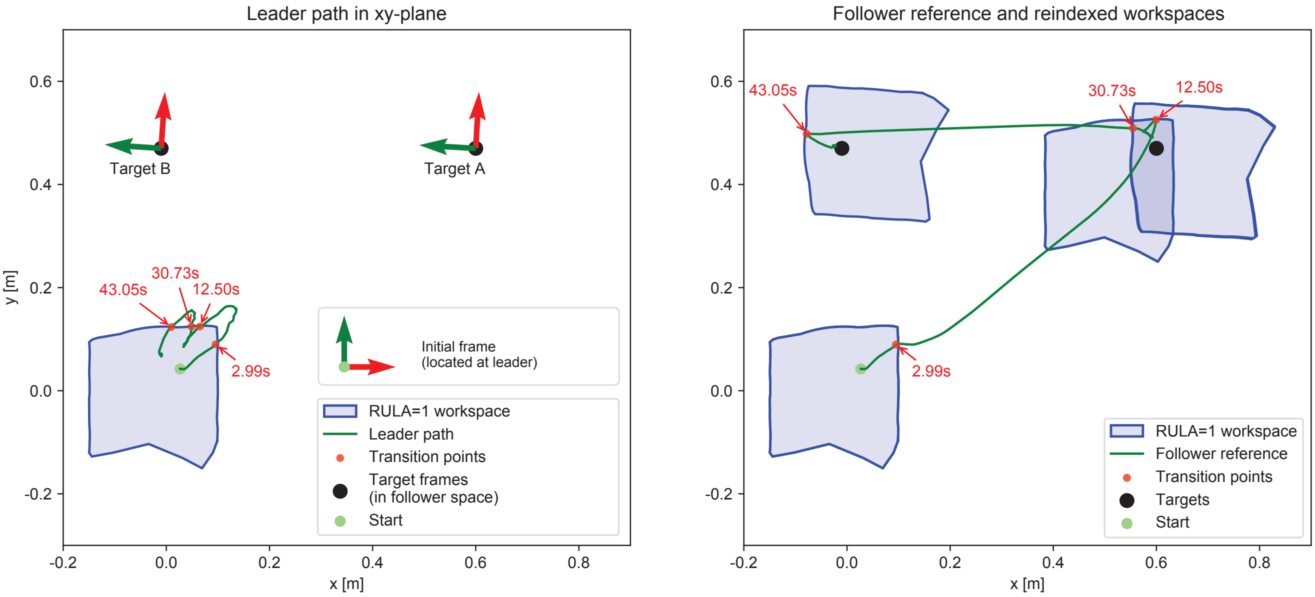


Fig. 7: Workspace re-indexing results in spatial format. Haptic device (leader) workspace and target frames are shown on the left graph, while the remote robot (follower) workspace with re-indexed ergonomic workspace over time is shown in the right graph. Figure 8 shows the same experiment in temporal format, where the red timestamp marks correspond to their counterparts on the x-axis. Note that the timestamps corresponding to rotational re-indexing are not shown.

1) Translate the remote robot towards *Target A* (without rotation).
2) Rotate the remote robot so that its frame aligns with *Target A* frame.
3) Translate the remote robot towards *Target B* (without rotation).

During task execution, the operator's posture was tracked and evaluated in real-time based on RULA. We then examined the movements and ergonomic scores during the task execution. The ergonomic scores are most crucial during the pose-to-pose mode, where interaction with the objects/task would happen for an extended duration. Ergonomic scores during the drift mode are less important, as workspace re-indexing is a transient action.

A. *Results: Workspace Re-indexing*

Figures 6 and 7 show the spatial results of the task execution using the proposed method. As seen from Fig. 7, Target A at the remote robot is far outside of the ergonomic workspace at the local side (indicated by the blue zone). To dynamically re-index the workspace offset towards Target A, the operator made a brief excursion by moving the haptic device slightly outside the translational ergonomic workspace in the target's direction between 2.99s and 12.50s. Consequently, the remote robot drifted towards *Target A*. When reaching the vicinity of *Target A*, the operator returned the haptic device back inside the ergonomic workspace, triggering the controller to switch from drift mode to pose-to-pose mode.

To achieve rotational alignment with *Target A*'s frame, the operator rotated the haptic device beyond the rotational ergonomic workspace, causing the workspace offset to rotate. This occurred in the period of [18.10s, 25.12s] (see Figs. 6 and 7). To reach *Target B*, the operator once more made a brief excursion by moving the haptic device outside the translational ergonomic workspace in the target's direction between [25.73s, 40.05s]. This movement again resulted in dynamic re-indexing of the remote robot's workspace offset.

In addition, Fig. 8 show the timeseries plots of the task execution, where pose-to-pose mode activation is highlighted

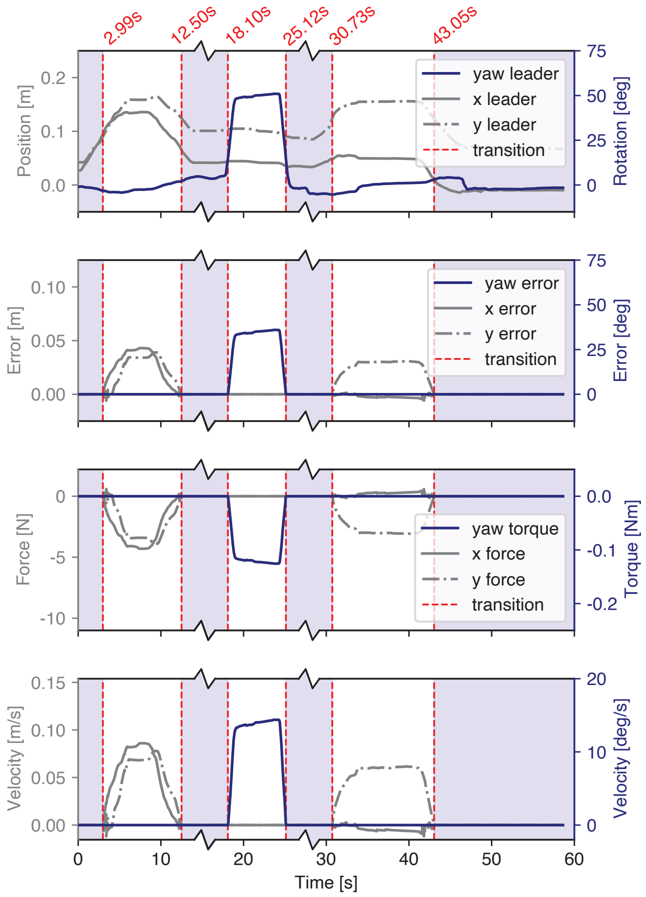
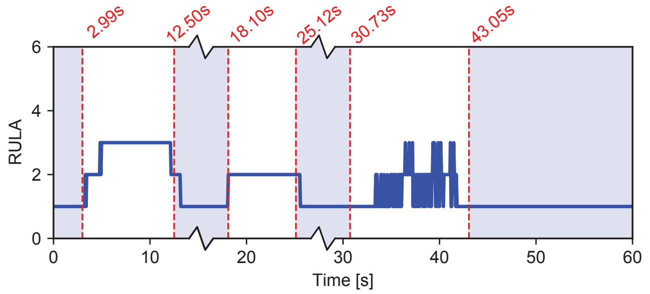


Fig. 8: Timeseries plot of workspace re-indexing results. The first graph shows the pose of the haptic device (leader). The second graph depicts brief excursions outside of the ergonomic workspace (error). The third graph illustrates the drift force rendered on the haptic device to give clues about the intensity of the drift. The last graph shows the drift velocity of the workspace offset on the remote robot (follower). Blue areas indicate the operator staying inside the ergonomic workspace, while white areas indicate the operator temporarily making an excursion to enter the drift mode. The zigzag lines along the top and bottom graph borders represent intervals where prolonged work on the target objects would be done in optimal ergonomic postures, even though transitions were quicker for this demonstration.

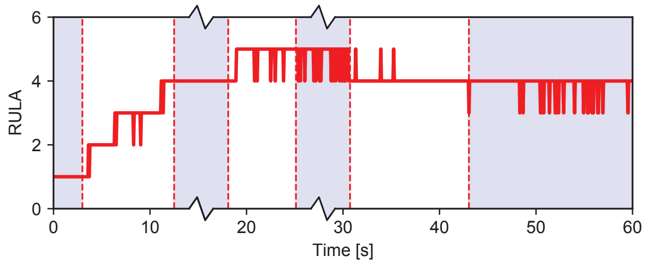
in light blue, and drift in white. During the translational re-indexing phases for *Target A* ([2.99s, 12.50s]) and *Target B* ([30.73s, 43.05s]), the remote robot's workspace offset was controlled by drift mode via its translational velocity. When the operator moved the haptic device outside the translational workspace, the drift force (third graph) was proportional to the error distance from its envelope (second graph), which in turn defined the offset drift velocity (fourth graph). Similarly, the operator used drift mode to re-index the workspace during the period [18.10s, 25.12s] related to Target A rotational action by controlling the rotational velocity of the workspace offset.

B. Results: Ergonomics

Figure 9 presents the ergonomic impact by showing the RULA scores during task execution over time. This figure compares RULA scores achieved with the proposed controller (Fig. 9a) against those from a conventional control



(a) RULA score during execution of the task using the proposed controller.



(b) RULA score during execution of the task using the conventional controller that does not address ergonomics.

Fig. 9: Comparison of RULA scores during both task executions with and without the proposed controller.

approach without ergonomic considerations (Fig. 9b). The conventional controller was defined as only the pose-to-pose mode of our system (i.e., (1)-(2)), without any ergonomic workspace boundaries or drift functionality, representing a standard direct teleoperation mapping.

We can see that RULA temporarily increased during the period of [2.99s, 12.50s] as the operator moved outside of the translational ergonomic workspace to dynamically re-index the workspace. In contrast, with the conventional controller, the operator had to extend their arm further, which resulted in RULA score increasing to 3 at around 10 seconds and then further up to 4 upon reaching *Target A*.

When workspace offset reached the vicinity of *Target A*, with the proposed controller, the operator moved back inside the ergonomic workspace and switched to pose-to-pose mode during the period of [12.50s, 18.10s]. This resulted in optimal ergonomic arm postures with RULA score of 1. Conversely, with the conventional controller, RULA remained at a score of 4 since the operator's arm had to be extended.

For rotational alignment with *Target A*, ([18.10s, 25.12s]), the operator left the rotational ergonomic workspace to re-index the workspace. With the proposed controller, the wrist rotation led to a temporary increase in RULA score to 2. Without it, the conventional controller, RULA score increased from 4 to 5 due to an extended rotation towards *Target A*. Subsequently, the operator returned to the ergonomic workspace to interact with *Target A* during [25.12s, 30.73s], lowering RULA score to 1. In contrast, with the conventional controller, RULA score remained at 5 as the operator's arm had to stay in an uncomfortable arm posture.

To reach *Target B* during the period of [30.73s, 43.05s], the operator moved outside of the translational ergonomic workspace to dynamically re-index the workspace toward that direction. This temporarily increased RULA score to 2 when our controller was employed. In comparison, with the conventional controller, RULA score decreases from 5 to 4 as the operator's arm moved toward *Target B*.

Finally, during the period of [43.05s, 60.0s], the operator returned inside the ergonomic workspace to interact with *Target B*, reducing RULA score again to the optimal ergonomic state of 1. In comparison, with the conventional controller, RULA score remained at 4 as the operator interacted with *Target B* in a relatively bad arm posture.

IV. DISCUSSION

In this paper, we proposed and evaluated a novel multi-modal dynamic workspace re-indexing method for addressing operator ergonomics and workspace limitations during teleoperation. The primary advantage of the proposed controller lies in its ergonomic workspace drift mode. This mode enables dynamic re-indexing of the remote robot workspace offset, allowing it to reach targets on the remote side that would otherwise be outside of the ergonomic workspace at the local side. Between re-indexing periods, pose-to-pose control facilitates intuitive and precise interaction with target objects in ergonomic arm postures.

Our dynamic re-indexing approach successfully addresses workspace limitations without requiring traditional clutching or motion scaling approaches. For instance, compared to the method in [27], which paused teleoperation via clutching to adjust the operator's arm to a more ergonomic posture, our solution operates continuously without such clutching. Additionally, in contrast to approaches that utilise virtual fixtures to guide operators from uncomfortable postures [26], our method does not limit the operator in any way within the defined ergonomic workspace.

The proposed approach is most effective when interactions with target objects, which are not within an ergonomic local workspace. When interacting with these objects, the ergonomics score is optimal, while drift mode can temporarily slightly worsen the ergonomics score (Fig. 9). If the task requires too many and too frequent workspace re-indexing and very short interaction with the targets, the effectiveness of this approach might be somewhat lower, as the ergonomics score might temporarily increase very often. Nevertheless, based on the results, it is still far better in terms of integrated ergonomics over time compared to conventional approaches that do not address ergonomics (Fig. 9 comparison). One way to avoid increases in RULA scores during drift mode would be to set the boundaries of the ergonomic workspace farther within the RULA=1 zone (i.e., a smaller zone within a zone). This means that excursions would take place within the RULA=1 zone, at the expense of a smaller workspace for pose-to-pose mode.

Workspace re-indexing with the drift mode can take quite some time when the target is far outside the ergonomic workspace. This issue can be mitigated by increasing the velocity scaling factor $\boldsymbol{B}_{\text{ew}}$ in (4), which would increase the velocity of workspace re-indexing. Nevertheless, increasing this factor too much could also cause overshoots. Therefore, when setting this parameter for a given task, the tradeoff between re-indexing speed and manageable accuracy should be considered.

One potential limitation of the proposed method is the non-uniform shape of the ergonomic workspace envelope. The ergonomic workspace is derived from an ergonomic assessment tool, which can produce a very complex envelope shape in 3D space. Such a shape of the ergonomic workspace may reduce the predictability of transitions between pose-to-pose mode and drift mode for the operator. One potential solution would be to employ an operator training to get them used to the non-uniform shape of the ergonomic workspace. Another solution would be to simplify the shape of the ergonomic workspace by cutting out some rough edges, at the expense of some fidelity.

For this study, RULA was adapted using certain simplifications. The complete RULA method includes rules regarding the operator's upper body as well, whereas this research only focuses on the arm-related rules. It was assumed that there were no upper-body movements during task execution. Since the task was performed while seated in a chair, the operator's upper body remained relatively still, resulting in no significant change in the RULA score due to upper body movement. Nonetheless, the upper body could be considered in the estimation when the operator is not sitting still (e.g., performing teleoperation in an ad-hoc setup in the field).

Additionally, it is important to note that the RULA method used here is a simple and effective lookup-table based method for ergonomic scoring. Alternatively, this work could also integrate advanced biomechanical models for a more detailed assessment. For instance, high-fidelity musculoskeletal models may offer enhanced accuracy in estimating joint loading and muscle fatigue [27] but require more complex implementation and computational resources. On the other hand, RULA is easy to implement and is computationally inexpensive. Furthermore, unlike musculoskeletal models that give us various internal body variables which still need to be linked to specific WMSD risks, RULA is experience-based and already incorporates such risks. Therefore, our use of a simplified RULA model was a pragmatic choice to prioritise a seamless operator experience while still providing a valid, real-time measure of postural ergonomics.

Finally, this study was conducted as a proof-of-concept with a single expert operator executing a sequential reaching task. A formal user study with multiple participants, executing a variety of tasks, would be required to validate the generalisability of these findings.

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