2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

COMBINED MOBILITY AND MANIPULATION CONTROL OF A NEWLY DEVELOPED 9-DOF WHEELCHAIR-MOUNTED ROBOTIC ARM SYSTEM

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***Abstract* - A wheelchair-mounted robotic arm (WMRA) system was designed and built to meet the needs of mobility-impaired persons with limitations of upper extremities, and to exceed the capabilities of current devices of this type. The control of this 9-DoF system combines the 7-DoF robotic arm control with the 2-DoF power wheelchair control. The 3-degrees of redundancy can be optimized to effectively perform activities of daily living (ADLs) and overcome some workspace limitations. The control system is designed for teleoperated or autonomous coordinated Cartesian control, and it offers expandability for future research, such as voice or sip and puff control operations and sensor assist functions.**

Index Terms – Redundancy, , Robot, WMRA, ADL, Rehab.

I. INTRODUCTION

A wheelchair mounted robotic arm can enhance the manipulation capabilities of disabled individuals, and reduce dependence on human aides. Unfortunately, most WMRAs have had limited commercial success due to poor usability and low payload. It is often difficult or impossible to accomplish many of the Activities of Daily Living (ADL) tasks with the WMRAs currently on the market. This project attempts to surpass available commercial WMRA devices by offering an intelligent system that combines the mobility of the wheelchair and the manipulation of a newly designed arm in an effort to improve performance, usability, control and reduce mental load on the user while maintaining cost competitiveness.

The latest available data from the US Census Bureau Census Brief of 1997 [1] showed that one of every five Americans had difficulty performing functional activities (about 53 million), half of them were considered to have severe disabilities (over 26 million). This work focuses on people who have limited or no upper extremity mobility due to spinal cord injury or dysfunction, or genetic predispositions. Robotic aides used in these applications vary from advanced limb orthosis to robotic arms [2]. Persons that can benefit from these devices are those with severe physical disabilities, which limit their ability to manipulate objects. These devices increase self-sufficiency, and reduce dependence on caregivers.

The two commercially available WMRAs lack the integration of the robotic arm controller with the wheelchair controller, and that leads to an increased mental load on the user. Combining the control of both the wheelchair and the robotic arm would decrease this mental burden and improve the usability of the device.

The main objective of this work is to develop a combined manipulation and mobility control system for a newly designed arm and the wheelchair. Redundancy resolution had to be optimally solved to allow larger wheelchair or manipulator motion depending on the proximity to the goal. The controller should be capable of moving autonomously or using teleoperation.

II. BACKGROUND

There are several designs of workstation-based robotic arm systems, but WMRAs combine the idea of workstation and mobile-base robots to mount a manipulator arm onto a power wheelchair. The most important design consideration of where to mount a robotic arm in a power wheelchair is the safety of the operator [3]. There have been several attempts in the past to create commercially viable wheelchair mounted robotic arms, including the two currently available commercial WMRAs: Manus and Raptor.

The Manus manipulator, manufactured by Exact Dynamics, available since the early 1990s [4], can be programmed in a manner comparable to industrial robotic manipulators. A picture of Manus mounted onto a Permobil Max90 wheelchair is shown in Fig 1. It is a 6 DoF arm, with servomotors all housed in a cylindrical base. Besides the fact that it is controlled independent of the wheelchair control, the current controller allows for Cartesian control, but when it comes close to a singularity, it stops and waits for the user to move it in a different direction. This kind of control increases the cognitive load on the user.

Another production WMRA is the Raptor, manufactured by Applied Resources [5], as shown in Fig 2, which mounts to the right side of the wheelchair. This manipulator has four degrees of freedom plus a planar gripper. The user directly controls the arm with either a joystick or a keypad controller. Because the Raptor does not have encoders, the manipulator cannot be controlled in Cartesian coordinates. This compromise was done to minimize the overall system cost.

Weighted least norm solution method was used by Chan et al [6] to penalize the motion of some joints over others. This method can be used in the case of WMRAs to make the wheelchair motion as a secondary motion when needed. The combination of mobility and manipulation in a robotic arm has been studied by researchers in the form of a mobile platform that carries a robotic arm. Chung, et al [7] resolved the kinematic redundancy by decomposing the mobile manipulator into two different subsystems, the mobile platform and the manipulator. Each one of these subsystems is controlled independently with an interaction algorithm between the two controllers.

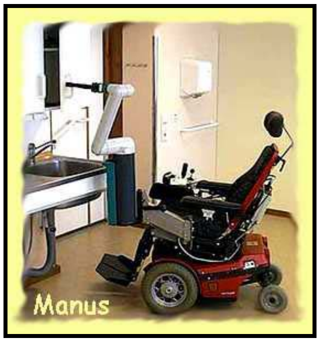


Fig. 1: Manus Arm

Fig. 2: Raptor Arm

Mirosaw [8] used external penalty functions to enforce the holonomic manipulability and collision avoidance. His results showed continuous velocities near obstacles. An extension to different redundancy resolution schemes has been proposed by Luca [9] to include the representation of mobile platforms in the jacobian. His simulation showed consistent results in simulation.

III. MOTION CONTROL OF THE 9-DOF WMRA SYSTEM

A. Wheelchair Motion

The differential drive used in power wheelchairs represents a 2-DoF system that moves in plane [10]. Assuming that the manipulator is mounted on the wheelchair with L2 and L3 offset distances from the center of the differential drive across the x and y coordinates respectively, the mapping of the wheels' velocities to the manipulator base velocities along its coordinates is defined by:

$$\dot{q}_c = J_c \cdot J_W \cdot V_c \tag{1}$$

Where:

$$\dot{q}_c = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} & \dot{\alpha} & \dot{\beta} & \dot{\phi} \end{bmatrix}^T \ , \quad V_c = \begin{bmatrix} \dot{\theta}_l \\ \dot{\theta}_r \end{bmatrix} \ ,$$

$$J_c = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \text{ and}$$

$$J_W = \frac{l_5}{2} \begin{bmatrix} c\phi_c + \frac{2}{l_1}(l_2 s\phi_c + l_3 c\phi_c) & c\phi_c - \frac{2}{l_1}(l_2 s\phi_c + l_3 c\phi_c) \\ s\phi_c - \frac{2}{l_1}(l_2 c\phi_c - l_3 s\phi_c) & s\phi_c + \frac{2}{l_1}(l_2 c\phi_c - l_3 s\phi_c) \\ \frac{-2}{l_1} & \frac{2}{l_1} \end{bmatrix}$$

The above Jacobian will be used to control the wheelchair with the jacobian of the arm after combining them together.

B. The 7-DoF Arm Motion

From the DH parameters specified earlier publications [11], the 6x7 Jacobian that relates the joint rates to the Cartesian speeds of the end effector based on the base frame is generated according to Craig's notation [12]:

$$\dot{r} = J_A \cdot V_A \tag{2}$$

where: $\dot{r} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} & \dot{\alpha} & \dot{\beta} & \dot{\gamma} \end{bmatrix}^T$ is the task vector, and $V_A = \begin{bmatrix} \dot{\theta}_1 & \dot{\theta}_2 & \dot{\theta}_3 & \dot{\theta}_4 & \dot{\theta}_5 & \dot{\theta}_6 & \dot{\theta}_7 \end{bmatrix}^T$ is the joint velocities vector.

Numerical solutions are implemented using the Jacobian to follow the user directional motion commands or to follow the desired trajectory. Manipulability measure [13] is used as a factor to measure how far is the current configuration from singularity. This measure is defined as:

$$w = \sqrt{\det(\underline{J_A} * \underline{J_A^T})} \tag{3}$$

Redundancy is resolved in the program structure using Pseudo Inverse of the Jacobian [13], and singularity is avoided by maximizing the manipulability measure. Since this method carries a guaranteed valid solution only at a singular configuration and not around it, the results carried high joint velocities when singularity is approached. We then decided to use S-R Inverse of the Jacobian [14] to give a better approximation around singularities, and use the optimization for different subtasks. S-R Inverse of the Jacobian is used to carry out the inverse kinematics:

$$\underline{J_A^*} = \underline{J_A^T} * (\underline{J_A} * \underline{J_A^T} + k * \underline{I_6})^{-1} \tag{4}$$

where I_6 is a 6x6 identity matrix, and k is a scale factor. It has been known that this method reduces the joint velocities near singularities, but compromises the accuracy of the solution by increasing the joint velocities error. Choosing the scale factor k is critical, if it is too high, the error will be too high and the system might destabilize, and if it is too small, the joint rates will go too high, and the system might destabilize. Since the point in using this factor is to give approximate solution near and at singularities, an adaptive scale factor is updated at every time step to put the proper factor as needed:

$$k = \begin{cases} k_0 * (1 - \frac{w}{w_0})^2 & \text{for} \quad w < w_0 \\ 0 & \text{for} \quad w \geq w_0 \end{cases} , \tag{5}$$

where w_0 is the manipulability measure at the start of the boundary chosen when singularity is approached, and k_0 is the scale factor at singularity. It was found that the optimum values are (w_0=0.02) and (k_0=0.35x10^{-3}) for our system.

Since singularity is taken care of, now we can use the joint redundancy to optimize for a secondary task as follows:

$$\underline{V_d} = \underline{J_A^*} * \underline{\dot{r}_d} + (\underline{I_7} - \underline{J_A^*} * \underline{J_A}) * \underline{f} \tag{6}$$

where f is a 7x1 vector representing the secondary task. That task can either be the desired trajectory in the case of pre-set task execution, or it can be a criterion function that represents the potential energy to be minimized.

C. The 9-DoF WMRA System Motion

Combining the two subsystems together by means of jacobian augmentation [9] can give the flexibility of using conventional control and optimization methods without compromising the total system coordinated control. In the case of combined control, let the task vector be:

$$r = f(q_c, q_A) \tag{7}$$

Differentiating (7) with respect to time gives:

$$\dot{r} = \frac{\partial f}{\partial q_c} V_c + \frac{\partial f}{\partial q_A} V_A \; = J_c J_W V_c + J_A V_A$$

$$= \begin{bmatrix} J_c J_W & J_A \end{bmatrix} \begin{bmatrix} V_c \\ V_A \end{bmatrix} \quad \text{or, } \dot{r} = J \cdot V \tag{8}$$

Solving (8) in conventional methods is now possible. Choosing the Projected Gradient method, which proved effective, gives:

$$\begin{bmatrix} V_W \\ V_A \end{bmatrix} = J^* \dot{r} + \left(I - J^* J\right) V_0 \tag{9}$$

Where $V_0 = a \nabla_q H(q)$ for conventional arms, and H(q) is the optimization criteria y=H(q).

The existence of the mobile platform means that V_o may not exist for non holonomic constraint such as that of the wheelchair. To go around this limitation [9] proposed the following: Differentiate the optimization criteria function "H" with respect to time as follows:

$$\dot{y} = \dot{H}(q) = \frac{\partial H}{\partial q_c} V_c + \frac{\partial H}{\partial q_A} V_A$$

$$= \nabla_q^T H \begin{bmatrix} J_W & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} V_c \\ V_A \end{bmatrix} \tag{10}$$

In this case, the value of V_H that improves the objective function is:

$$V_H = \pm a \begin{bmatrix} J_W^T & 0 \\ 0 & I \end{bmatrix} \nabla_q H(q) \equiv V_0 \tag{11}$$

and that velocity vector can be used for optimization. This gives a good representation of the arm joints' velocities and the wheels' velocities of the wheelchair.

Weighted Least Norm solution can also be used as proposed by [6]. In order to put a motion preference of one joint rather than the other (such as the wheelchair wheels and the arm joints), a weighted norm of the joint velocity vector can be defined as:

$$|V|_W = \sqrt{V^T W V} \tag{12}$$

where W is a 9X9 symmetric and positive definite weighting matrix, and for simplicity, it can be a diagonal matrix that represent the motion preference of each joint of the system. For the purpose of analysis, the following transformations are introduced:

$$J_W = J\, W^{-1/2} \text{ and } V_W = W^{-1/2}\, V \tag{13}$$

From (12) and (13), it can be shown that the weighted least norm solution is:

$$V_W = W^{-1} J^T \left(J\, W^{-1} J^T\right)^{-1} \dot{r} \tag{14}$$

The above method has been used in simulation of the 9-DoF WMRA system, and the results will be shown later in this paper.

IV. Design of the New Arm

A. Hardware Design of the Arm

An entirely new WMRA was developed, designed and built [11]. The goal was to produce an arm that has better manipulability, greater payload, and easier control than current designs. As found in previous research [15], side mounting is preferable overall because it provides the best balance between manipulability and unobtrusiveness.

This manipulator is intended for use in Activities of Daily Living (ADL), and for job tasks of a typical office environment. As such, it is important that the arm be strong enough to move objects that are common in these environments. Approximately 4 kg mass is set as the upper limit for a typical around-the-house object that must be manipulated. This was set as the baseline payload for the arm at full horizontal reach at rest. Then, an extra margin of 2 kg was added to allow for a choice of end-effector capable of this load.

The arm is a 7-DoF design, using 7 revolute joints. It is anthropomorphic, with joints 1, 2 and 3 acting as a shoulder, joint 4 as an elbow, and joints 5, 6 and 7 as a wrist as shown in Fig 3. Throughout the arm, adjacent joint axes are oriented at 90 degrees as shown in Fig 4. This helps to meet two goals: mechanical design simplicity and kinematic simplicity with low computational cost. All adjacent joint axes intersect, also simplifying the kinematics. The basic arrangement for each joint is a high-reduction gearhead, a motor with encoder and spur-gear reduction, and a bracket that holds these two parts and attaches to the two neighbouring links.

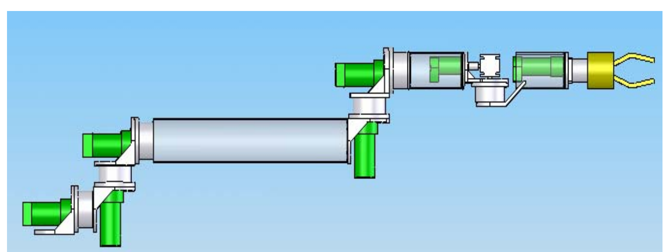


Fig. 3: Complete SolidWorks Model of the Arm

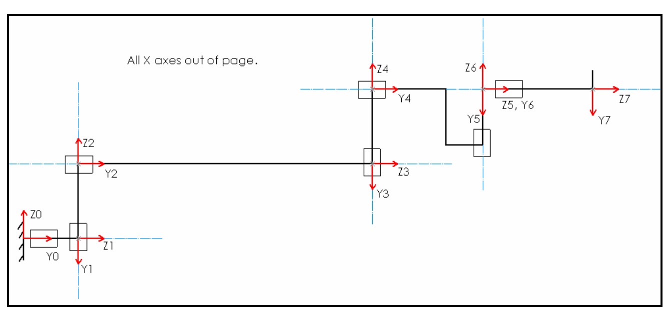


Fig. 4: Kinematic Diagram, with Link Frame Assignments

B. Hardware Design of the Controller

As shown in Fig 5, PIC-SERVO SC controllers (C1 through C7) that support the DC servo actuators (J1 through J7) were chosen. This unit has a microprocessor that drives the built-in amplifier with a PWM signal, handles PID position and velocity control, communicates with RS-485, and can be daisy-chained with up to 32 units. It also reads encoders, limit switches, an 8 bit analog input, and supports coordinated motion control. Data for the entire arm is interfaced to the main computer using a single serial link. The PIC-Servo SC controllers use RS-485, and a hardware converter interfaces this with the RS-232 or a USB port on the host PC. A timer has been utilized to cut the arm's power off after a preset time to minimize power consumption while not in use. An emergency stop button is placed to cut the power off the motors and leave the logic power on so that the system can be diagnosed without rebooting.

The current host PC is an IBM laptop, running Windows XP. However, the communications protocol is simple and open, and could be adapted to virtually any hardware/software platform with an RS-232 or USB port. Currently, the tested user interfaces are the keyboard and a SpaceBall controller.

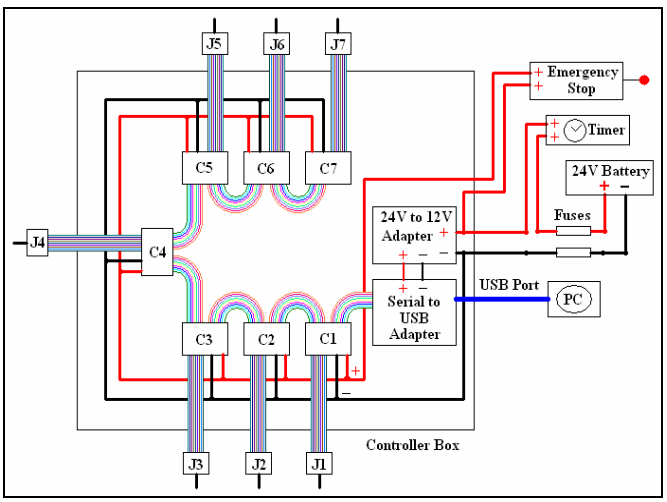


Fig. 5: Control System Circuitry

C. Control Modes

Different pre-set ADL tasks were chosen to be programmed into the control system. These tasks range from reaching/ carrying/ placing objects to turning on/off switches.

The control of the new WMRA is designed to satisfy two main modes. The first mode is the scaled teleportation mode; this mode is for the user to control the arm in real time using a joystick or a keyboard. The second mode is the autonomous mode, where a goal is specified and a trajectory needs to be generated and followed. This mode is used for pre-specified tasks to be executed when the user needs these tasks.

Sensory suite including a camera, a laser range finder, and proximity sensors will be added at the end effector and around the wheelchair to allow autonomous and semi autonomous control of the system. Scaled teleoperation control system is implemented to filter out the involuntary user input or signal noise and to scale up the intended user input for the required task. With the integration of the scaling and the sensory input in the control structure, the system can be very effective in avoiding unintentional motion of the wheelchair-robot system due to user errors. It can also lead to a better user safety measures that are important for users with disabilities.

D. The Wheelchair

A proper wheelchair "Action Ranger X Storm Series" has been chosen to mount the robotic arm on. The wheelchair has been modified by adding an incremental encoder on each one of the wheels. The controller module of the wheelchair has also been modified using TTL compatible signal conditioner and a DA converter so that the signal going to the wheels can be controlled using the same PIC-Servo SC controllers used in the arm. Figure 6 shows the WMRA system installed.

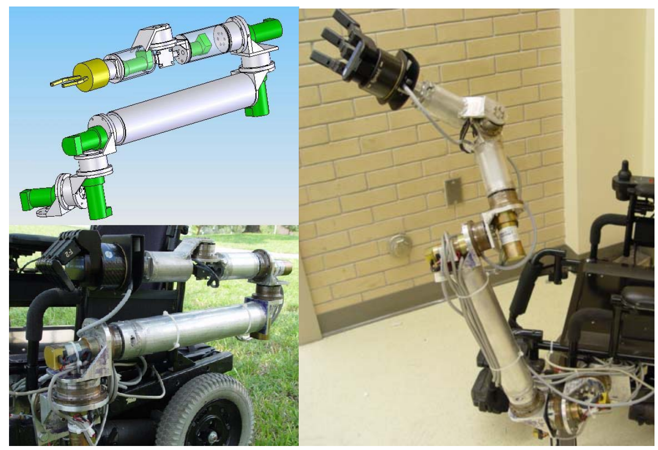


Fig.6: WMRA SolidWorks Models and the Built Device

V. SIMULATION RESULTS

The control system of the 9-DoF WMRA system is implemented in simulation using Matlab 7.0.4 installed on a PC running Windows XP. Figures 7 and 8 show the initial pose of the arm and the initial position and orientation of the end-effector.

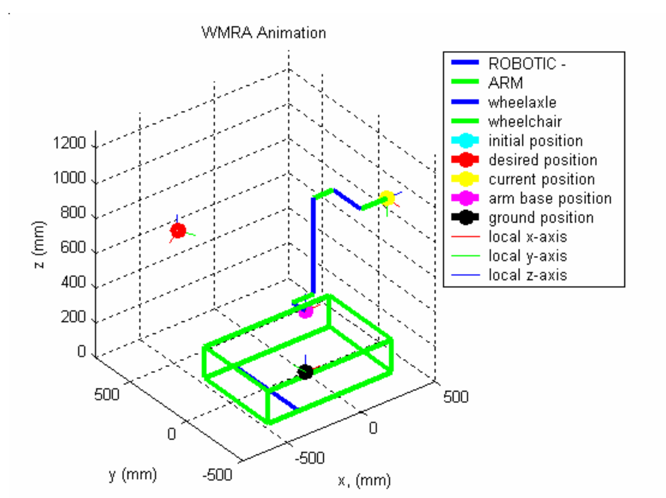
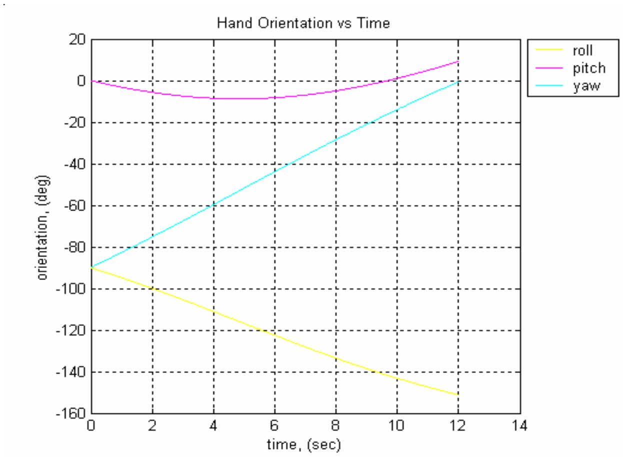


Fig.7: WMRA in the Initial Position



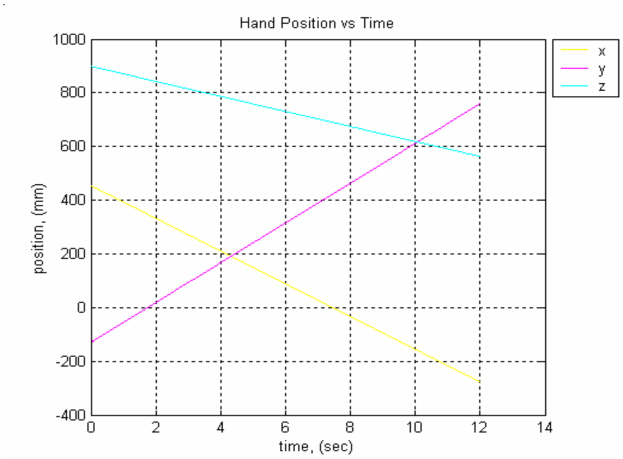


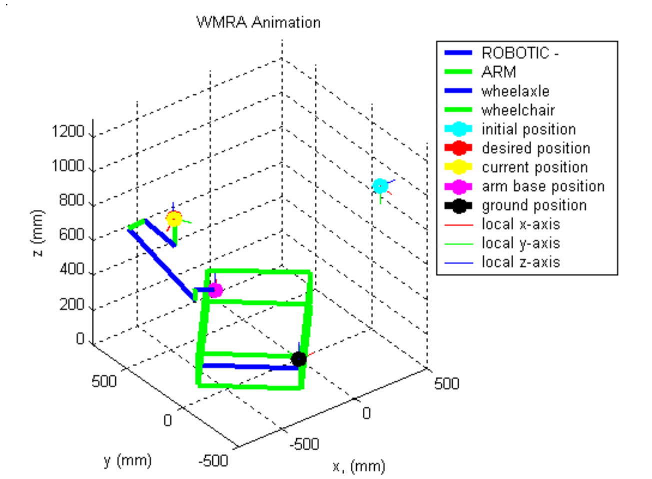
Fig.8: Initial Position and Orientation of the WMRA's End Effector

Several methods are being tested in this simulation. In this paper, we will limit our findings to the Weighted Least Norm solution control. The weight matrix of the first run carried in its diagonal elements "10" for each of the seven joints of the arm, and "1" for each of the two wheels of the wheelchair. This means that the wheels will be 10 times more likely to move than the arm joints will. In the second run, the weigh matrix carried in its diagonal elements "1" for each of the seven joints of the arm, and "10" for each of the two wheels of the wheelchair. This means that the arm joints will be 10 times more likely to move than the wheels will. The WMRA system is shown after reaching its destination in simulation with both w = $[10\ \ 10\ \ 10\ \ 10\ \ 10\ \ 10\ \ 10\ \ 1\ \ 1]^T$ at the top, and w = $[1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 10\ \ 10]^T$ at the bottom of figure 9. It can be clearly seen that the wheelchair in the first case (top) has moved more than it moved in the second case (bottom) because of the imposed weight matrix on the solution.

Another comparison can be seen in figure 10 showing the distances travelled by the two wheels of the wheelchair in both cases. Figure 10 (top) shows a distance of about 300 mm travelled by each of the wheels, while figure 10 (bottom) shows the same wheels reluctantly travelling a distance of about 60 mm. Other noteworthy results are shown in figure 11 that shows the angles travelled by each one of the 7-DoF arm joints in both cases. Figure 11 (top) shows how the joints started with minimal motion, while the case in figure 11 (bottom) shows these joints started moving rapidly from the beginning of the simulation, indicating the motion priorities imposed by the weight matrix, which is what is expected.

VI. Conclusions and Recommendations

A wheelchair-mounted robotic arm (WMRA) was designed and built to meet the needs of mobility-impaired persons, and to exceed the capabilities of current devices of this type. Combining the wheelchair control and the arm control with the augmentation of the jacobian to include representations of both jacobians resulted in a control system that simultaneously controls both devices at once. The mechanical design incorporates DC servo drive with actuators at each joint, allowing reconfigurable link lengths and thus greater adaptability to a range of workspaces.



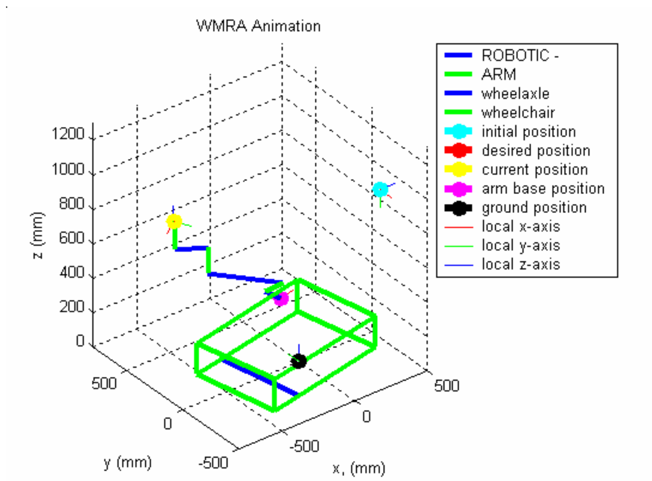


Fig.9: WMRA after Reaching its Destination Using Two Wight Cases

Seven principal degrees of freedom allow full pose control, even while operating in the constricted workspace afforded by a side mount on a power wheelchair. The control system is designed for coordinated Cartesian control with singularity robustness and task-optimized combined mobility and manipulation. A custom designed gripper will be designed based on the ADL uses to be performed.

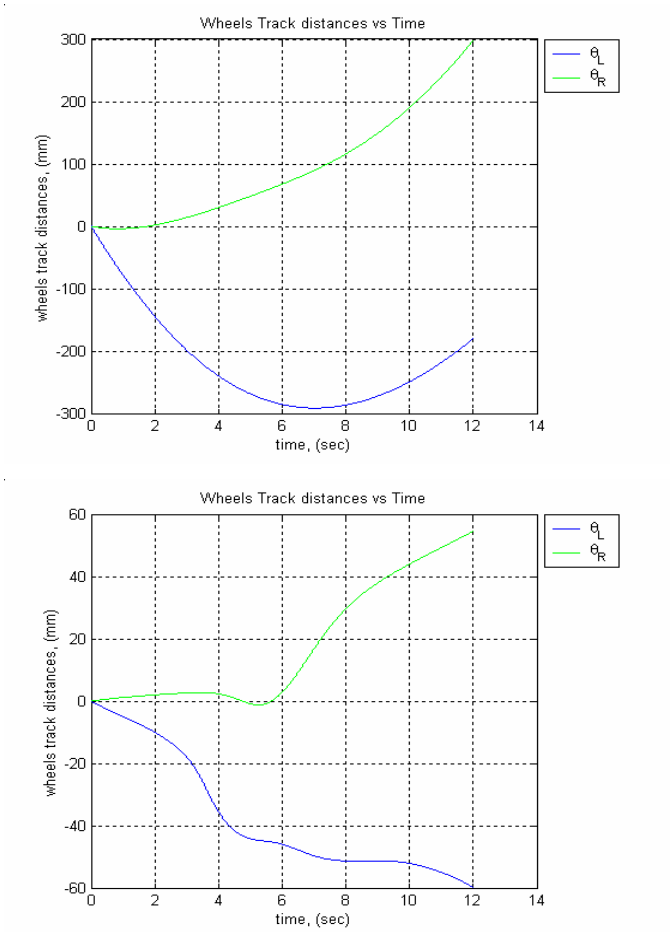


Fig.10: Wheels' Travelled Distances with Two Weight Cases.

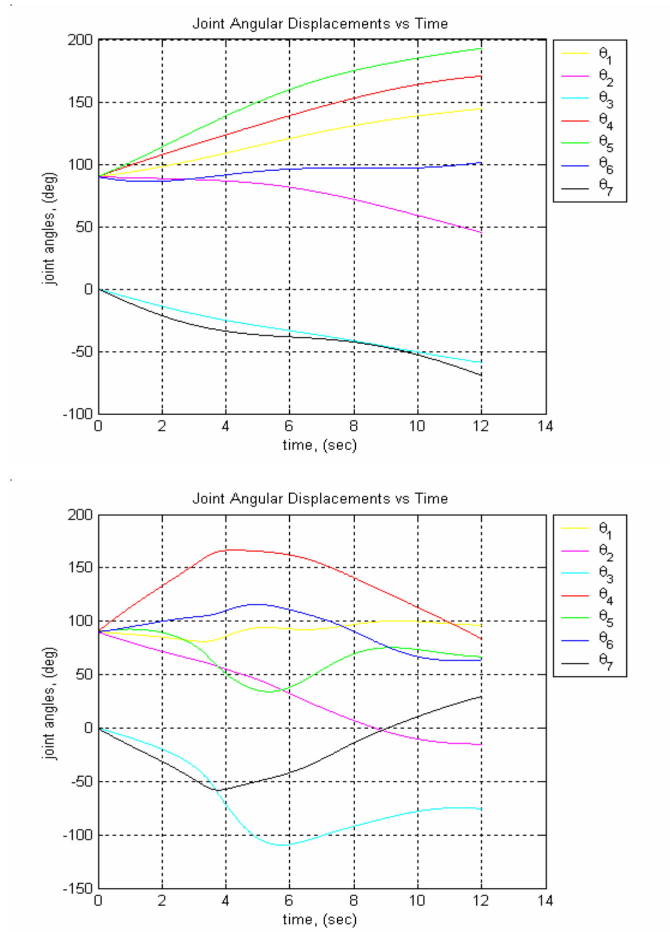


Fig.11: Joint Angles Travelled by Each of the Robotic Arm Joints.

Besides the joystick, the keypad, multiple input devices will be programmed to control the system, including head switches, foot switches, hand tracking devices and haptic devices. Testing the new system with human subjects with disabilities will be conducted after making the proper safety measures and under the supervision of the VA and Shriners Children hospital. More future developments include the use of remote controlled devices with an LCD screen to control the wheelchair-arm system from a remote location. This enables the user with disabilities to perform different tasks without the need to be on the wheelchair.

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