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Enhanced Bimanual Manipulation Assistance with the Personal Mobility and Manipulation Appliance (PerMMA)

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Abstract—**In this paper, we investigate the enhanced ability of manipulation with the newly developed Personal Mobility and Manipulation Appliance (PerMMA). PerMMA is a new assistive device that integrates bimanual manipulation with smart mobility to assist people with severe physical disabilities and enhance their quality of lives. Different from the fixed mounting method used in most existing systems, a novel mounting system was designed on PerMMA to enhance its capability of manipulation assistance. With a workspace characterized by essential daily living tasks, we evaluated PerMMA's performance of manipulation using a comparative study between PerMMA and classic design, such as single arm and fixed mounting, used in most existing systems. Simulation results demonstrate significant improvements with PerMMA in both of its reachability and manipulability.**

I. INTRODUCTION

OVER 10 million Americans reported a daily activity limitation in the 2008 Census, whose activities of daily living (ADLs) usually require assistance from tools or personal caregivers [1][2]. However, the shortage and high cost of experienced caregivers fail to fulfill the rapidly growing needs for more personal assistance. Technology which aids in these tasks is in great demand, and it must allow the user to independently and safely control both mobility and manipulation within an unstructured environment in their home and community [3].

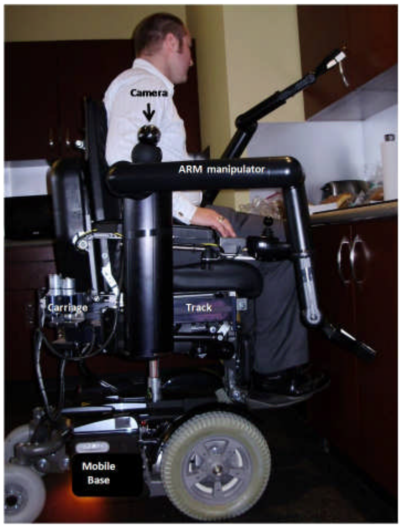

Fig. 1. The PerMMA is used to open a closet in kitchen.

Robotics technology has been applied in rehabilitation technology and assistive devices to enhance the performance of assistance and quality of life of people with disabilities. By attaching a robotic manipulator to a mobile base, such as a wheelchair or a mobile robot, several robotic assistive devices have been developed to provide both mobility and manipulation assistance to people with severe physical impairments [9-12]. However, most existing devices only provide a single-arm manipulation, which greatly reduce their efficiency of assistance and restricts their ability to perform complex manipulation tasks which require the involvements of both arms, for example, open the refrigerator with one arm and pick up a bottle of water with the other one.

In this paper, we investigate enhanced manipulation assistance with our newly developed Personal Mobility and Manipulation Appliance (PerMMA), as shown in Fig. 1. PerMMA is capable of providing efficient and flexible bimanual manipulation as well as smart mobility to people with severe physical disabilities. Different from the fixed mounting method used in most existing systems, a novel track and carriage mounting system is developed, which not only preserves relative mobility between the base and the arms, but also provides extra degrees of freedom (DoFs) to the robot arms. PerMMA's capability of manipulation was evaluated using numerical analysis within a workspace characterized by essential daily living tasks. Two important criteria, reachability and manipulability, are compared between PerMMA and classic single arm fixed mounting designs.

II. RELATED WORK

Power wheelchairs are important appliances for mobility assistance for people with severe physical disabilities. Since a powered wheelchair has similar characteristics as a mobile robot in mechanical structure, drive-systems and navigation methods, robotics technology has been applied to powered wheelchairs to achieve more intelligent mobility assistance. An example of a combination of a mobile robot and powered wheelchair is the IBOT, which is a wheelchair that can raise the user up to eye level or climb stairs. Studies have shown that the IBOT has the potential to improve employment

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satisfaction of wheelchair users and increase their participation in community activities [4]. Another robotic wheelchair, the TopChair, has four wheels for driving and uses tracks to climb stairs and shows good performance in curb negotiation and stair climbing [5]. Utilizing different sensors, several robotic wheelchairs, such as the Wheelsley, RobChair and Rolland, can automatically navigate with a direction commanded by the user while avoiding obstacles [6-7]. However, many smart wheelchair users still have difficulty in retrieving a remote control, book/magazine, or a drink if not placed in their immediate proximity. Therefore, the capability of providing manipulation assistance together with enhanced mobility is in great need for personal assistive devices.

Robot arms have advanced in the past two decades to allow people with upper extremity impairment or amputation to retrieve partial or full capability of completing manipulation tasks in their daily living [8]. An early manipulation assistance system utilizing robot arms was the Desktop Vocational Assistant Robot (DeVAR) [9], which consisted of a small robotic arm mounted on an overhead track system above a desk and was controlled using discrete word voice commands. Following the DeVAR was the Professional Vocational Assistant Robot (ProVAR), which incorporated force sensors and different interface modes [10]. With 6 degrees of freedom and a universal docking socket at both ends, the ASIBOT allows either end to function as the fixed point or the gripper [11]. By mounting a Barrett WAM arm and hand on a mobile base, the Home Exploring Robotic Butler (HERB) was developed as a platform to validate advanced machine intelligence algorithms [12].

One of the most commonly investigated robotic arms in rehabilitation research is the commercially available Manus Assistive Robot Manipulator (ARM) [13]. The ARM has 6 degrees of freedom (DoFs) plus a simple two-fingered gripper for general manipulation. An advantage of the ARM is its compatibility to wheelchairs and other mobile bases, which makes it a good tool to provide mobile manipulation assistance [14]. The ARM has also been attached to a small mobile robot to follow the wheelchair user around and provide manipulation assistance [15].

Several customized robotic assistive devices combing both mobile base and robot arm have been developed to overcome the limitations of the Manus ARM in the range of movements and dexterity. The KIAST Rehabilitation Engineering Service (KARES) developed at the Korean Institute for Advanced Science and Technology (KAIST) attach a customized 6-DOF robotic arm to the side of an EPW [16]. A 9 DoFs robotic arm developed by the University of Southern Florida tried to provide more DoFs to achieve more dexterity in manipulation assistance [17]. A new robot specifically designed for door opening task, the DORA, is being developed at University of Massachusetts, Lowell [18]. However, customized systems are still not available for practical rehabilitation applications because of availability, safety and reliability concerns. A safe and efficient assistive system that can perform real tasks for people with disabilities in their home is in great need.

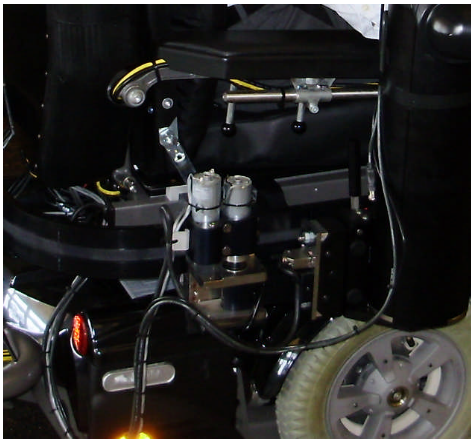


Fig. 2. Design of the track and carriage system of the PerMMA.

III. DESIGN OF PERMMA AND THE NOVEL MOUNTING SYSTEM

Most mobility assistive devices lack manipulative capability to provide users with limited hand dexterity or function the ability to perform activities like opening a door, holding a glass of water, or preparing food in a microwave. The ultimate goal of the personal mobility and manipulation appliance (PerMMA) is to provide a “zero-gap” in both mobility and manipulation between people with disabilities and unimpaired person [19]. Therefore, it should provide its users with both intelligent mobility and intuitive bimanual manipulation. Considering the safety and reliability requirement for the entire system in practical daily use, we have chosen to utilize commercially available products with add-on customized features to build the PerMMA, although several fully customized systems have been investigated by other researchers. A commercialized PerMobil C500 (PerMobil Inc, USA) electric powered wheelchair (EPW) was selected as the mobile base because of its flexibility and powered seating system. The original mechanical structure and user-machine interface of the C500 was adopted to allow users to control the mobility and seat functions, but all original electronics were replaced with customized sub-systems for integrating advanced features. An after-market encoder was attached to the caster of the C500 and a 6-DoF inertia sensor was integrated into the seat to detect vibration, roll rates and wheel slip while PerMMA is driven over different terrains. A control algorithm based on a 3D kinematics model of the C500 was developed to automatically switch between velocity/traction control modes to reduce the wheel slip and provide robust mobility assistance on different terrains [20].

To provide people with severe physical impairments with the enhanced capability of manipulation is another important concern in the design of the PerMMA. Many essential manipulation tasks in daily living require the involvement of both arms, for example, holding a bottle with one hand while opening the cap with the other one. The capability of providing bimanual manipulation will significantly improve the efficiency and usability of manipulation assistance. As the first assistive device that provides bimanual manipulation, PerMMA integrates two Manus ARMs with its smart mobile base. The two ARMs are symmetric in their mechanical structure and provide a much larger reachable range for manipulation. Although several mounting patterns for a wheelchair mountable robot arm have been introduced in literature [21], including front mounting, side mounting and rear mounting, all of these mounting patterns fix the robot arm position with respect to the mobile base. Once an object is out of the range of the robot arm, the user has to move the wheelchair to re-approach the object in order to perform the manipulation, which greatly restricts the effectiveness and efficiency of the robot arm. Different from classic mounting methods, we developed a novel track and carriage system to mount two Manus ARMs on the C500 EPW, as shown in Fig. 2, which preserves the relative mobility between the robot manipulator and the mobile base. A U-shaped track was attached to the seat frame and can move with the powered seat function, which provides the users the same capability of manipulation no matter which direction they are facing and how they are seated. A short supporting bridge was attached to each ARM, and was connected to a carriage system mounted on the track. The carriage system allows each ARM to move along the track as well as rotate about the axis of the carriage, which provides two extra DoFs in addition to the original 6 DoFs of the Manus ARM. The entire track is within the footprint of the mobile base, which adds no extra width and does not affect the original seating functions of the C500. The extra translational DoF not only allows both ARMs to approach target objects without base movement, but also can relocate them behind the seat back along the track. When the two ARMs are folded and hidden behind the seat back, no extra width will be added, which maintains the same mobility of PerMMA in narrow environments, such as doorways and hallways. The extra rotational DoF allows both ARMs to re-orientate to face all directions on the side of the PerMMA without moving the mobile base. This track and carriage system significantly enhances the flexibility and ease of use of the system and improves the efficiency of the manipulation and the effectiveness for the users.

IV. KINEMATICS OF PERMMA'S BIMANUAL MANIPULATION

The kinematics model of the PerMMA with two ARMs mounted using the track and carriage system can be abstracted as shown in Fig. 3. Following the notations in [22], let $\omega \in \mathbb{R}^3$ be the rotational axis of a revolute joint and q be a point on this axis, then a revolute joint can be represented by its twist coordinates $\xi = \begin{bmatrix} -\omega \times q \\ \omega \end{bmatrix} := \begin{bmatrix} v \\ \omega \end{bmatrix}$ and the value of this joint θ, where $v \in \mathbb{R}^3$ is the translational velocity generated by this joint. For a prismatic joint, let v represent the direction of the translation, a prismatic joint can be represented by its twist coordinates $\xi = \begin{bmatrix} v \\ 0_{3\times1} \end{bmatrix}$ and its translational motion θ.

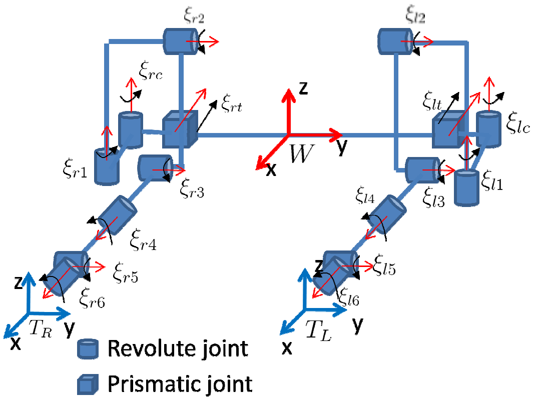


Fig. 3. Kinematics model of PerMMA: two ARMs on the wheelchair with the track and carriage system.

Let us first consider kinematics of the left ARM. Since the right ARM is similar to the left one in kinematics and they are symmetrically mounted on both sides of the mobile base, the kinematic model of the right ARM can be obtained following the same procedure. Attaching a wheelchair frame, W, to the center of the seat on the EPW and a gripper frame, T_L, to the gripper of the left ARM. The six revolute joints of the left ARM can be represented by their twists coordinates

$$\xi_{l1} = \begin{bmatrix} 380 \\ -240 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \xi_{l2} = \begin{bmatrix} -445 \\ 0 \\ 240 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \xi_{l3} = \begin{bmatrix} -45 \\ 0 \\ 240 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

$$\xi_{l4} = \begin{bmatrix} 0 \\ 45 \\ -470 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \xi_{l5} = \begin{bmatrix} -45 \\ 0 \\ 570 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \xi_{l6} = \begin{bmatrix} 0 \\ 45 \\ -470 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

and its six joint angles $[\theta_{l1} \quad \theta_{l2} \quad \theta_{l3} \quad \theta_{l4} \quad \theta_{l5} \quad \theta_{l6}]^T$. Similarly, the revolute joint on the track and the prismatic joint on the carriage can be represented by their twist coordinates

$\xi_{lt} = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T, \xi_{lc} = [380 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1]^T$ and the translational motion along the track, θ_t, and the rotation angle of the carriage, θ_c.

Let $g_{wt_l} = (p_{wt_l}, R_{wt_l}) \in \mathbb{R}^{4\times4}$ represent the rigid body transformation of frame T_L relative to frame W, where

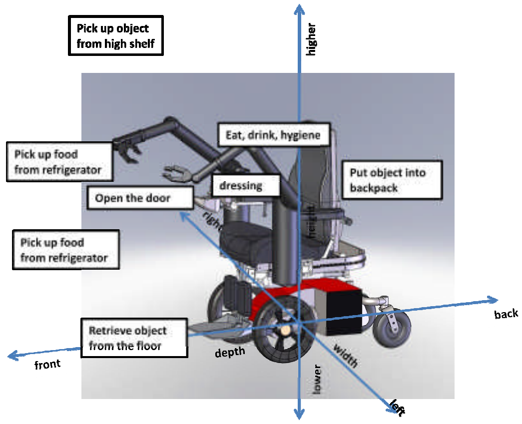


Fig. 4. Workspace characterized by daily living tasks

$p_{wt_l} \in \mathbb{R}^3$ represents the translation between two frames and $R_{wt_l} \in \mathbb{R}^{3\times 3}$ is the rotation matrix. Let $g_{wt_l}(0)$ represent the rigid body transformation of frame T_L relative to frame W when the left ARM is in its reference configuration. The forward kinematics of the left ARM is [22]

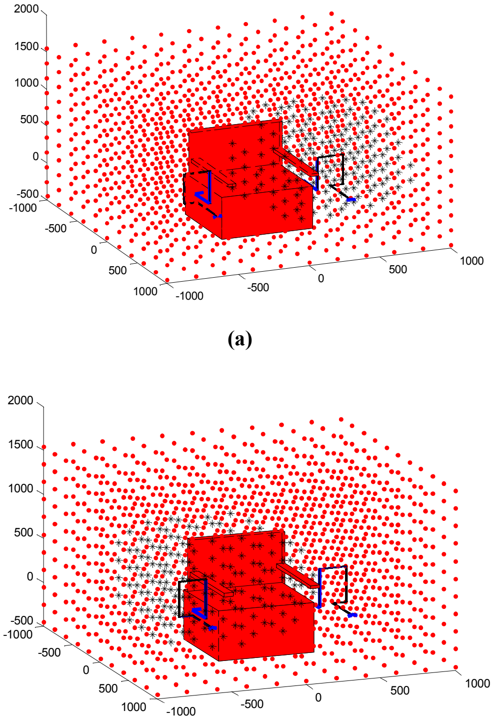
$$g_{wt_l} = e^{\hat{\xi}_{lt}\theta_{lt}} e^{\hat{\xi}_{lc}\theta_{lc}} e^{\hat{\xi}_{l1}\theta_{l1}} \cdots e^{\hat{\xi}_{l6}\theta_{l6}} g_{wt_l}(0) \qquad (1)$$

Let $V^s_{wt_l} = \begin{bmatrix} v^s_{wt_l} \\ \omega^s_{wt_l} \end{bmatrix} \in \mathbb{R}^6$ be the spatial velocity of the frame T_L relative to the wheelchair frame W, where $v^s_{wt_l} \in \mathbb{R}^3$ is the translational velocity and $\omega^s_{wt_l} \in \mathbb{R}^3$ is the rotational velocity. Its relationship with the joint values of the left ARM can be represented as $V^s_{wt_l} = J^s_{wt_l}(\Theta_l)\dot{\Theta}_l$, where $J^s_{wt_l}(\Theta_l)$ is the spatial Jacobian of the left ARM and $\Theta_l = \begin{bmatrix}\theta_{lt} & \theta_{lc} & \theta_{l1} & \cdots & \theta_{l6}\end{bmatrix}^T$ is the ARM's configuration. With the similar procedure, we can calculate the rigid body transformation of the right ARM $g_{wt_r}(\Theta_r)$ and its spatial Jacobian matrix $J^s_{wt_r}(\Theta_r)$ in terms of the right ARM's configuration Θ_r by following its forward kinematics. Interested readers can refer to [22] for more details on twist coordinates and the product of exponentials method.

V. ENHANCED MANIPULATION ASSISTANCE WITH PERMMA

For a manipulation assistance device, its ability to reach a certain configuration is one of the important criteria to evaluate its usability and performance. In order to provide people with disabilities the same capability of manipulation as people with no impairment, the system should be able to complete most essential tasks that are tightly related to the independent living of people with disabilities, which include retrieving objects from the floor, picking up objects from a high shelf, retrieving food from refrigerator, feeding and hygiene, dressing, etc [23, 24]. Parameterized by the width (w), depth (d) and height (h), the desirable workspace for manipulation assistance can be evaluated using these daily living tasks, as shown in Fig. 4. Since the PerMMA combines mobility assistance with manipulation assistance, without loss of generality, we define the local workspace as a relative region around the mobile base and we only analyze PerMMA's reachability in this local workspace without movement of the mobile base. The general reachability of PerMMA can be obtained by expanding this local reachability using movements of the mobile base.

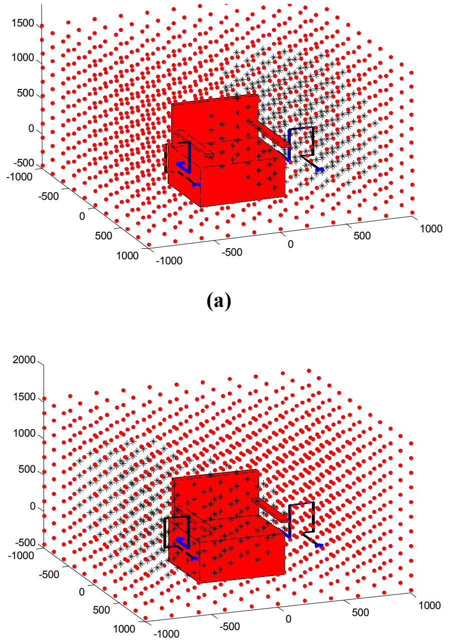
We define the local workspace of PerMMA, denoted by $\mathbf{W}$, as a rectangular cube with w=[-1000, 1000], d=[-1000, 1000] and h=[-450, 1550] (unit: mm), which covers all essential daily living tasks discussed above. Since it is extremely difficult to obtain a closed form of PerMMA's local reachability, we applied a numerical analysis to study its reachability at certain positions within $\mathbf{W}$. With a grid size $200 \times 200 \times 200$ (mm), we discretized the entire $\mathbf{W}$ into grids, as shown in **Fig. 6**. Considering the safety of the user inside the wheelchair, the workspace within a predefined safe region is defined to be unreachable to avoid collisions between the ARMs and the mobile base as well as collisions between the ARMs and the user. Therefore, all the nodes inside the safe region are removed from the workspace and not considered. Outside the safe region, a total of 1280 grid nodes are defined in PerMMA's local workspace, and for any



(a)

(b)

Fig. 5. Reachability with side mounting: (a) Left ARM; (b) Right ARM.



(a)

(b)

Fig.6. Reachability with track and carriage system: (a) Left ARM; (b) Right ARM.

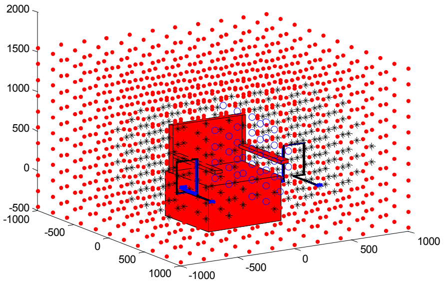


Fig. 7. Bimanual reachability of the PerMMA with side mounting.

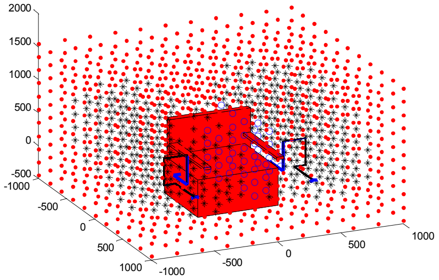


Fig. 8. Bimanual reachability of the PerMMA with track and carriage system

grid node, joint values of both ARMS to reach this grid point are computed with a numerical inverse kinematics algorithm uisng the following procedure: (1) Calculate $d = \|p_d - p_{now}\|$; (2) If $d > d_{tol}$, calculate current Jacobian matrix J; (3) Move the ARM toward p_d with J for δt; (4) repeat step 1. The movement limits of all joints are defined as $\theta_{lt} \in [-150, 150]$, $\theta_{rt} \in [-150, 150]$, $\theta_{lc} \in [0, \pi]$, $\theta_{rc} \in [-\pi, 0]$, $\theta_{l5} \in [-\frac{\pi}{2}, \frac{\pi}{2}]$, $\theta_{r5} \in [-\frac{\pi}{2}, \frac{\pi}{2}]$, and values of all other joints are limited within $[-\pi, \pi]$.

First, we evaluated the enhanced reachability of the PerMMA provided by our track and carriage system. With a classic side mounting method, the reachable configurations in the local workspace of either ARM are shown in Fig. 5. A node that can be reached by an ARM is represented as "*" and an unreachable node is represented as "·". Each ARM is able to reach 161 grid nodes, out of the total 1280 predefined configurations. With our novel track and carriage system, the reachable configurations in the local workspace of each ARM are shown in Fig. 6. Each ARM now is able to reach 243 grid nodes. Therefore, the reachability of the PerMMA is increased by 50.93% with our track and carriage mounting method.

Second, we evaluated the enhance reachability of the PerMMA provided by our novel bimanual design. It is obvious that the PerMMA can reach much more configurations with two ARMs than only using only one. The bimanual reachabilitiy of the PerMMA with the classic side mounting method is shown in Fig. 7. The grid nodes that can be reached by both ARMs is represented as "o". Totally 281 nodes can be reached by either ARM with the bimanual design, which is a 74.5% increase compared to a single arm design. The bimanual reachability of PerMMA with the track and carriage system is shown in Fig. 8. A total of 445 nodes can be reached by either ARM, which is a 58.4% increase over the bimanual design with fixed mounting, an 83.2% increase over the single arm design with the track and carriage mounting, and a 176.4% increase over the single arm design with fixed mounting. Moreover, either with side mounting method or with our new track and carriage system, 41 nodes can be reached by both ARMs with the bimanual design, which are mostly located in front of the user in the wheelchair. This significantly increased the flexibility of PerMMA's manipulation assistance, and allows the users to complete essential tasks that require involvement of both arms. A summary of the comparison is shown in Table 1.

	Single arm with fixed mounting	Single arm with track and carriage	Bimanual with fixed mounting	Bimanua l with track and carriag
Reached nodes	161	243	281	445
Increase	0%	50.93%	74.5%	176.4%
Increase	-	0%	15.6%	83.2%
Increase	-	-	0%	58.4%

Table 1. Summary of reacability with different designs

Another important factor to evaluate the performance of a manipulation assistive system is its manipulability, which represents the ability to change its position or orientation in a defined configuration. A frequently used manipulability measurement is the manipulability ellipsoid, which represents the ability of the robot to transform a unit movement in joint space to a movement in its workspace [25]. The volume of the ellipsoid can be calculated from the Jacobian matrix of the robot as

$$V = \sqrt{\det(JJ^T)}. \tag{2}$$

The manipulability of each Manus ARMs at its reachable configurations in **W** was calculated using the measurement (2). For the left ARM, manipulability measurements for its reachable configurations with classic side mounting method and the proposed track and carriage system are shown in Fig. 9. Manipulability measurements of the right ARM is shown in Fig. 10. Comparing with the rigid side mounting method, the track and carriage system obviously improves the manipulability of both Manus ARM at all reachable configurations. The minimal increase is 53.57% for both

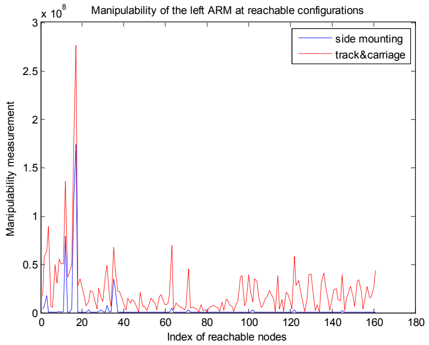


Fig. 9. Manipulability measurement of the left Manus ARM

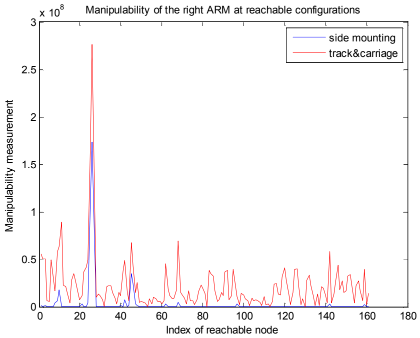


Fig. 10. Manipulability measurement of the right Manus ARM

Arm, and the maximal increase is over 50000 times.

VI. CONCLUSION AND FUTURE WORK

In this paper, we investigated the enhanced manipulation assistance provided by a newly developed personal mobility and manipulation appliance (PerMMA). This bimanual design of PerMMA significantly improved its performance and efficiency of manipulation assistance. Different from all existing systems, we developed a novel mounting system to attach two ARMs on a PerMobil C500 EPW, which not only preserved the relative mobility between the ARMs and the base but also provided two extra DoFs to each ARM. With a workspace characterized by essential daily living tasks, we evaluated PerMMA's reachability and manipulability with a comparative study between PerMMA and classic design used by other existing systems. Simulation results have shown that the bimanual design and the novel track and carriage system greatly improve the reachabilty of the ARM and significantly increase the manipulability of the ARM in the workspace.

In this paper, we did not consider the mobility of the base in our analysis. In future work, we plan to investigate the coordination between mobility and manipulation, and utilize the mobile base and seating functions to further improve the manipulation assistance. Moreover, we will design daily living experiments to evaluate performance of the PerMMA in bimanual manipulation tasks.

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