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Design and Analysis of a Wheelchair Mounted Robotic Arm with Remote Actuation System

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ABSTRACT: *This paper presents a new design of foldable, compact and cost-effective Wheelchair-Mounted-Robotic-Arm (WMRA).The design is based on remote actuation using stepper motors placed near the wheel- chair armrest and a synchronous belt system. This design helps to shift the weight closer to the wheelchair and maintain the required speed, torque and inertia while delivering full dexterity by actively driving each joint of the robot. The robot will assist patients with different conditions of impairments to eat, drink, and move objects accurately. The lightweight structure designed from hollow PVC tubes and aluminum sheets helps to ease and facilitate port ability. The placement of the whole robot and coupled joints are taken into consideration to reduce physical and sensory interference with the user and the wheelchair. The strength and deflection of critical parts of the robot have been tested through finite element analysis (FEA) and the workspace of the robot has been studied through Kinematics analysis. The testing results indicate that the designed WMRA is strong enough to handle and manipulate objects as heavy as 4kg in a wide range of workspace.*

Keywords - ADL, Assistive Devices, Assistive Technology, WMRA

I. INTRODUCTION

Assistive technology systems are one of the highly active areas of recent robotic research. In the past few years, the demand for high performance robots for daily human activities increased rapidly due to the advancement of robotics technology. New robot technologies, acting in collaboration with humans, have the potential to increase greatly both productivity and quality of life. One such evolving co-robot technology is the WMRA. The goal of the WMRA is to augment the abilities of people with disabilities to accomplish routine day-to-day activities. In 2013, 50.7 % of Americans age 75+ were classified as having a disability, with 33% of them have ambulatory disabilities. Considering all Americans, about 20.7 million Americans potentially need wheel chairs or other mobility assistance devices [1]. Assistive technologies such as robotic arms hold a promising future in helping the elderly and people with disability. Currently, many WMRAs are proposed/designed [2–5]. However, there are still many challenges and issues that limits the advancement of the technology for instance the availability of effective controls, higher performance actuators, cost, safety, size, payload and user interface. All these considerations made the design difficult. Some of the issues that need to be addressed in the mechanical design of WMRA are range of motion, comfort, low inertia and safety. Similarly, in the control of WMRA issues like control ability, smooth motion generation and flexibility are required. Of particular interest are the ability to design, Implement, and test assistive control strategies.

People with varying degrees of disability can use the WMRA. Finding a control system that is compatible with all users is a key part to a successful WMRA. Many users have limited muscle control in their arm/hands, making switches and joysticks hard to manipulate with care. One possible solution to this might be the incorporation of visual recognition software into the arm similar to [6]. The user can then input through voice/touchpad which object in the field of view is to be picked up/moved. A nine-degree of freedom robotic arm system controlled by user brain wave is developed in [7]. The user wears a cap with sensors in it, and when a stimulus is detected, the arm moves accordingly. All users, regardless of the degree of disability can utilize this ideal interface system. Another desire is to have the ability to recognize beyond the field of view. An example of this would be checking into a hotel and inputting room number and the WMRA will access the elevator, open the doors etc. to get into the room [8].

Another challenge to WMRA is the design of a gripper capable of doing different tasks. The gripper must be able to perform a variety of tasks, including picking up objects at different angles, opening doors, pushing buttons, etc. Some tasks, such as picking up a glass of water, are best done with two fingers. Other tasks like opening knob style doors may require three fingers in order to get a sufficient grip. Rapacki tested a three-finger arm on a variety of doorknobs [9], and the results were surprising. Even with a rubber coating on the fingers, the arm could not grip most knobs. A possible solution to this would be to increase the torque applied to the fingers. Although increasing torque means increasing quality of components, leading us back to the affordability problem.

The current market offers WMRAs in the price range of $5,000 to $40,000 [10], which is too costly to be utilized by many users. In this paper, three specific issues associated with the WMRA are explored: 1) maximizing workspace of the robotic arm, 2) reducing weight in the arm through remote-actuation system, and 3) keeping the cost of the WMRA low while maintaining a good balance of maneuver ability and functionality. It is expected that with this design many people with varying degrees of disability will be benefited.

II. MECHANICAL DESIGN

The mechanical design is approached to meet the list of requirements such as space constraints (able to be stored on the side of the wheelchair), lightweight (under 5kg weight), foldable and extendible up to 1m, ability to lift and hold a weight of 4kg object, ability to feed the user, and affordability (under $1,000). Considering these and other factors, the overall shape and size of the WMRA is outlined as shown in Fig. 1. To keep the arm lightweight, durable and low cost, the robotic arm components are made from PVC tubes and aluminum sheets. The PVC tubes also added an aesthetic value to the robot by discreetly hiding the pulleys, cables and belts. The design also provides a clear access to the motors, cables and joint pulleys for a simple maintenance without having a major disassembly.

Figure 1: The general layout of the WMRA in extended and folded position

2.1 Base Swivel

The base consists of a stationary motor mount bracket, mounted to the wheelchair, and carries the complete arm assembly as shown in Fig.2. The complete arm assembly will pivot around a single bolt ran through the fixed bracket, and supported by a thrust and axial bearings. Rotational motion will be supplied via a Nema 17 stepper motor with gearbox (capable of 3 Nm) connected via pulley and synchronous belt to a pulley that is fixed to the arm assembly. After the pulley reduction, the output torque is 8Nm.

2.2 Shoulder and Elbow Joints

A Nema 23 stepper motor with gearbox (capable of 40 Nm) mounted in the motor box will power the shoulder joint. Power will be transferred via a 2:1 pulley and belt system to a pulley that is fixed to the PVC shoulder joint of the arm (Fig.2).The final output torque of the motor after gear reduction is 80 Nm.The elbow joint will have a pulley fixed to it via brackets inside the elbow (Fig.3). A synchronous belt will run inside the PVC arm from the elbow joint to the shoulder joint. The Nema 23 stepper motor (capable of 40Nm) for the elbow joint is kept at the base in order to keep a low center of gravity in the arm. The stepper motor output shaft will run directly through the pivot point to the shoulder joint, and have a pulley fixed to the shaft on the inside of the PVC arm. The pulley configuration will yield a 60 Nm torque capability.

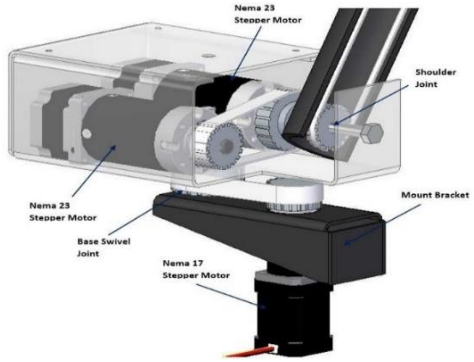

Figure 2: The motor box located at the base of the arm. The base swivel, shoulder and elbow joints are powered from these motors. (PVC arm sectioned for clarity)

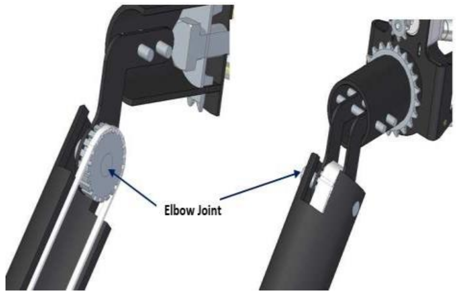

Figure 3: The elbow joint: powered via the motor located in the base and belt ran inside the PVC arm).

2.3 Gripper Assembly

The gripper assembly uses a Nema 17 stepper motor fixed to the gripper assembly, and sprocket fixed to the arm assembly to allow for wrist rotation. See Fig.4. Dual pneumatic cylinders (Bimba #021-6-DXP) power the wrist pivot, providing a lifting force capable of supporting 5.4 kg. A single pneumatic cylinder (Bimba #020.65-D) powers the dynamic gripper finger. This gripper finger has a gripping strength of 40N in the center of the palm. The wrist swivel joint is actuated using a NEMA stepper motor. The gripper wrist joint is capable of pivoting approximately 90 degrees. Coupled with the wrist joint swivel capability of 180 degrees, this will allow a full range of motion for the hand. The rounded finger base and extending fingertips will help hold bottles and other objects securely. The grippers can also be easily lined/covered with rubber to grasp different size of objects without causing any damage to the object.

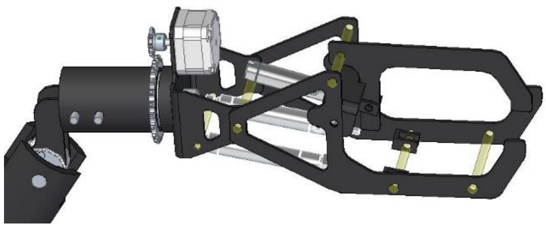

Figure 4: Gripper assembly, stepper motor and sprockets provide rot provides dual air cylinder provide wrist joint movement, and single air cylinder provides finger gripping.

2.4 Actuation System

Nema stepper motors combined with a belt system are used to actuate the main joints of the WMRA. These stepper motors provide the desired amount of torque and are also widely used, readily available and relatively inexpensive [11].The stepper motors will be powered through a Tiny GCNC controller board. The board has four stepper motor drivers and a microcontroller integrated into the board (Fig.5),the detail features of the board can be obtained in [12].To maintain a smooth motion and a constant jerk, a cubic polynomial will be used in the trajectory planning. Input from the user will be via surface electromyography (EMG) signals. This will allow users of any level of disability to control the arm.

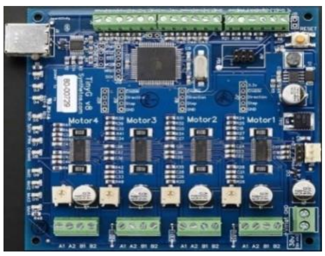

Figure 5: TinyG CNC controller board [12]

III. KINEMATICS ANALYSIS OF THE WMRA

The designed WMRA is a serial chain robot and its forward kinematics equations are defined by a transformation from the base frame to the end- effector frame. These equations provide the set of all positions reachable by the robot for the given joint inputs. The Denavit-Hartenberg convention [13– 15] is frequently used to assign reference frames to each link of the robot defined as a series of joint axes denoted by S_i, where, i= 1, ...,n (Fig.6). In this convention, link coordinate frames are attached so that the z-axis is directed along the axis S_i and its x-axis is directed along the common normal A_{ij}. Considering $x=(x, y, z)^T$ to be coordinates in moving frame (M) and $X= (X,Y,Z)^T$ to be coordinates measured in the fixed frame (F), the screw displacement along a joint axis, S_i, is defined by $X = [Z(\theta_i, d_i)]x$, Similarly, the screw displacement from one joint axis to another along the X-axis by the amounts a_{ij} and α_{ij}, which is defined by X = [X (α_{ij}, a_{ij})]x, where,

$$[Z(\theta_i, d_i)] = \begin{bmatrix} cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$[X(\alpha_{ij}, a_{ij})] = \begin{bmatrix} 1 & 0 & 0 & a_{ij} \\ 0 & \cos\alpha_{ij} & -\sin\alpha_{ij} & 0 \\ 0 & \sin\alpha_{ij} & \cos\alpha_{ij} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

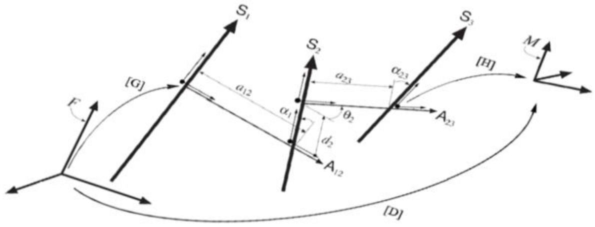

Figure 6: A serial chain with its joints

The set of all positions reachable by the robot is defined by its kinematic equations as the set of all homogenous transformation [D] from the base frame to the end-effect or frame as follows,

$$[D] = [G][Z(\theta_1, d_1)][X(\alpha_{12}, a_{12})][Z(\theta_2, d_2)] \dots [X(\alpha_{n-1,n}, a_{n-1,n})][Z(\theta_n, d_n)][H] \tag{3}$$

Where, [G] and [H] are the coordinate transformations from the base frame to the first joint axis and from the last joint axis to the end-effector frame, respectively. Equation (3) provides the work space of the robot parameterized by the joint variables, (θ_i, d_i), and the link dimensions, (α_{ij}, a_{ij}).

The DH-Parameters for the designed WMRA are shown in Table.1. Based on these parameters, the forward kinematics have been analyzed using RoboAnalyzer software [16]. The kinematic model of the robot is formulated as shown in Fig.7. For the given trajectory and range of joint angles (Fig.8), the corresponding end-effector/gripper positions are shown in Fig.9.

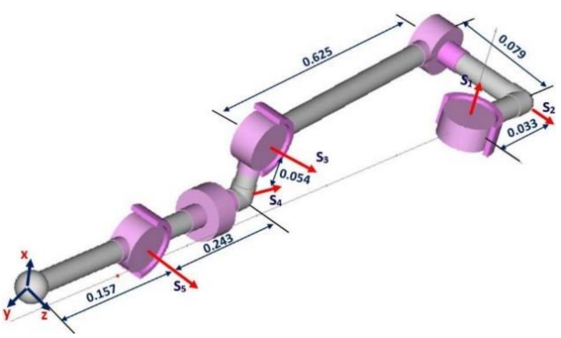

Figure 7: Kinematic Model of the WMRA: all measurements are in meters

TABLE 1: DH-Parameters of the Designed WMRA

Joint	Joint Offset (d_i) in meters	Joint Angle(θ_i) in degrees	Common normal Length(a_{ij}) in meters	Twist Angle(α_{ij})
1	*0*	θ1	*0.033*	*90⁰*
2	*0.079*	θ2	*0.625*	*0⁰*
3	*0*	θ3	*0.054*	*90⁰*
4	*0.243*	θ4	*0*	*-90⁰*
5	*0*	θ5	*0.157*	*0⁰*

The workspace of the robot is analyzed in the CAD environment. Considering physical interference with the wheelchair, the user and applying the range of motion of each joint of the arm (Table 2), the workspace of the WMRA is developed (Fig.10). This workspace of the robot arm will allow the user to perform several tasks easily.

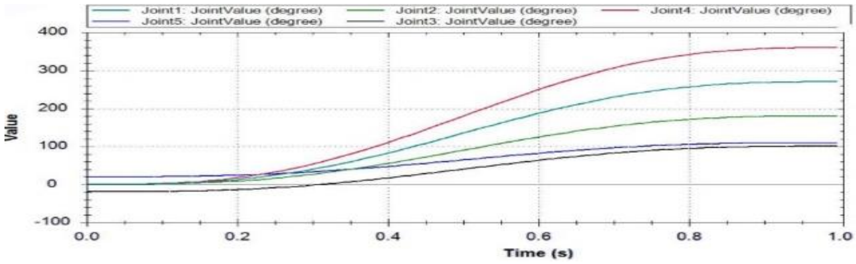

Figure 8: Trajectory of Joint angles

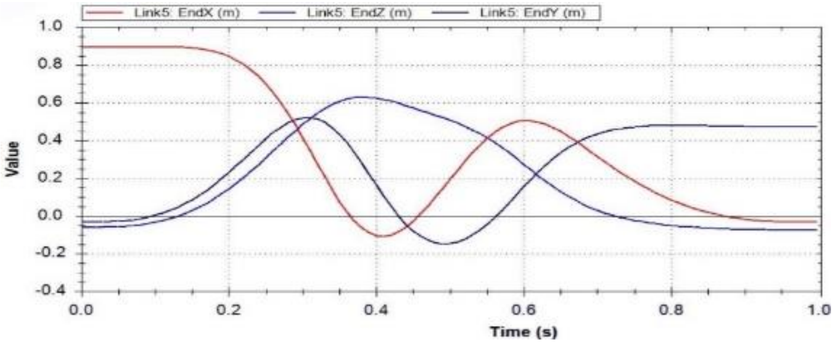

Figure 9: Gripper positions

TABLE 2: Range of motion of each joint of the WMRA

Joint	Range of Motion
The gripper wrist	Pivot 90^0
The gripper assembly	Rotate 180^0
The elbow joint	Pivot 180^0
The shoulder joint	Pivot 210^0
The base pivot	Rotate 310^0

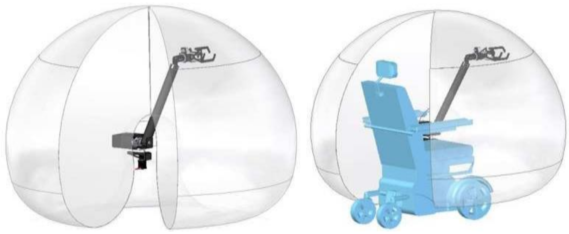

Figure 10: Workspace of the WMRA

IV. TESTING AND SIMULATION RESULTS

An FEA static study was performed on the overall assembly using Solid Edge ST8 software with NX Nastran solver. Gravity effects are taken into consideration and the point load value of 42N is applied at the center of the gripper palm. The wheelchair mount bracket is held fixed during the analysis. The arms pivot points are constrained as rigid connection. Four node linear tetrahedral elements are used in the mesh, with mesh properties; mesh type: solid mesh, subjective mesh size: 1.85mm, total nodes: 300,400, and total elements: 166,400. The material properties assigned in the analysis are shown in Table 3.

3.1 Stress Analysis

The FEA results show that the Von Mises stress is located in the bolt that the base assembly pivots on (see Fig.11). According to the model, this bolt is subjected to a stress of 17.7 kpsi. This number is on the conservative side, considering that in the final product this bolt is supported from bending/buckling with bearings. Considering the outside edge of the bolt is under tensile load, we can use the tensile strength of a 3/8 Grade 8 bolt of 150 kpsi. This will provide a factor of safety of 8.4 for this specific scenario.

TABLE 3: Materials used and their properties

Material	Modulus of Elasticity (10^6 Psi)	Poisson's Ratio	Yield Strength (K psi)	Ultimate Strength (K psi)	Used in
PVC	0.345	0.4	8	7.5	Arm links
Aluminum 6061-T6	10	0.33	40	45	Base box, Bracket, Gripper
Steel	30	0.29	38	52	Bolts, Shafts

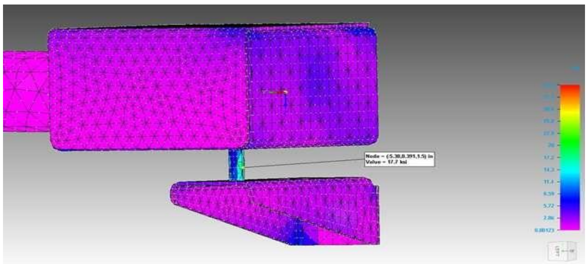

Figure 11: Von Mises Stress of 17.7 kpsi in the Main Pivot Bolt of the Base Assembly

3.2 Deflection

The deflection at the palm of the gripper, when fully loaded with 4 kg, is approximately 25 mm as shown in Fig.12.While this is the worst case scenario, it is more than we desire. The analysis shows that we can reduce a great deal of this deflection by adding a stiffening tab to the base motor box.

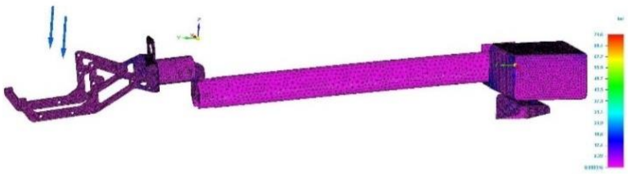

Figure 12: Stress and strain analysis of the arm assembly

3.3 Payload

Considering the weight of most of the common items in the home and grocery stores, the WMRA was designed with a payload of 4 kg. Based on the FEA simulation, it is confirmed that the robot arm can lift an object up to 5.4 kg.

3.4 Costs

PVC was chosen as the arm linkages due to its great strength and affordability. The gripper assembly and mounting brackets will be made of aluminum sheet metal due to its light weight and ease of manufacturability. In order to keep costs low, standard parts that are easily accessible off-the-shelf are used in the design; machining is only required for a few parts with a minimal amount of machining time. The designed WMRA has a total cost of under $800, which allows more number of people to have access to the technology. This is the lowest cost of a WMRA that we found during our research.

3.5 Prototype

A prototype was created in order to test the design parameters. The air cylinders provide an effective gripping and holding capability to the gripper (see Fig.13). Although the air hose routing could be further improved. Overall, the design strengths and range of motion were as expected. Implementing user-friendly control systems will help to conduct additional tests on the WMRA.

Figure 13: A prototype of the WMRA

V. CONCLUSIONS

The proposed WMRA is cost effective, it costs under $800 to produce. This is considered very affordable compared to other designs. Using affordable materials such as PVC pipes and aluminum sheet metals helps to lower the budget. Production and assembly of the WMRA are easy due to the use of readily available components with minimal machining required. This could allow many people to build their own WMRA. The strength and stiffness of the critical components have been tested through finite element analysis. The remote actuation system helps to minimize inertia and power requirements by keeping the load closer to the wheelchair. Similarly, the functionality of the robot arm is demonstrated through its reach of a wider workspace while holding various size and shape of objects. In the future, the control aspect of the robot will be explored through joy sticks, sEMG signals and EEG inputs toaccommodate people with various disability conditions.

VI. Acknowledgements

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