

Analysis, Evaluation and Development of Wheelchair-Mounted Robotic Arms

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Abstract - This paper focuses on kinematic analysis and evaluation of wheelchair mounted robotic arms (WMRA) [3]. It addresses the kinematics of the WMRA with respect to its ability to reach common positions while performing activities of daily living (ADL). A procedure is developed for the kinematic analysis and evaluation of a WMRA. In an effort to evaluate two commercial WMRAs, the procedure for kinematic analysis is applied to each manipulator. Design recommendations and insights with regard to each device are obtained and used to design a new WMRA to overcome the limitations of these devices. This method will benefit the researchers by providing a standardized procedure for kinematic analysis of WMRAs that is capable of evaluating independent designs.

I. INTRODUCTION

A wheelchair mounted robotic arm can enhance the manipulation functions of people with disabilities. To better understand the effectiveness of a robotic arm, it must be analyzed with respect to its kinematics and the workspace in which it operates. Data from the US Census Bureau Statistical Brief of 1993 showed that over 34 million Americans had difficulty performing functional activities [1]. The primary focus of Rehabilitation Engineering [2] and robotics is to increase the quality of life of individuals through increasing functional independence and decreasing the costs associated with the assistance required by the individual. In the case of spinal injury or dysfunction, robotic arm aids are most appropriate for individuals with spinal deficiencies ranging from cervical spine vertebrae-3 through cervical spine vertebrae-5 [3]. Individuals that require mobility assist devices such as a power wheelchair can benefit from various robotic devices because the power wheelchair provides a platform with which to mount the device as well as a power supply, using the wheelchair's batteries.

WMRA combines the idea of a workstation and a mobile-base robot 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 [9]. WMRA can be mounted in the front, side or rear of the wheelchair [10]. There have been several attempts in the past to create commercially viable wheelchair mounted robotic arms, including the two commercial WMRAs available, the Manus and the Raptor.

The Manus utilizes a front mounting location to the left of the operator's left knee, which makes the manipulator arm obtrusive [11]. The Manus manipulator is controlled by a joystick and a keypad. The joystick is used to manually

operate the manipulator, and the 16- button keypad can be used to perform coordinated control of multiple joints with preprogrammed gestures that can be taught to the Manus and stored for future use. A closed loop system is used to allow further integration of the arm into more complicated and intelligent systems that can assist the operator.

Another production of WMRA is the Raptor, which mounts to the right side of the wheelchair. This increases the width of the power wheelchair and makes it more difficult for the operator to maneuver through doorways and tight hallways [7]. This manipulator has four degrees of freedom and a planar end effector. The arm is directly controlled by the user by either a joystick or 10-button controller. Because the Raptor does not have encoders to provide feedback to the controller, the manipulator cannot be pre-programmed in the fashion of industrial robots. An open loop controller places a human directly in the loop of controlling the arm. The operator continuously directs the arm one joint at a time into its final position, which requires higher levels of concentration and eye-hand coordination from the operator.

The focus of this paper is to analyze and evaluate WMRAs and develop an analytical procedure to systematically study the effectiveness of WMRAs. Kinematic analysis background for WMRAs is presented in Section II. Section III provides evaluation procedure using Solid Works model. Section IV provides the evaluation results for "Manus" and "Raptor" arms. Section V discusses the development of a new WMRA based on the findings to overcome some of the limitations found in the two evaluated WMRAs. Conclusions and recommendations are given in section VI.

II. KINEMATIC ANALYSIS

A workspace has been chosen which reflects specific requirements of individuals with disabilities [12]. Horizontal planes (x-y) were chosen with respect to the floor defined as the vertical axis $z = -31.8''$. The origin of the user-coordinate system is $31.8''$ above the floor and all values given are referenced above the floor. A value of $2''$ above a given plane was required in order to give room for the manipulator to reach an object. The value in parenthesis is the z-axis height with respect to the user coordinate system as seen in Fig. 1, and they are as follows: Small objects on the floor: $2'' (-29.8'')$, Larger light objects on the floor: $9'' (-22.8'')$, Height of electric socket: $18'' (-13.8'')$, Low coffee table: $26'' (-5.82'')$, Height of standard table and door knob: $31'' (-0.8'')$, Kitchen counter top: $38'' (6.18'')$, Wall-mounted light

switch: 50" (18.2"), Low shelf above kitchen counter top 56" (24.18"). The distances in the x-axis of the user coordinate system can be seen in Fig. 1.

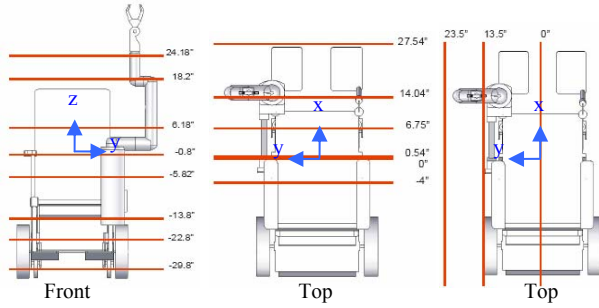


Fig. 1: Workspace: Horizontal and vertical planes.

Starting from the farthest point and working toward the operator is described as follows: 2" in front of the footrest of the power wheelchair 27.54" (This is the primary reference y-z plane), 14.04" in front of the operator (This is 13.5" behind the first y-z plane), 6.75" in front of the operator (This is half the distance of the 13.5" grid), 0.54" is front of the operator (This is 13.5" behind the second y-z plane), the y-z plane at the origin of the user reference plane, The y-z plane that reflects the mouth of the operator (4" behind the origin).

To create the individual points, a third plane (x-z) is defined. The plane located at the origin separates the chair into two lateral halves and is shown in Fig. 1. The wheelchair used for the analysis is 27" wide including the width of the drive wheels. The y axis in the user frame of reference is positive moving from the body to the right hand extended out along the arm, these planes are: The plane intersecting the origin, 13.5" from the origin toward the mounted arm, 23.5" from the origin toward the mounted arm (10" from the outermost edge of the wheels).

A concept known as the manipulability ellipsoid is introduced as well as the volume of the ellipsoid as the manipulability measure [14]. Manipulability is defined as the determinant of the Jacobian matrix (J) of the positional sub-matrix of the final transformation matrix of the manipulators arm reference frame. Both manipulators being studied have three degrees of freedom. The relation between the velocity vector v and the joint velocity is:

$$v = J(q)\dot{q} \quad (1)$$

Considering the set of all possible joint velocities and the resultant end effector velocities, the volume of the manipulability ellipsoid is:

$$\|\dot{q}\| = \sqrt{(\dot{q}_1^2 + \dot{q}_2^2 + \dot{q}_3^2)} \quad (2)$$

Which must be less than or equal to unity [14]. In the case being analyzed the manipulability ellipsoid will have three axes as shown in Fig. 2. In the special case where all the ellipsoid axes are equal, the ellipsoid will actually be spherical, where the end effector can move in any direction with the same maximum velocity. The larger the size of the ellipsoid the faster the end effector can move. One possible method of analysis is to determine the volume of the ellipsoid. This is defined as follows:

$$C_m = \begin{cases} 2\pi^{m/2}/[2 \cdot 4 \cdot 6 \cdots (m-2) \cdot m] & \text{if } m \text{ is odd} \\ 2(2\pi)^{(m-1)/2}/[2 \cdot 3 \cdot 5 \cdots (m-2) \cdot m] & \text{if } m \text{ is even} \end{cases} \quad (3)$$

$$W = \sigma_1 \sigma_2 \sigma_3 \quad (4)$$

The value of C_m is constant when m is fixed, which is the case when $m = 3$. In this case, we can see that the volume of the ellipsoid

is proportional to the value of w . We refer to w as the manipulability measure, which has specific properties that allow us to define it readily from the Jacobian and known joint angles. The manipulability measure shown is defined as:

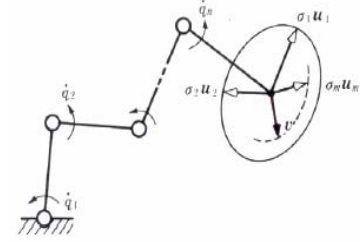


Fig. 2: Manipulability ellipsoid.

$$W = \sqrt{\det J(q)J^T(q)} \quad (5)$$

For our specific case, the manipulator is non-redundant, and the previous equation reduces to:

$$W = |\det J(q)| \quad (6)$$

This shows that at a singular configuration, the value of w approaches zero. The manipulability measure, which is the volume of the manipulability ellipsoid, is the determinant of the Jacobian.

III. EVALUATION PROCEDURE

Solid Works is used to determine the joint angles of each robot arm in order to find the manipulability measure and to verify it within the solid model. The Jacobian matrix is derived from the D-H parameters using the appropriate formulae [13].

The inverse kinematics of the robotic arms was determined with a program in MatLAB to determine the joint angles of the robotic arm for a given point in 3-D space. In order to create a procedure for the kinematic analysis of WMRA it is necessary to separate the process into a series of steps as follows: After creating a D-H parameter table and transformation matrices for the manipulator to be measured, link transformations for the manipulator are calculated, and hence, the Jacobian matrix is developed. Then, the manipulator and a generic power wheelchair were modeled in Solid Works so that angle and joint relationships can be shown graphically. A series of points (grids) surrounding the wheelchair / arm assembly are specified according to specific applications in rehabilitation engineering. A computer program is created using numerical methods approach to determine the joint angles of the arm for a given point in the workspace. The joint angles are then used to determine the manipulability of the arm for the given point.

Fig. 3 shows the frames of reference for the power wheelchair, Manus and Raptor respectively. The D-H parameters for Manus and Raptor with 3 DOF are outlined in Tables I and II respectively. From these parameters, each respective frame transformation is calculated, and hence the

final transformation relating the end effector position with respect to the user frame is obtained.

With the Raptor manipulator mounted securely, a significant amount (1" - 2") of play could be felt at the end effector. Values for the manipulability measure are plotted in

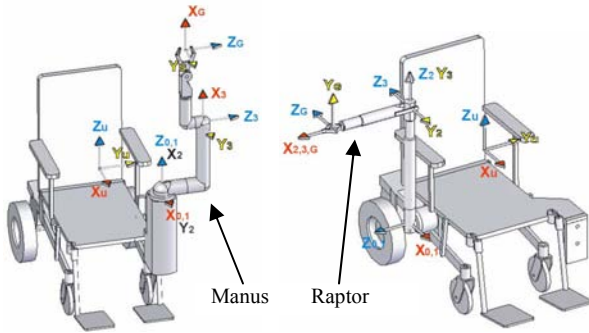


Fig. 3: Reference Frames

both horizontal and vertical planes. The grid density in the analyzed workspace is greater along the z axis, which gives a greater number of points with which to observe trends and changes of the manipulability measure. In order for a point in the workspace to be defined as accessible, it must have a manipulability measure of at least 100 [14]. The maximum value of the manipulability measure in the data set was 7084.4 at point [-4, -6.75, 13.5]. A method for representing the relative value of the normalized manipulability measure (nmm) and a qualitative determination are shown in Fig. 4.

TABLE I
MANUS D-H PARAMETERS.

| i | α_{i-1} | a_{i-1} | d_i | θ_i |
|---|----------------|-----------|-------|-----------------|
| 1 | 0 | 0 | 0 | θ_1 |
| 2 | -90 | 0 | 0 | (θ_2-90) |
| 3 | 0 | 15.75 | 9.20 | θ_3 |
| 4 | 0 | 18.77 | -3.94 | 0 |

TABLE II
RAPTOR D-H PARAMETERS.

| i | α_{i-1} | a_{i-1} | d_i | θ_i |
|---|----------------|-----------|-------|------------|
| 1 | 0 | 0 | 5 | θ_1 |
| 2 | 90 | 0 | 27 | θ_2 |
| 3 | -90 | 0 | 0 | θ_3 |
| 4 | 0 | 15.75 | 0 | 0 |



Fig. 4: Manipulability measure.

IV. EVALUATION RESULTS

Fig. 5 shows a sample of the normalized manipulability measures (nmm) of the Manus within the defined workspace. The maximum manipulability measure for the Manus manipulator was found at [-4, -6.75, 13.5] in Fig. 5a. Approaching the analysis from horizontal slices better fits the requirements for designing a manipulator as an assistive device. Most objects rest on horizontal surfaces that have standard heights above ground level. It is interesting to note that regions where the arm traditionally has lower manipulability measures are the areas that have the highest measures at $z = -29.8''$.

Fig. 6 shows the normalized manipulability measures (nmm) for the Raptor arm as mounted on the Arrow Storm Series power wheelchair. The Raptor has its highest manipulability measure at the point [0, -13.5, 16.5], which is shown in Fig. 6a.

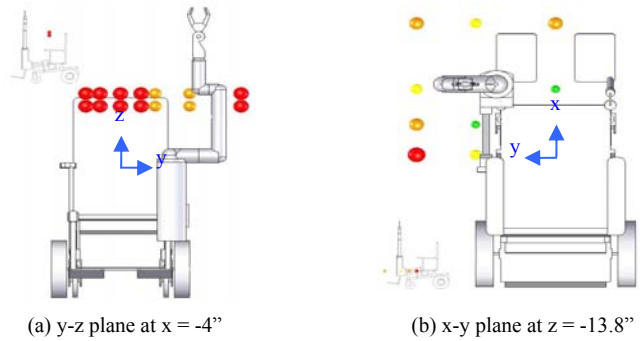


Fig. 5: Manipulability measure sample for MANUS.

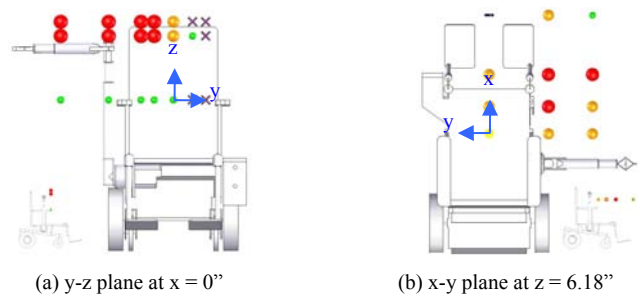


Fig. 6: Manipulability measure sample for RAPTOR.

The Raptor has its highest manipulability measure at the point [0, -13.5, 16.5], which is shown in Fig. 6e.

A summary of effectiveness in reaching areas common to activities of daily living (ADL) is shown in Table III for both Manus and Raptor. The qualitative assessment is based on the average of the normalized manipulability measure of all possible wheelchair orientations possible to accomplish the task. Six possible qualitative assessments could be given for each task.

TABLE III
COMPARISON BETWEEN MANUS AND RAPTOR EFFECTIVENESS.

| Category | Manus | | Raptor | |
|--------------------|-------|-----------|--------|--------------|
| | nmm* | Rating | nmm* | Rating |
| Pick-up off ground | 0.33 | Limited | 0.57 | Good |
| Coffee table | 0.57 | Good | 0.55 | Good |
| Door knob | 0.53 | Good | 0.59 | Good |
| Kitchen countertop | 0.54 | Good | 0.54 | Good |
| Light switch | 0.65 | Very Good | 0.35 | Limited |
| Low kitchen shelf | 0.64 | Very Good | 0.05 | Very Limited |
| Reach into lap | 0.57 | Good | 0.31 | Limited |
| Access to mouth | 0.81 | Excellent | 0.55 | Good |

*nmm is the normalized manipulability measure.

V. DEVELOPING A NEW WMRA

We are currently designing and constructing an entirely new WMRA at the University of South Florida (USF). Our

goal is to produce an arm that has a better manipulability, greater payload, and easier control than current designs. Reconfigurability of the arm will increase the number of applications. Of course, cost and ease of manufacture have been considered from the beginning, and the new arm has to exceed the performance of current WMRA's without increasing cost. Cost has not been the major hurdle to widespread adoption of these devices, but rather poor utility and difficulty of use.

Extra degrees of freedom are a sure way to improve manipulability. This is evidenced by the considerable increase going from Raptor's 4 DOF to the 6 DOF of MANUS. Our new design incorporates 7 joints, and once finished we will determine if this extra expense is justified.

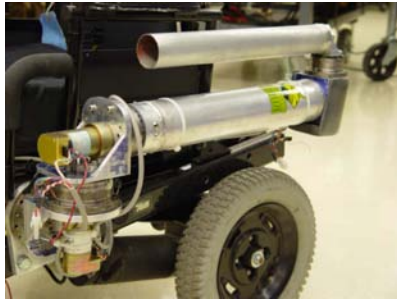


Fig. 7: New WMRA under construction

Reconfigurable arm lengths allow greater leverage on the engineering input. This is only practical with electric direct drive. The MANUS, for example, houses all drive motors in the base and uses a complex drivetrain to drive the joints and gripper. Reconfiguration in this context means a complete redesign. The new design requires only a few hundred dollars in parts and an hour of a technician's time.

Side mounting is preferable overall. However, care must be taken to prevent widening of the power chair. The new arm is mounted as far forward and upward as possible while still in a side mount configuration, and does not significantly increase chair width. This allows the arm to be parked by folding it back, then wrapping the forearm behind the seat. It virtually disappears when not in use, especially when the arm is painted to match the chair. The arm must be slightly longer than with a forward mount, requiring greater shoulder joint torque and heavier gearboxes. This is compensated by the inherent efficiency of harmonic gearheads used in our direct drive, allowing greater payload at less weight than the MANUS.

Cartesian control is necessary. Raptor lacks encoders and therefore control is just bang-bang with a human doing all the work. Quadrature encoders are a cost-effective way to provide closed-loop control. The controllers of the new WMRA have PWM voltage regulation, and have built-in support for acceleration limits. They communicate with the host PC over a RS-485 serial link, which is daisy-chain connected to each one. This allows easy scalability for grippers or even control of the base wheelchair, all through one standard control system.

VI. CONCLUSIONS AND RECOMMENDATIONS

Two commercial WMRA's were evaluated for performing activities of daily living (ADL). The kinematic analysis procedure developed in this paper will be useful for designing and evaluating new WMRA's. It will also help in developing customized designs for individuals with disabilities.

A 4 DOF arm, such as the Raptor, represents the bare minimum to be useable at all. The first three joints provide position control, leaving only one joint to control orientation. This wrist joint must rotate in the main axis of the forearm, which is detrimental to manipulability, especially when the forearm is not level (such as when reaching to a low kitchen shelf). Testers in our labs have found it extremely difficult to avoid spilling a cup of water, for example. This problem is only compounded by the Raptor's lack of Cartesian control, requiring the user to constantly adjust each joint individually to keep a cup roughly level as it is brought to the mouth.

The MANUS has 6 degrees of freedom, allowing full position and orientation control. This is the primary reason for its better manipulability scores. A forward, high mount allows a shorter arm to be used effectively, although ground access is limited by this choice. While this mount is preferred by our mathematical analysis, in practice it is not so desirable. There is no way to park the arm out of the way, and it is always a visual distraction for people the user interacts with.

Controller design is a vital consideration when designing a complete robotic manipulator system. Significant gains for robotic manipulators in rehabilitation applications will come from advanced controllers and user interfaces for easy programming and operation.

Using the analysis results presented in this paper, a new reconfigurable WMRA is designed to overcome some of the limitations found in Raptor and Manus. A brief description of the new design is presented.

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