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Design and Development of a Low Cost, Light Weight, Hydraulic Manipulator for Mounting on a Wheelchair

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Abstract

This research presents an alternative low cost design option to the current wheelchair-mountable robotic arms (WMRAs) available for paralyzed patients. According to a 2009 study, more than 5.5 million people struggle with paralysis in the U.S. alone. Due to the high numbers affected, there is an urgent need to develop a WMRA that will increase the quality of life for paralyzed patients by restoring some of the independence they have lost. Current robotic arms on the market are cost-prohibitive and mostly electrically powered, which produces less power than hydraulics for the same size system, resulting in reduced payload capacity of the robotic arm. Thus, the major load bearing components on the proposed robotic arm will be powered by hydraulics, with only a few low loading components requiring electrical power. Major design considerations are: cost, payload capacity, storage, aesthetics, location of the WMRA, and ease of use (i.e. low maintenance and no interference with wheelchair user's freedom). Several designs were considered and the final design was chosen with a decision matrix that considered the most important design criteria including: cost, payload capacity, maneuverability, storage, and weight. In order to analyze the structural integrity of the robotic arm, free body diagrams were created and a kinematic analysis of the motion of the robot was performed. SOLIDWORKS and MATLAB also complemented the design analysis process, allowing simulations to view the motion of each link and characterize their dynamics. The results of this research and the hydraulic manipulator created will provide limitless help to those bound to wheelchairs by their paralysis, providing them with a better and more normal life.

Keywords: Arm, Robotic, Hydraulic

1. Introduction

A wheelchair-mounted robotic arm (WMRA[1]) is an assistive manipulator that allows a person in a wheelchair to have more flexibility and reach. This is especially useful for those with limited movement capability in the hand and arm regions, which is a common condition for those with paralysis.

Robotic arms in general have been a subject of interest, study, and advancement for years and will remain so for years to come. With the continued developments in the robotic world, there are increasingly more ways that robotic arms can be designed with a greater degree of flexibility that will allow better performance. But while these developments take place, the major degree of complexity also adds a large amount of cost. The need for a vast degree of flexibility makes for designs that are hard to produce without using many complex and expensive parts. Eventually, as robotic arms become more common, their price will gradually decrease, making these arms more accessible to the "general" public. But this could be years in the future, for while robotic arm technology has come a long way since beginning, the technology still has great strides to accomplish the design of a complex and able robotic arm system without greatly increased costs. The majority of the scientific world seems to be focused on increasing the ability of the robotic arm, while almost losing sight at times that these devices are aimed at helping people such as those with paralysis. These people often cannot afford robotic arms for wheelchairs because of the already high medical bills. Thus, until mass production brings the cost of the robotic arm down to reasonable levels, there is an urgent need for a low cost option for those who don't have the funds to spend $25,000 on a robotic arm for their wheelchair, which is the lowest general price for robotic arms on the market today.[2]

With a good understanding of the needs of those who use the robotic arms, as well as good information on the cost of components and design ideas, a better design for a robotic arm can be born. One that not only has great ability, but is also strong, aesthetically pleasing, un-obstructive, and has a much lower unit cost. When designed properly, the low cost robotic arm will be able to complete a wide range of tasks, most notably Activities of Daily Living or ADLs.[1] This has become imperative for any wheelchair-mounted robotic arm to be able to accomplish, and yet the degree of complexity and flexibility needed to complete the wide range of jobs does not make it easy to keep the cost low. This research shows the journey through designing just such a robotic arm.

2. Background

2.1 Project Motivation

Why is this research project important? A vast number of people are affected by paralysis, which is the target audience for this project. In 2009 a study estimated that over 5.5 million people in the US alone struggled with some type of paralysis,[3] with over 60% paralyzed to one extent or another from the neck down.[4] In fact, over 69% of all paralysis is a result of strokes, spinal cord injuries, and multiple sclerosis. As a result, 90% of stroke survivors live with a high level of paralysis while 86% of spinal cord injury victims are paralyzed from the neck down. These numbers show that paralysis is a major problem, and a robotic arm will be able to help these people perform ADLs and live life more independently. Of these ADLs, which most people do without thinking, a few crucial ones are eating, drinking, and general hygiene. Not only will a robotic arm allow the paralyzed person to perform these tasks, leading to greater independence and happiness, but it will also cut down on overall healthcare costs as the need for hired help and healthcare providers lessens.

An interesting fact to note is that statistics were found showing that almost 50% of those with paralysis come from the age range between 40 and 60 years of age, with a majority of these people falling into the 40-50-yr-old category.[5] These statistics show that paralysis is heavily affecting an aging population that may already be experiencing other health problems as well, increasing the urgency in their need for an assistive device to help them.

But as mentioned previously, current robotic arms for this purpose are generally very expensive, with most being over 20,000 dollars. Thus it is paramount that some attention is focused around designing a lower cost model. In addition to the arms themselves being expensive, studies reveal that those with paralysis, the specific target population for this project, have much lower incomes per household than the average household in the United States.[6] Paralyzed households earned $30,665 on average in 2009, instead of $51,190 for "normal" households.[7]

With the general welfare as well as the future of those paralyzed in mind, there is also a general need for increased human and robotic interaction and collaboration, which will lead to an improved quality of life and happiness for those bound to wheelchairs.

2.2 Current Market Designs And Limitations

There are several different types of robotic arms available on the market, with a few depicted in Figure 1 below.

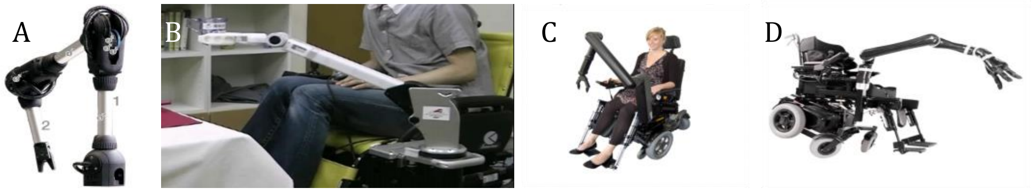
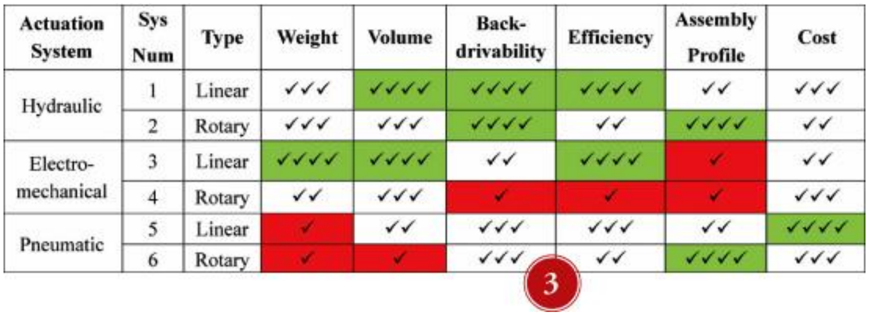


Figure 1. (a) The Robolink, (b) RAPUDA, (c) iArm, and (d) Jaco robotic arms pictured from left to right

The Robolink robotic arm (pictured far left in Figure 1a), has very limited payload capacity. While it is still being developed, the current calculations place the estimated payload capacity under 1.5 lb, severely limiting a person from doing a lot of everyday household duties. For example, a gallon of milk is about 8 or 9 lb, which this arm clearly could not handle. The RAPUDA robotic arm is also not a good choice because of it's extremely slow movements. It took over 2 minutes for the RAPUDA to grasp a cup from the table, lift it to the user's mouth, and set it back on the table. While that may or may not sound that long, it would seem like quite a long time if it actually took that long for someone to get a drink. The iArm and the Jaco robotic arms in Figure 1c and 1d, respectively, are both extremely versatile, flexible, and useful, but they are both extremely expensive as well. Current costs for the iArm are over $29,000, and the Jaco is even more expensive at $35,000. From these prices, it is clear that these arms are not a good choice price-wise for the "normal" household in America. An important item to note here is the fact that it appears neither medicare or medicaid plans cover additions to a wheelchair. While they will in most cases cover the wheelchair itself if need is demonstrated, in most cases they will not cover additional items such as a robotic arm because they are "unnecessary additions."

In addition to the varying limitations mentioned above, most of the current robotic arms on the market are powered entirely by electrical power. While it may be convenient to tie into the already existing electrical system such as on an electric wheelchair, there are also severe limitations to what a battery powered robotic arm can do. To gain the same payload capacity with an electrical system requires a much larger and more expensive system as compared to what can be done with fluid power. Table 1 highlights some of the main differences between electric versus hydraulic actuation.

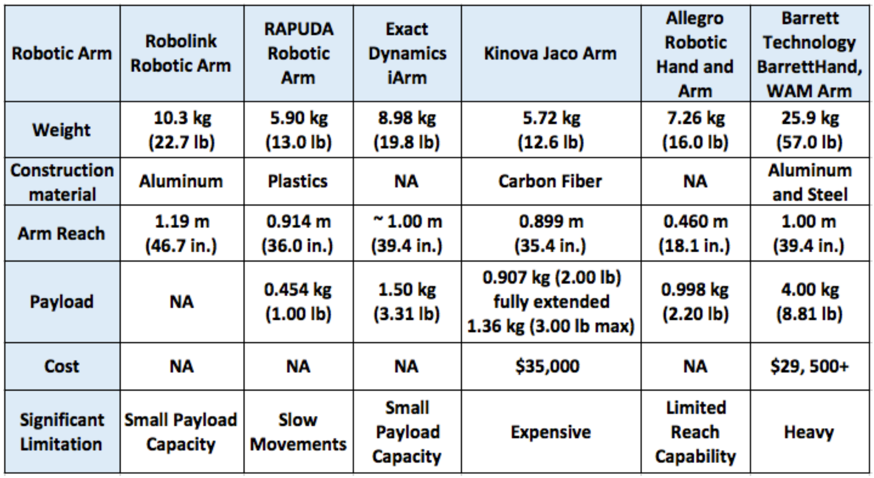
Table 1. chart comparison of hydraulic, electro-mechanical, and pneumatic systems[8]



Actuation System	Sys Num	Type	Weight	Volume	Back-drivability	Efficiency	Assembly Profile	Cost
Hydraulic	1	Linear	✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓	✓✓✓
	2	Rotary	✓✓✓	✓✓✓	✓✓✓✓	✓✓	✓✓✓✓	✓✓
Electro-mechanical	3	Linear	✓✓✓✓	✓✓✓✓	✓✓	✓✓✓✓	✓	✓✓
	4	Rotary	✓✓	✓✓✓	✓	✓	✓	✓✓✓
Pneumatic	5	Linear	✓	✓✓	✓✓✓	✓✓✓	✓✓	✓✓✓✓
	6	Rotary	✓	✓	✓✓✓	✓✓	✓✓✓✓	✓✓✓

And Table 2 compares the robotic arms previously mentioned along with other robotic arms currently available for purchase.

Table 2. comparison of several different robotic arms currently on the market



Robotic Arm	Robolink Robotic Arm	RAPUDA Robotic Arm	Exact Dynamics iArm	Kinova Jaco Arm	Allegro Robotic Hand and Arm	Barrett Technology BarrettHand, WAM Arm
Weight	10.3 kg (22.7 lb)	5.90 kg (13.0 lb)	8.98 kg (19.8 lb)	5.72 kg (12.6 lb)	7.26 kg (16.0 lb)	25.9 kg (57.0 lb)
Construction material	Aluminum	Plastics	NA	Carbon Fiber	NA	Aluminum and Steel
Arm Reach	1.19 m (46.7 in.)	0.914 m (36.0 in.)	~ 1.00 m (39.4 in.)	0.899 m (35.4 in.)	0.460 m (18.1 in.)	1.00 m (39.4 in.)
Payload	NA	0.454 kg (1.00 lb)	1.50 kg (3.31 lb)	0.907 kg (2.00 lb) fully extended 1.36 kg (3.00 lb max)	0.998 kg (2.20 lb)	4.00 kg (8.81 lb)
Cost	NA	NA	NA	$35,000	NA	$29, 500+
Significant Limitation	Small Payload Capacity	Slow Movements	Small Payload Capacity	Expensive	Limited Reach Capability	Heavy

It's important to take note that most of the robotic arms have a limited payload capacity, with most not being able to handle loads over 3.5 lb. This can severely limit a wheelchair-bound person's ability to complete necessary everyday tasks. Also, although many of the robotic arm prices were "not available," the prices that are shown are very high at $29,000+ and $35,000. Most of the robotic arm websites do not seem to list the price directly, rather they direct the reader to contact the company for a price quote. Many times when prices are hidden it means that the product is expensive and the company wants to explain why it is needed despite the price, before purchasers are deterred by seeing the cost. Another noteworthy item from the chart, but in a positive sense, is the fact that most of the robotic arms have a reach of around one meter. This shows a general uniformity among most robotic arms, revealing the best reach length that allows performance of all functions as needed. All of this information was used to guide the project as a whole, but specifically the design decisions made.

3. Methodology

3.1 Design Decisions

In order to thoroughly understand what parameters the arm needed to be designed for, extensive research was conducted on current robotic arm designs, their limitations, and all areas that needed improvement. Through this process, several target criteria were identified that defined the features of a desirable design. These criteria consisted of low cost, relatively high payload capacity, excellent maneuverability, compact storage, and low weight. The first and most important criteria on the list is cost. This is given a weight of 30% of the total design decision. Cost is the single greatest factor preventing average households from purchasing a robotic arm that would greatly improve the quality of life of paralyzed patients. As mentioned previously, most robotic arms on the market are $20,000+, requiring an absolute maximum price cap of $10,000 to be set for the new design to satisfy the low cost requirement of the design, with realistic hopes that the final unit cost would be well below this amount, and possibly even below $5,000.

The second criteria, given a weight of 25% in the overall design decision, is payload capacity. Low payload capacity is a serious handicap to those trying to complete everyday tasks and chores, and is a problem that plagues almost all of the current robotic arm designs on the market, as seen in Table 2. These low payload capacities prompted a push for the new robotic arm to increase that payload capacity to around 10 lb, which is very attainable with the current design.

The third criteria, given 20% of the overall design decision, is maneuverability. Even though maneuverability is an extremely important criteria, it is listed third most important based on the fact that there will have to be a few sacrifices in flexibility in order to bring the cost down. Storage and overall weight are also important but lower on the list, having weights of 15% and 10% respectively. This is because one of the first priorities is to design for ease of use, with storage being a lesser concern. Weight is considered, but bears menial weight percent on the decision because of the fact that any added weight is felt by the wheelchair only and not the user, meaning much fewer limitations on the overall weight capacity than if the user had to bear all of the extra weight.

From these criteria, further specifications were also defined. Because one meter was found to be a generally satisfactory reach length for most robotic arms, that standard was adopted for the new design, with the major portion of the arm having a one meter reach length; the end effector adding a few extra inches at the tip of the arm. Also, because of the obvious advantages of hydraulics as seen in Table 1, the major load bearing components in the new robotic arm design will be powered by hydraulics. Additionally, from background research detailed under the project motivation, the arm and interface design will be targeted at the 40-50-yr-old population. And finally, the controls and interface design will be targeted at paralysis victims with very limited arm and hand movement, as these would benefit the most from such an arm.

Part of the overall design consideration also took into account the possible limitations of mounting the arm on a wheelchair. It was determined that less than 5 inches should be added to the total width of the wheelchair in order for it to be able to navigate general areas and doorframes with ease. The overall weight limit was set at 100 lb additional weight to the wheelchair. In accordance with all of these design considerations, it is paramount that the robotic arm be relatively easy to control, thus improving human and robot interactions and collaboration.

Keeping the aforementioned design criteria and considerations in mind, three design sketches were created. Design 1 contained all cylinders on top of the robotic arm, but this severely limited the folding ability of the arm. Design 3 housed parts of the cylinders inside of the arm links, appearing as if modeled after current excavators, but this design was also quite limited on arm reach configurations and especially would not allow the arm to fold up for compact storage. Design 2 featured a revolutionary design that folded into itself, allowing for very compact storage while retaining great flexibility. A decision matrix of all three designs containing the major design criteria of Cost (30%), Payload Capacity (25%), Maneuverability (20%), Storage (15%), and Weight (10%), was used to objectively select the best design. Rating the designs on each criteria allowed the addition of their ratings for a "total score" which quite clearly revealed that Design 2 best met the design criteria, and a slightly-modified version of Design 2 was chosen for the final robotic arm design.

The final design had the following characteristics. It had low cost at around $5000 on the low end compared to other robotic arms around $20,000 on the low end. It also increased the payload capacity from less than 3.5 lb to around 10 lb. As far as maneuverability is concerned there are a few limitations, but for the most part it can complete any task that other designs are able to perform. The robotic arm also has excellent storage capability which other robotic arms do not have, which is not only aesthetically pleasing, but is also very handy for the occupant while wheeling around. And finally, weight considerations are satisfactory as there appear to be no stability issues, as will be demonstrated later.

3.2 Analysis

In order to understand how the robotic arm design would react or function under certain circumstances, it was important that some preliminary calculations took place in order to ascertain that no problems would arise further in the design process. In order to facilitate this process, the robotic arm was modeled in SolidWorks and side profile views of each link were used in place of sketches for analysis. Figure 2 shows a "break-down" of each of the robotic arm's degrees of freedom, links, and their respective axes.

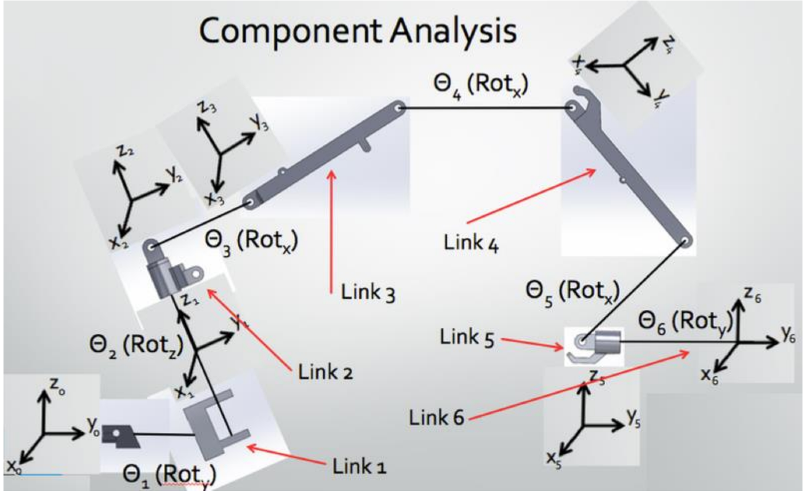


Figure 2: Screenshot showing detailed SolidWorks Links of the 6DOF robotic arm design with each coordinate axis defined

Of the 6 Degrees of Freedom (DOFs) shown in the figure for the robotic arm, about half of them ($\Theta_3 - \Theta_5$) are contained within the arm itself. Θ_1 is a result of the joint between two components of the wheelchair mounting system, while Θ_2 is a result of the relation between the wheelchair mount and the base of the robotic arm. And finally, Θ_6 will be added at the joint between the end effector and the third link in the robotic arm.

3.2.1 stability of the robot arm

Preliminary calculations had to be determined which would reveal whether the tentative design configuration had any stability issues. This is an important factor in considering arm reach and positioning. With the main portion of the arm being designed at just over a meter in length, extra length had to be calculated in for the end effector reach and base length additions, yielding an estimated total reach length of about 49 inches, which is what was used in the stability analysis. Calculations were completed in Engineering Equation Solver (EES). A worst case static analysis (with a payload range of 1-15 lb) was performed where a worst case scenario was considered in which the payload was grasped in the end effector at the end of the horizontal, outstretched arm. Free body diagrams were generated for this static position and analysis including the sum of the forces in the y direction and the sum of the moments around the front wheel of the wheelchair were performed.

The calculations revealed that a 75 lb person could keep the wheelchair stable with up to a 10 lb payload (the current design limit), and that even with a 15 lb payload added, the wheelchair occupant only needed to be 90 lbs. A general wheelchair weight was used that was somewhat of an average for many different standard wheelchairs, with the realization that a heavier wheelchair such as an electrical wheelchair would just increase the stability of the wheelchair/robotic arm system. An estimated weight of 45 lb was used for the weight of the robotic arm, which appears to be highly accurate and takes into consideration each and every component of the arm design. These calculations reveal that there should be no stability issues whatsoever when mounting the robotic arm on a wheelchair as virtually no wheelchair occupants will be less than the 75 lb (or even 90 lb in the extreme case) needed for stability.

3.2.2 robot arm forward kinematic transformation matrices

In order to develop software code to control the robotic arm it is imperative that the position of the end effector be known at all times. Thus, a more complete and thorough understanding of the abilities and dynamic behavior of the robotic arm is needed. To accomplish these goals transformation matrices are needed to relate all of the links and their respective positions to each other, to the global coordinate system, and ultimately the position of the end effector to the global origin. The general case of the transformation matrices needed to model the position of the end effector are shown in Figure 3.

$$T_{01} = \begin{bmatrix} C_1 & 0 & S_1 & dx_1 \\ 0 & 1 & 0 & dy_1 \\ -S_1 & 0 & C_1 & dz_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathrm{T}_{12} = \begin{bmatrix} C_2 & -S_2 & 0 & dx_2 \\ S_2 & C_2 & 0 & dy_2 \\ 0 & 0 & 1 & dz_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathrm{T}_{23} = \begin{bmatrix} 1 & 0 & 0 & dx_3 \\ 0 & C_3 & -S_3 & dy_3 \\ 0 & S_3 & C_3 & dz_3 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathrm{T}_{34} = \begin{bmatrix} 1 & 0 & 0 & dx_4 \\ 0 & C_4 & -S_4 & dy_4 \\ 0 & S_4 & C_4 & dz_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathrm{T}_{23} = \begin{bmatrix} 1 & 0 & 0 & dx_5 \\ 0 & C_5 & -S_5 & dy_5 \\ 0 & S_5 & C_5 & dz_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}, T_{56} = \begin{bmatrix} C_6 & 0 & S_6 & dx_6 \\ 0 & 1 & 0 & dy_6 \\ -S_6 & 0 & C_6 & dz_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 3: The general case of the transformation matrices needed to determine the position of the end effector of the robot in MATLAB, where dx_1=movement of link 1 (in the x direction) and so on, and C = cos(Θ_i) and S = sin(Θ_i)

The above transformation matrices are in the form $T_{ij} = \begin{bmatrix} R_{ij} & {}^{i}d_j \\ 0 & 1 \end{bmatrix}$, where R is a 3x3 rotational matrix relating coordinate frame i and j , and ${}^{i}d_j$ is a translational vector that represents the origin of coordinate frame j with respect to frame i. The vector is of the form ${}^{i}d_j = \begin{bmatrix} dx_j \\ dy_j \\ dz_j \end{bmatrix}$ where dx_i, dy_i, and dz_i denote the position along the x, y, and z –axis, respectively relative to the i frame. In Figure 3, C_i and S_i denotes cos(Θ_i) and sin(Θ_i), respectively. The general format of the position of the end effector with respect to frame 0 (global coordinate system) is denoted as ${}^{0}P_e$ and is given in Equation 1 in terms of the transformation matrices relating all of the robots links.

$${}^{o}\mathrm{P}_e = \mathrm{T}_{01}\mathrm{T}_{12}\mathrm{T}_{23}\mathrm{T}_{34}\mathrm{T}_{45}\mathrm{T}_{56}\,{}^{6}P_e \tag{1}$$

Equation 1 details how the position of the end effector in relation to the absolute origin can be obtained by multiplying all of the transformation matrices from reference frame to reference frame through the last frame relation, and then multiplying the entire resulting matrix by ${}^{6}\mathrm{P}_e$, denoting the position of the end-effector with respect to frame 6.

MATLAB was used to verify the transformation matrices by animating the robot. From the modeling and animation done in both SolidWorks and MATLAB, the position of each link and the range and extent of motion of each could be analyzed. This helped immensely with defining parameters for future work on the control of each link relative to the position of the end effector and the global origin. It also helped to analyze exactly how the robotic arm would move and react in each position and how well it would reach the ground as well as its reach height.

4. Results

The robotic arm design that was chosen and modeled granted the ability for great reach, flexibility, and strength, but at the same time allowed compact folding for effective storage. This provides the user with “the best of both worlds,” where they can use the arm effectively to get tasks accomplished, but the arm can be stowed away without hindering their ability to get around, with the most important aspect of the design being that it achieves all this while also being affordable. The current estimates place the cost of producing this arm around $5,000 for materials. This value excludes the price of actually producing the final product. Total estimates though, even when allowing very generous price boundaries and including all additional accompanying systems, still place the full cost of such a robotic arm under $10,000. This price is much more affordable than the roughly $20,000+ currently being paid for similar designs. A close up view of a CAD model of the robotic arm design is shown in Figure 5 below.

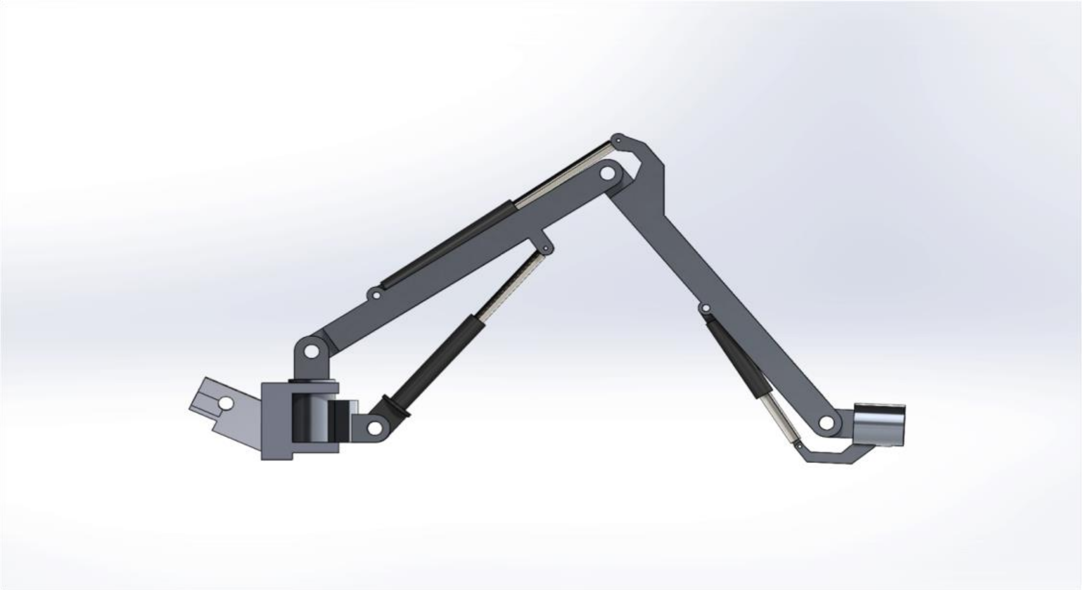


Figure 5: A close up view of the CAD model of this robotic arm design

The number of links for the design was chosen by acknowledging the need for at least 6 degrees of freedom to accomplish the tasks required, while realizing that the more links added, the more complexity, which leads to higher costs and greater design complexity. Due to the greater ease of control, the fewest links possible were chosen that still provided the needed flexibility. This "perfect" number turned out to be two major load bearing links, with a short third link to which the end effector will be attached. Following are some pictures in Figure 6 of the resulting robotic arm design detailed in SolidWorks and mounted on a wheelchair, with a 3D dummy model as the wheelchair occupant.

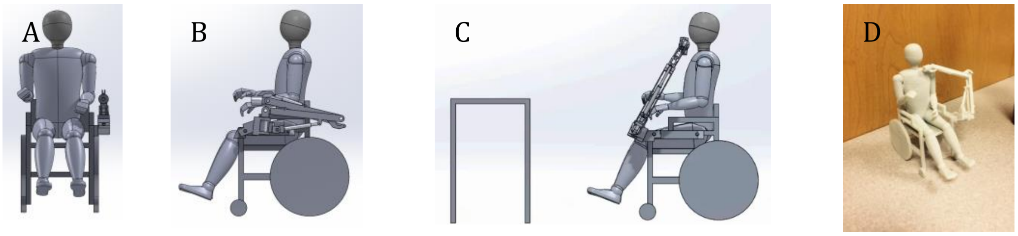


Figure 6: Some figures showing (a) Front profile view of wheelchair/robotic arm system, (b) Side profile view of wheelchair/robotic arm system, (c) View of arm holding cup to mouth, and (d) Picture of 3D-printed scale model of project

Modeling a wheelchair in solidworks and mounting the robotic arm on it, as well as printing a scale figure, helped to see how well the arm would work with a person in the chair, and how well it could be used while mounted on a wheelchair. To put these figures in perspective, the "person" in the wheelchair is a 6 ft. dummy modeled in SolidWorks. The two pictures in Figure 6 on the left show the compact folding design for storage, while the two pictures on the right show how the arm can reach up to the mouth to hold a cup for drinking or food for eating. These figures show just how nice it stores away when not in use, adding ~ 4.5 in. additional width to the chair (meeting the < 5 in. parameter), and folding nicely out of the way alongside the wheelchair when not needed. At the same time, the arm still retains a high level of flexibility and reach, being able to feed and hydrate the wheelchair occupant which fulfills two of the most important ADLs, eating and drinking.

5. Discussion & Conclusion

By appropriating the data gathered from the robotic arm analysis and using proper equations and calculations, the forces and torques necessary for each possible position of the robotic arm can be obtained. The extent of the arm's reach and effectiveness can also be visualized through SolidWorks modeling and animations, with help from Matlab programming. With the calculation results in hand, design specifications such as actuation and rotational speeds, link positions and dimensions can be further honed to meet the needs of the design and ultimately the needs of the end user. With further analysis and study of the calculated results, the stability, usability, and practicality of the robotic arm to fulfill the target application can be assessed. This process will culminate in testing with an actual design prototype, in the end producing a fully functioning and production design for worldwide use.

But with all of this information, it's important not to forget that a major reason for doing this project is that there are a vast number of paralyzed people in this world, so many would benefit from this arm which are unable to buy the current expensive robotic arms. With the high costs, as well as the limited payload of those previous robotic arms "out of the way," the hope is that many more people will be able to benefit from this design and that it will become more of a common "household item" for people with paralysis all across the world.

The specific contributions that I have been privileged to lend to this project are the geometric design of the 6DOF robotic arm, static stability analysis in EES, development of forward kinematics, and a preliminary estimate of hydraulic system cost.

Success for this project was measured by the way the final design fulfilled the decision matrix criteria comprised of: cost (correlated with degrees of freedom (30%)), payload capacity (25%), maneuverability (20%), storage (15%), and weight (10%). And since the current design model does meet all of these criteria very well, it is safe to say that the research has been successful in accomplishing its intended goals.

6. Future Work

After the work accomplished over this summer, future work for this project would be determination of joint forces and torques, development of the dynamics for the WMRA, researching and sizing of the hydraulic system and cylinders, development of the control and system interface, integration of safety features, and design of the end effector or gripper.

While it is acknowledged that these additions may bring unexpected costs to the final production of this project, provisions were made for these added costs in the final estimates, revealing total price estimates that remain well under $10,000, even with the additional systems.

7. Acknowledgements

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8. References

[1] Scholarcommons.usf.edu, 2015. [Online]. Available: http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=2959&context=etd. [Accessed: 02- Aug- 2015].
[2] Robots.com, 'How much do industrial robots cost?', 2015. [Online]. Available: https://www.robots.com/faq/show/how-much-do-industrial-robots-cost. [Accessed: 02- Aug- 2015].

[3] Spinal Cord Injury and Paralysis Research Center, 'Paralysis Facts & Figures', 2015. [Online]. Available: http://www.christopherreeve.org/site/c.mtKZKgMWKwG/b.5184189/k.5587/Paralysis_Facts__Figures.htm. [Accessed: 10- Jun- 2015].

[4] Apparelyzed.com, 'Spinal Cord Injury Statistics', 2015. [Online]. Available: http://www.apparelyzed.com/statistics.html#usastatistics. [Accessed: 10- Jun- 2015].

[5] Spinal Cord Injury and Paralysis Research Center, 'Paralysis Facts & Figures', 2015. [Online]. Available: http://www.christopherreeve.org/site/c.mtKZKgMWKwG/b.5184241/k.ACBD/Average_age_average_length_of_time_since_paralysis_and_SCI.htm. [Accessed: 05- Aug- 2015].

[6] Spinal Cord Injury and Paralysis Research Center, 'Paralysis Facts & Figures', 2015. [Online]. Available: http://www.christopherreeve.org/site/c.mtKZKgMWKwG/b.5184247/k.963E/Household_income.htm. [Accessed: 05- Aug- 2015].

[7] A. Noss, *Household Income for States: 2009 and 2010*, 1st ed. 2015, pp. https://www.census.gov/prod/2011pubs/acsbr10-02.pdf.

[8] Y. Li, E. Hsiao-Wecksler, J. Xi, W. Durfee, G. Banco and J. K, 'Medical Motion: Actuation System Selection Analysis for Human Assist Applications', *TMD - Today's Medical Developments*, 2012. [Online]. Available: http://www.onlinetmd.com/tmd0212-fluid-power-actuation-systems.aspx#.VcMH3pNViko. [Accessed: 06- Aug- 2015].