2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 1-5, 2023. Detroit, USA

A Shared Autonomous Nursing Robot Assistant with Dynamic Workspace for Versatile Mobile Manipulation

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2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) | 978-1-6654-9190-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/IROS55552.2023.10342401

***Abstract*— This paper presents a novel integration of a shared autonomous mobile humanoid robot for remote nursing assistance. The proposed nursing robot has a motorized versatile supporting structure to allow flexible integration of the system components, autonomously adjust its mobile manipulation workspace and improve its reachability and manipulability to operate in a cluttered environment. The robot also provides a novel integration of robot autonomy to reduce the human effort to coordinate the motorized chest and arm motion, control the precise manipulation of objects and camera viewpoint, and handle complex collision avoidance in human-guided gross manipulation. Moreover, we developed an open-source virtual testbed that integrates ROS- and Unity-based robot simulation and benchmark mobile manipulation nursing tasks and scenarios in a realistic simulation of a hospital environment. The virtual testbed supports various contemporary gaming and AR/VR interfaces to control the virtual human and robots, and provides autonomy for navigation, manipulation, and remote active perception assistance. We conducted a user study (N=9) to validate that the versatile supporting structure and shared autonomy of the physical testbed can effectively reduce the human effort to control unstructured manipulation, and improve the robot's reachability and manipulability. In addition, we conducted a pilot study (N=8) to test the usability of the virtual testbed and collect feedback from representative users.**

I. Introduction

In the near future, caregivers will be able to control or supervise the nursing robots deployed to hospitals, homes, and other facilities to provide nursing and living assistance. The remote patient care and living assistance enabled by nursing robots can effectively reduce the risk of infection, work stress, and discomfort of working in personal protective equipment (PPE) for an extended time in quarantine patient care. The adoption of robots will ease the shortage of the nursing workforce and improve the sustainability of healthcare for an aging society.

In this paper, we present a novel integration of a shared autonomous mobile humanoid robot for remote nursing assistance. Compared to the state-of-the-art nursing assistance robots (e.g., [1]–[4]), our proposed system has a versatile supporting structure to allow flexible integration of system components (e.g, the numbers of manipulators and cameras, the mounting locations and angles). The motorized chest expands the system's manipulation workspace and improves its reachability and manipulability, allowing it to efficiently operate in a cluttered environment. It also incorporates novel shared autonomy to reduce human efforts to adjust the manipulation workspace and to control the complex base, arm, and camera coordination in unstructured mobile manipulation. Specifically, the robot provides autonomy for collision avoidance, base-arm coordination, and action support for precise manipulation, while the human remotely guides the robot's motions using various gaming and VR control interfaces.

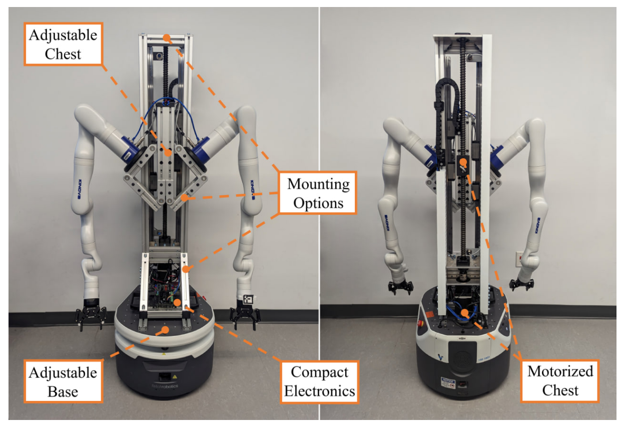

Fig. 1: Nursing assistance robot with versatile supporting structure and motorized chest.

Another contribution of our work is the development of an open-source virtual testbed that integrates the simulation of nursing assistance robots and benchmark tasks. Recent simulations developed to support physical human-robot interaction (e.g., [5]–[12]) tend to: 1) provide application-specific benchmark tasks (e.g., from general mobile manipulation task to specific caregiving tasks) and more realistic simulation of task scenarios (e.g., home, clinic room, patient room); 2) incorporate controllable or autonomous virtual humans and robot agents to test multi-robot and physical human-robot interactions; 3) be compatible with widely used open-source development frameworks and platforms (e.g., ROS, Unity); 4) support contemporary AR/VR interfaces and human tracking devices (e.g., HTC Vive and body trackers, Meta Quest); 5) support the co-design of virtual and physical testbeds; 6) support robot learning in simulation and sim-to-real skill transferring. Our proposed virtual testbed integrated **all** of the above desirable features. Compared to the RCare World [12], the most comprehensive open-source simulation for patient caring robots, our proposed virtual testbed provides a more comprehensive hospital environment, with various frequently performed mobile manipulation nursing assistance tasks identified in our prior work [13] that involve complicated coordination of base, arm and camera control.

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Moreover, our system enables the virtual human agent to be controlled using VR interfaces (e.g., Meta Quest and KAT Walk VR Treadmill), to evaluate the HRI design in a more immersive setup as a patient or collaborative human nursing worker.

II. System Integration

A. Physical Testbed

1) Physical Robot Components: As shown in Fig. 3, the physical robot integration has a ***compact*** profile, with a height of 1700 mm (between the globally averaged height of male and female), and adjustable width of 530 to 850 mm (depending on how the arms are mounted on the chest), which makes it easy to pass a narrow entrance and maneuver in a cluttered patient room. The robot can be untethered since all the computing, sensing, and acting components are integrated onboard. The data streaming between the robot and the operator console can be supported by wireless communication. The key insight of our system integration is the development of the ***versatile supporting structure*** to enable an easy configuration and customization of the physical testbed based on the task and application context. As shown in Fig. 3, the chest is motorized in the z-axis and can accommodate a mounting with configurable angles and locations of up to four robot manipulators. The position of the supporting structure can be adjusted on the base. Furthermore, it provides various mounting options for cameras and additional peripheral equipment on the base and body. Fig. 3 presents a typical configuration of the physical testbed, which consists of two 7-DOF manipulator arms (Kinova Gen3, with eye-in-hand RGB+D cameras) with two-fingered Robotiq-85F grippers, and one Freight Research Platform non-holonomic mobile base. A panoramic camera is mounted on the chest, with a small offset to the right side, to better observe the arm for manipulation.

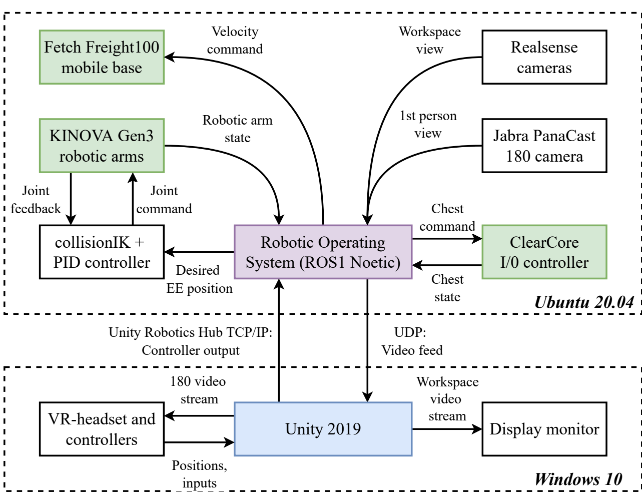

Fig. 2: Physical testbed software architecture.

2) Software Architecture and Control Interface: Fig. 2 shows the software architecture of our system integration. The mobile base runs Linux operating system with Robot Operating System (ROS) to communicate with all onboard ROS-driven hardware components, including the robot arm, base, motorized chest, and cameras. Meanwhile, Unity on Windows operating system of the operator console computer supports the control interfaces, including the virtual reality (VR) system (HTC Vive, Meta Quest 2), keyboard, graphical user interface (GUI), and devices for gaze and motion tracking. UnityRobotics-Hub TCP/IP is used to send the control commands to the robot and stream the camera videos to the operator's screen-based or head-mounted display. We proposed and implemented a highly extensible ROS-Unity framework for the software architecture so that the physical testbed can easily: 1) incorporate a wide range of ROS-compatible robot hardware (see the robots using ROS `https://robots.ros.org/`), 2) support various contemporary robot control interfaces and VR systems compatible with Unity, 3) benefit from the development and testing using our virtual testbed, which has a similar software architecture (see Section II-B), and 4) be shared as an open-source software architecture with the robotics research community.

3) Autonomy to assist manipulation control: Our physical testbed integrated several shared autonomy control approaches to reduce the efforts to perform mobile manipulation.

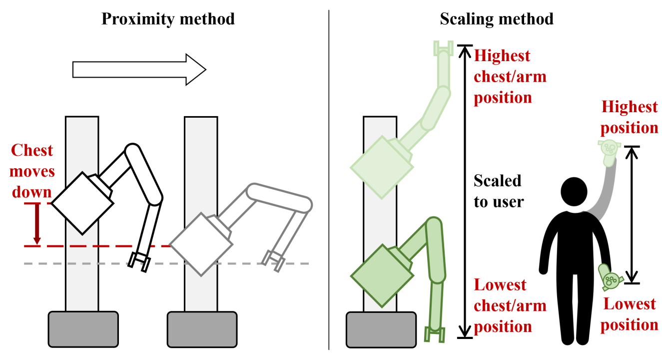

Fig. 3: Two autonomy methods for chest-arm coordination. **Proximity method** (left): the chest autonomously adjusts when the end-effector is close to its reachability limits. **Scaling Method** (right): maps the upper and the lower motion limits from the user to the robot workspace.

- ***Autonomy for Chest-Arm Coordination***: We developed two simple but effective shared autonomy methods to reduce human effort to control the coordination of the motorized chest and manipulator arms. While human focuses on the control of the manipulator's end-effector motion, our proposed Proximity to Vertical Workspace Boundaries Method (i.e., the ***Proximity Method***) autonomously moves the motorized chest to prevent the robot's end-effector from reaching its upper and lower vertical z-axis motion limits (with a pre-defined margin δ_P). We also proposed a Scaled Vertical Absolute Motion Mapping Method (i.e., ***the Scaling Method***) which maps the range between the upper and the lower motion limits (absolute coordinates in the z-axis) from the operator to the robot workspace, and proportionally couples the robot's end-effector and chest motion in the z-axis to follow the human hand-held controller's position. Overall, the Proximity Method was developed to improve the robot end-effector's manipula-

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bility, while the Scaling Method was designed for a more intuitive mapping between human and robot arm motion.

- ***Fatigue-adaptive shared autonomous control***: Our recent prior work in [14] proposed a novel shared autonomy to enable humans and robots to complement each other's strength in the collaborative control of unstructured robot manipulation tasks. Overall, human operators can use their hand motions and poses to guide the robot's gross manipulation to approach a target and move across the cluttered workspace, so that they can freely determine the task procedures and action sequence. Meanwhile, the robot autonomously performs precise manipulation actions (e.g., grasping, stacking, camera viewpoint control), which tend to cause arm and back muscle efforts and fatigue. The human's goal and action of the precise manipulation can be inferred based on prior knowledge of typical action sequences, controlled robot motions, and human gaze tracking. In this work, we improved the prior shared autonomy design by introducing robot motions to express its inferred goal and action intent. Before executing a precise manipulation action, the robot end-effector moves slightly toward the target object to grasp. The human can approve the action if the intended inference is accurate or control the robot's gross manipulation to move in a way that can help the robot to resolve the intent inference ambiguity. Here we present a simple proof-of-concept implementation that determines the target to grasp by the distance between the robot end-effector and the object. When the robot cannot determine the object to grasp because none of the objects nearby is close enough, the robot shakes the end-effector, which implies that humans need to move the robot closer to the target. This expressive robot motion is developed for the robot control scenarios in which augmented reality interfaces and visual assistance are not applicable/available. While the fatigue-adaptive shared autonomy will reduce the human's workload to control precise manipulation actions, we expect the augmented expressive motion will further communicate to humans when the autonomous action assistance is ready to use and how to enable the action assistance if it is not ready.
- ***Relaxed IK***: Our system incorporated the Relaxed IK proposed by Rakita *et al* in [15] to resolve inverse kinematics for the robot manipulators, create smooth and feasible robot motions, avoid joint-space discontinuities and kinematic singularities, and effectively handle self-collisions.

B. Virtual Testbed

1) System Components: As shown in Fig. 6, we adopted a similar ROS-Unity software architecture to ensure the development of the virtual testbed can be transferred to the physical one, including the robot platform, interface, autonomy and augmented visual and haptic feedback.

Our open-source virtual testbed (Fig. 4) uses the same mobile base and manipulators with grippers as the physical testbed, and can incorporate additional components and sensors (e.g., cameras, LIDAR) with ROS-compatible interfaces. The simulated environment renders the typical hospital interior and facility, including individual and shared patient rooms, clinic rooms, nurse stations, and storage rooms. It also includes movable furniture and objects, and virtual human/robot agents to interact with. The robot and virtual humans can be controlled by both human and robot autonomy (see the "control interface and autonomy" of this section for details).

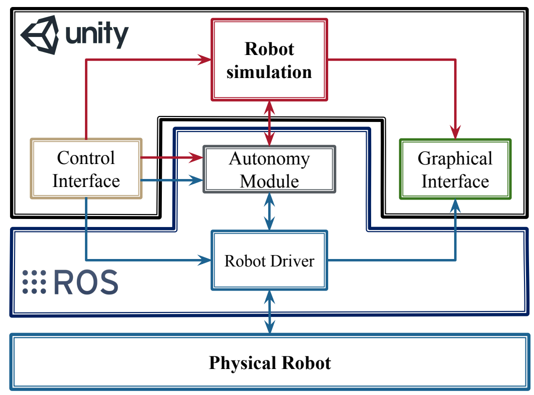

Fig. 6: Virtual testbed system architecture.

Shown in Fig. 4 (right), the GUI integrates the essential interface primitives to enable users to intuitively monitor the robot/task states, robot control mode, and the selected primary and complementary camera viewpoints. Furthermore, a 2D navigation map is provided to track the up-to-date robot location, goal-directed navigation path plan, and obstacle detection.

2) Benchmark Tasks: With the focus on mobile manipulation, we developed various nursing assistance tasks which may require the robot to: 1) move its base in order to improve the reachability and manipulability of the manipulator's arm, and reduce the occlusion of the robot's cameras, 2) use its arms to manipulate the environment and objects to facilitate the navigation. As shown in Fig. 5, our virtual testbed provides the following task scenarios:

- *Goal-directed navigation*: The robot delivers test samples and medical supplies to the designated room and location. The robot is guided by a pre-planned path but must avoid any encountered obstacles and human agents along the way.
- *Moving IV stand*: The robot uses its manipulator to grasp an IV stand and move it to the designated room and location. The robot needs to maneuver the IV stand to pass narrow gateways and passages while avoiding collisions.
- *Pushing a medical cart*: The robot uses both manipulators to grasp the handle of a medical cart and push it to the designated room and location. The medical cart needs to be reoriented to pass narrow gateways and passages. The bulky medical cart is clumsy to maneuver and may prevent the robot from detecting and avoiding obstacles.
- *Removing roadblocks*: The robot follows the guidance of a pre-planned path and uses manipulators to push/pull the obstacles that block the path.
- *Monitoring vital signs*: The robot approaches a medical

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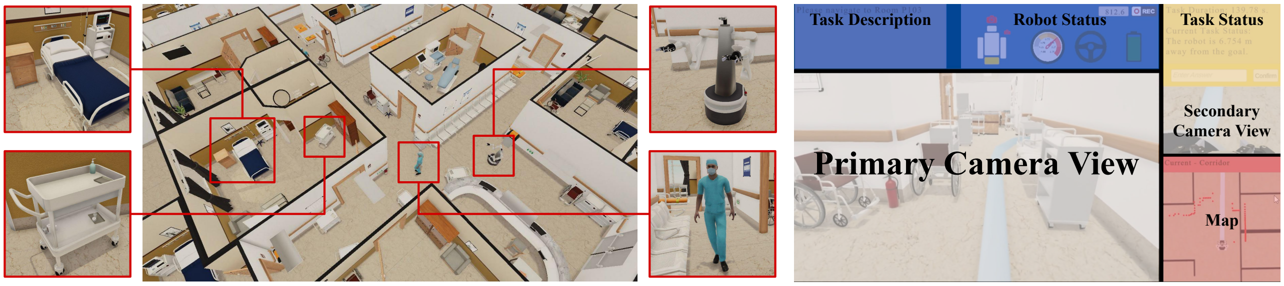

Fig. 4: ***Virtual testbed:*** on the left, the simulated hospital, including hospital equipment, nurses, and robot model. On the right, the graphical user interface.

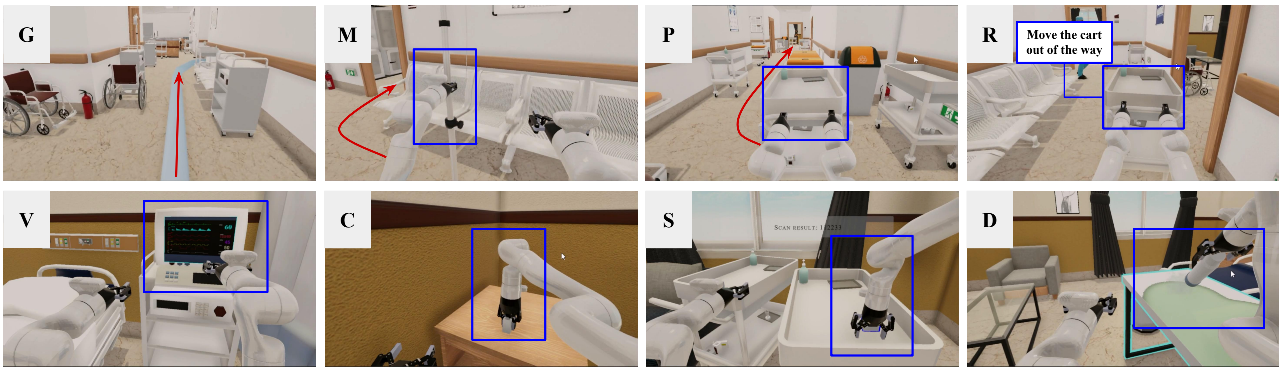

Fig. 5: ***Benchmark tasks for mobile manipulation and active perception:*** Goal-directed navigation (G), Moving an IV stand (M), Pushing a medical cart (P), Removing a roadblock object (R), Monitoring vital signs (V), Collecting medical supplies (C), Scanning barcode (S), and Disinfection (D).

device on a bedside table monitor and reads the displayed vital signs through a telepresence camera.

- *Collecting*: The robot moves its base to approach a bedside table and picks up a medicine container. This task may be set to collect multiple objects scattered in the rooms and storage space.
- *Scanning barcode*: The robot moves its base and arm to approach the target object and adjusts the camera viewpoint for scanning. This task may involve objects in a medical cart and storage space.
- *Disinfection*: The robot uses its end-effector sprayer to disinfect a table.

3) Control Interfaces and Autonomy: Both physical and virtual testbeds use Unity to stream the inputs from various control interfaces, including the basic keyboard and mouse control, and virtual reality systems (e.g., Meta Quest, HTC Vive). The current virtual testbed can support additional gaming interfaces (e.g., haptic gamepad, racing simulator). The control inputs may be sent directly to the low-level controllers of the robot model, or through the autonomy module, which augments the human control with motion- and action-level support. Specifically, the robot has the autonomy for general collision detection and avoidance with static and dynamic obstacles and path planning to guide goal-directed navigation given the floor plan. When the operator moves the robot end-effector close enough to the target and gives approval for autonomy activation, the robot can autonomously grasp a known object or align the camera viewpoint angle and viewing distance with the region of interest. The virtual testbed autonomously collects and synchronizes the data the experimenter selects to record during the user studies, including the robot/task/environment states, camera stream, control inputs, and the screen-based human gaze tracking from Tobii Pro Nano.

III. Evaluation

A. Testing in Virtual Testbed

We conducted a pilot study with N=8 participants (age 23.9 ± 2.8, 3 males and 5 females) to test the integration of the virtual testbed, and collected user feedback to improve the interface, robot autonomy, and benchmark tasks. Participants controlled a mobile humanoid nursing robot using a mouse and keyboard, and the graphical user interface was displayed on a desktop monitor. Participants performed the benchmark mobile manipulation tasks in a randomized sequence. As shown in Fig. 7, we used paired t-Test (with benjamini-hochberg procedure) to compare the completion time of each task performed under ***Direct*** and ***Assisted*** control. It shows that the robot autonomy significantly reduced the completion time ($p < 0.05$) for Pushing a medical cart (P) and Removing roadblocks (R) which involve the precise control of reaching to grasp the medical cart handle, but not for goal-directed navigation (G) and moving IV stand tasks (M), that heavily depended on the autonomy for path planning and navigation with collision avoidance. Assistive autonomy significantly reduces the task completion time ($p < 0.05$) for tasks that heavily depend on the precise control of camera viewpoint and manipulation, including Collecting (C), Scanning barcode (S), and Disinfection (D). The NASA-TLX survey also shows a significantly lower perceived mental workload ($p < 0.05$) for all tasks performed with assistive autonomy. Overall, we found that autonomy for assisting robot manipulation and camera viewpoint control is more important for the performance of mobile manipulation

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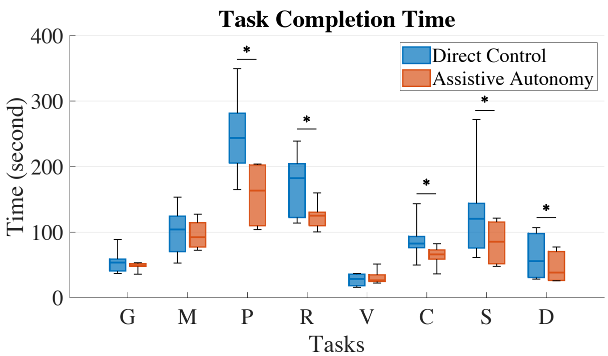

Fig. 7: Comparison of task completion time between direct control and assistive autonomy modes for Goal-directed navigation (G), Moving IV stand (M), Pushing a medical cart (P), Removing roadblocks (R), Monitoring vital sign (V), Collecting (C), Scanning barcode (S), and Disinfection (D).

tasks. The freeform comments from participants indicate that it would be useful to have augmented reality visual cues and assistive autonomy to mitigate the remote/virtual perception problems (e.g. limited field of view, loss of depth perception, possible motion sickness), and visualize the robot's reachability and manipulability.

B. User Study

We conducted a pilot user study to evaluate the unique features of our integrated physical testbed, compared to the state-of-the-art mobile manipulator nursing robots (e.g., Diligent's Robots [1], AvaTRINA [4]). Our evaluation investigated: 1) whether the versatile supporting structure of the physical testbed integration can effectively improve the reachability and manipulability of the nursing robot; 2) whether our proposed autonomy for chest-arm coordination can effectively reduce the operator's effort to control the complex mobile manipulator platform; and 3) whether the behavior of the robot autonomy is easy to understand and predict.

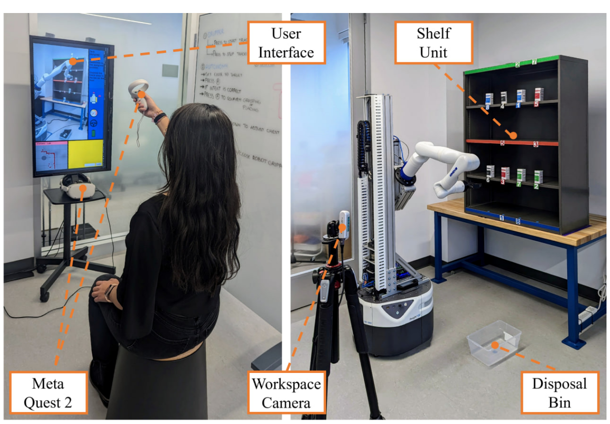

Fig. 8: Experimental setup: task space and remote control interface.

1) Experiment Setup: Our experiment simulated the nursing assistance task for inspecting and managing the medical supplies storage room. As shown in Fig. 8, participants were asked to follow a pre-defined order to handle eight medical containers in a five-shelf storage unit. The six medical containers labeled in red, blue, and green had to be moved to their designated locations, while the two labeled in black color had to be disposed in the plastic bin on the floor. During the experiment, participants employed an Meta Quest 2 hand-held controller to teleoperate the robot through a graphical user interface that displayed the video stream from a workspace camera. The operators could use their freeform hand motions to approach a medical container or the target location and press a button on the controller to activate pick and place autonomy. The robot would tentatively move and point at the target to indicate the goal location or object it inferred (based on distance). The operators could then press the hand controller's button to confirm the robot's intended action or move the robot closer to a different target location and activate pick and place autonomy again. Participants could also use the joystick of the controller to manually adjust the z-axis position of the motorized chest. The task required reaching up to 2.48 m high to manipulate the medical containers on the top of the shelf and reaching close to the floor to drop the medicines to be disposed of. The robot base was positioned at a pre-defined location in front of the shelf, to encourage the operators to utilize the chest and arm motions for the task, assuming the robot has to minimize its base motion in a cluttered workspace.

2) Experiment procedure and data collection: Our user study recruited N=9 participants (age mean 26.2 $\pm$ 5.6 years old, 6 males and 3 females). Before the experiment, participants reported their experience with different technologies (e.g., tele-robotic systems, VR interfaces, and video games) in a pre-study survey. The experimenter then provided verbal instructions and demonstrations to teach the participants the task, robot and interface, and allowed them to practice each chest control mode until they felt comfortable using the system. During the formal study, participants performed two trials per task for each of our proposed chest control autonomy designs (i.e. the ***Proximity Method***, ***Scaling Method*** modes), and the ***Manual Control*** mode. The control modes order was randomized for each participant to avoid learning effects. The data we collected includes the robot/task states, the videos and time-stamped images of the workspace and synchronized display on the graphical user interface, and the inputs from the control interface. After the experiment, participants filled in several standard and customized surveys, including NASA Task Load Index (NASA-TLX) and System Usability Scale (SUS), to report their perceived performance, workload, and usability of the integrated systems.

IV. Data Analysis and Results

Paired t-Test (with benjamini-hochberg procedure) was used to compare the task performance and robot motion characteristics between the three control modes for chest-arm coordination: the **Manual Control (M)**, and the autonomous controls using the **Proximity Method (P)** and **Scaling Method (S)**. Here is a comparison of the significant differences ($p < 0.05$) from the objective measurements and standard survey feedback (NASA-TLX and SUS):

- **Task completion time**: S < M, P

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- **Number of unreachable pick-and-place attempts at current chest height**: S < P
- **Total travelled chest distance**: P < M, S
- **Robot end-effector manipulability**: P < S
- **Physical demand** (NASA-TLX): M, P < S
- **Performance** (NASA-TLX): P < S
- **Total SUS score**: P < S

Among the 12 questions in our customized survey, we also found significant differences ($p < 0.05$) for the following:

- **[Q2]** Was it easy for you to learn how to control the motorized chest? (1 - very easy, and 7 - very hard): S < P, M
- **[Q3]** How important is it for you to know the current position of the motorized chest at all times? (1 - not important, and 7 - very important): S < P, M
- **[Q4]**: How important is it for you to have the motorized chest in the camera field of view at all times? (1 - not important, and 7 - very important): S < P < M
- **[Q6]** Is it easy for you to predict how the system (the motorized chest and the robot arm) will perform an action/motion following your control? (1 - very easy, and 7 - very hard): M < P
- **[Q8]** How easy was it for you to control the robot's large and fast motions (e.g., moving an object from one shelf to another) with different motorized chest control modes? (1 - very easy, and 7 - very hard): S < P

The results reveal the pros and cons of the three control methods. Overall, the **Scaling Method** is the best for task performance, robot reachability and manipulability, and enhances the responsiveness of the motorized chest. Moreover, it has more predictable and understandable behavior and is easier to learn and use for large and fast motion control. However, this method tends to cause high physical workload. This is due to the absolute mapping, which prevented operators from repositioning their arms when controlling the robot, thus leading to discomfort and fatigue while performing the task on the upper shelves. The **Proximity Method**, on the other hand, is overall the worst for task performance, usability, and robot reachability and manipulability. It caused a comparable physical workload to the **Manual Control** but tends to be more difficult to learn and to use, because the behavior of robot autonomy is not quite understandable and predictable. Through the pilot study, we found that the margin δ_P of the **Proximity Method** needs to be carefully chosen so that the motion of the motorized chest can be more smooth, intuitive, and predictable.

V. Conclusion and Future Work

Through this work, we contributed with a novel integration of a physical mobile manipulator nursing robot with enhanced reachability and manipulability to work in a cluttered workspace. Additionally, we introduced an open-source virtual testbed to test a mobile manipulator nursing robot (system integration, interface, assistive autonomy) using the benchmark mobile manipulation tasks in a realistic simulation of a hospital environment. Our pilot user studies for evaluating the physical and virtual testbeds revealed that while the overall integrated systems have good usability, the assistive autonomy needs to enable humans and robots to contribute their complementary skills to mobile manipulation tasks. Our future work will refine the two methods for autonomous chest-arm coordination, and optimize for better reachability, manipulability, and predictability. We will refer to the recent work for coordinated control of macro-micro structure manipulator (e.g., [16]), and incorporate augmented reality visual cues (e.g., [17]) to enhance the remote perception in mobile manipulation.

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