Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME/CFDSC/CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

NUMBER

Design and Development of SIARA 2: A Low-Cost Assistive Robotic Arm for Individuals with Upper Body Disabilities

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18th March 2025

***Abstract*—A significant portion of the Canadian adult population faces daily challenges due to upper body neuromotor disabilities, which impair the ability to perform tasks such as picking and moving objects. While robotic arms provide an effective solution for these tasks, their high cost often limits accessibility. With the advancements in 3D printing technology and cost-effective actuators, it is now feasible to develop a low-cost robotic arm that can perform daily activities typically requiring manipulation of objects. This paper presents the geometric overview of the assistive robot arm, and the design considerations related to materials and actuators. The actuator testings to achieve the torque requirements are discussed, alongside the design of the wrist section. The paper concludes with a discussion of the future direction of the project, focusing on further progress and testing of the low-cost assistive robotic arm.

***Keywords-component*—Robotics, assistive technologies, mechatronics, 3D printing.**

I. INTRODUCTION

A significant portion of the population lives with a disability. For instance, a study conducted between 2003 and 2014 [1] revealed that neuromotor difficulties affect 1,344 out of every 100,000 Canadian adults, with an annual increase of 8%. These neuromotor difficulties often lead to a loss of muscular function which, in turn, can impair arm movement. [2] Such challenges severely hinder daily tasks, particularly those that involve manipulation like picking up and moving objects. While the symptoms of neuromotor disabilities vary between individuals, most affected people encounter significant obstacles in their everyday lives.

To assist individuals with upper body neuromotor disabilities, there is the solution of assistive technologies, such as robotic arms designed specifically for this purpose. In fact, these robotic arms have ergonomic and intuitive controls, allowing users to perform daily tasks involving reaching and grasping with the help of the robot. Wheelchair-mounted robotic arms are not a new concept, with examples such as the Manus arm [3], the Raptor arm [4], and the Weston system [5]. Currently available options include the iARM from *ExactDynamics* [6] and the JACO from *Kinova* [7] [8]. These robotic arm systems share common requirements, such as a sufficient payload capacity for everyday tasks, an adequate workspace envelope, good ergonomics, ease of use, and cost-effectiveness. In fact. studies showed an increase in quality of life while using the JACO robotic arm from the ease of use. [9] [10].

However, the cost of assistive robotic arms is a crucial factor, as solutions that are too expensive may not be accessible for end users. In fact, the cost ranges from 20K$ CAD [6] to around 40K$ CAD [11], presenting a significant financial burden.

Presently, the growing use of 3D printing and cost-effective actuators has made it possible to create more affordable robotic arms. While no used for robotic assistance, these robots have a far lower cost than the robot arms previously discussed, at

This project was supported by the Centre for Interdisciplinary Research in Rehabilitation and Social Integration (Cirris) and the Fonds de recherche du Québec–Santé (FRQS) #296761.

a price varying from 1.7K$ CAD [12] to 16K$ [13].

Lastly, the *IngReadapt* research laboratory at the Laval University developed an early version of a robotic arm, as a proof of concept, called the Six-DoF Assistive Robotic Arm (SIARA) [14] [15]. This arm features six degrees of freedom (DoFs), including an actuated base to raise and lower the arm. It was primarily fabricated from aluminum and utilizes *Dynamixel* servomotors for all its joints. The arm can carry a payload of 0.6 kg at half reach and 0.3 kg at its full 0.9-meter reach. However, the number of joints makes it difficult for the arm to reach objects directly in front of the user and the overall weight of the arm is greater than anticipated, because the arm is primarily made out of aluminum square tube with thick walls.

II. Goal and Objective

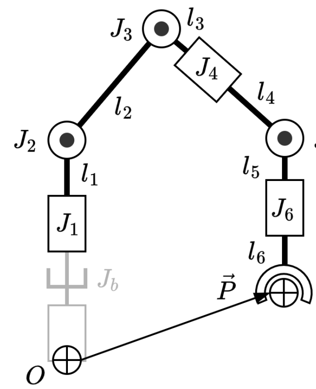
The primary goal is to create an affordable solution capable of effectively handling common household items. In this scope, the objective of this project is to develop a low-cost assistive robotic arm that enables individuals with upper body neuromotor disabilities to pick up and manipulate objects during daily activities. Based on the typical weight range of daily objects (approximately 0.3 kg) [16] [17] and considering the performance of existing robotic arms on the market, a set of requirements has been established to achieve this objective. A key requirement is a maximum reach of 0.9 m, which should allow the arm to reach objects on the ground as well as reach up to the user's head. Moreover, insights from the SIARA robot arm indicate the importance of ensuring that the workspace directly in front of the user is adequately covered. In this case, the arm should be able to reach at least 0.2m in front of the user, if not closer. The payload capacity is specified as 0.6 kg at half reach and 0.3 kg at full reach. Furthermore, the total manufacturing cost of the arm must not exceed 2K$ CAD. Additional requirements, including control modes, ergonomics, torque limiting, and safety features, are also considered in the design. However, for the purposes of this paper, the primary focus is on the workspace, payload capacity, and cost constraints.

III. Methodology and results

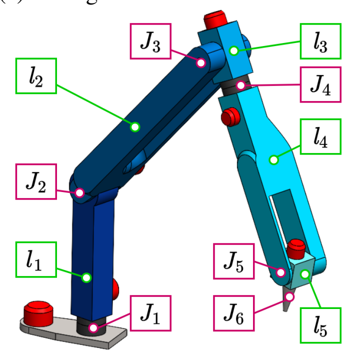
The robot arm is a six degrees of freedom robot (DoFs) presented in figure 1a. The configuration is as such to decouple the cartesian motion in space, using the joints J_1 to J_3, and the wrist motion, using the joints J_4 to J_6. There is the possibility to add a linearly actuated base, J_b, to raise and lower the arm. It is not considered as an active joint in the kinematic, but as a binary joint with two states: raised and lowered.

A. Geometry analysis

One of the main concern of the robot arm is its range of motion. In this case, there are two main constraints to look for: The maximum radius r_M and the minimum radius r_m. Such constraints will define the workspace of the robot arm, as shown in figure 2a and 2b. Its maximum reach is a function of the maximum radius r_M, whereas its minimum reach is a function of the minimum radius r_m. These limits are defined as singularities.



(a) Configuration of the robot arm.



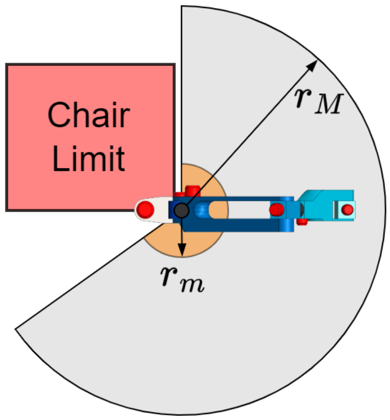
(b) Simplified design of the robot arm made in CAD. Used for evaluation of the workspace.

Figure. 1: Geometric design

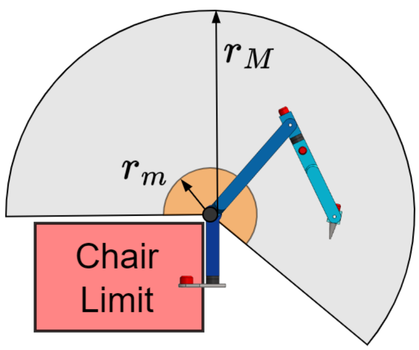
The maximum radius r_M is the sum of the lengths of the links l_2 to l_6. Briefly, it is the scenario when all members of the robot are collinear. A linear motion other than inward is not possible. There is the common case where the wrist is usually bent when moving objects, such that the maximum radius should be based on the sum of the lengths of the links l_2 to l_5. However, for the analysis, the links l_2 to l_6 are considered the maximum radius. As previously mentioned, the requirement for the maximum reach is 0.9m. So, $r_M = 0.9m$. The evaluated scenario is the robot in the horizontal position. To find the length of the links, the length of l_5+l_6 is defined as 0.2m. A short link length at the end of the arm is preferable to reduce the torque required at the actuators furthest from the base. Then, the sum of the length l_2 and $(l_3 + l_4)$ can be defined from the next equation:

$$l_2 + (l_3 + l_4) = r'_M = r_M - (l_5 + l_6) = 0.7m \quad (1)$$

The minimum radius comes from the minimum angle θ_{min} between the link l_2 and the link $l_3 + l_4$. As shown in figure 3, due to the physical dimensions of the arm for l_2 and $l_3 + l_4$, such as the width and height, the minimum angle is limited.



(a) Top view



(b) Side view

Figure. 2: Workspace of the robot arm. The main limits are defined by the minimum radius r_m and the maximum radius r_M. The placement of the robot arm on the chair result in a physical workplace limit labeled "Chair Limit".

In this case, the minimum radius should be lower than 0.2m with a minimum angle of up to 30°. The limit makes a sphere in the workspace.

By analysis the figure 3, the value of r_m is defined from the following equation:

$$r_m^2 = l_2^2 + (l_3 + l_4)^2 - 2l_2(l_3 + l_4)\cos(\theta_m) \qquad (2)$$

From the equation 1, it is possible to change $l_3 + l_4$ for the equation 2 to $r'_M - l_2$. Then, to find the length of l_2, the equation 2 is derived, which gives the next equation:

$$0 = 2l_2 + 2r_M l_2 + 2l_2 + 4l_2\cos(\theta_m) \qquad (3)$$

Isolating l_2 from the previous equation gives this result:

$$l_2 = \frac{r_M}{2(1 + \cos(\theta_m))} \qquad (4)$$

Since $\cos\theta_m$ has a range of 0 to 1, the range of the length l_2 is from $0.25r'_M$ to $0.5r'_M$. However, there is the constraint of having a length l_2 greater or equal to $(l_3 + l_4)$. Since the links 3 and 4 are further up the arm, there is a structural and dynamic advantage to have the shortest links at the end of the arm. For this reason, the length l_2 is set to be equal to the length $(l_3 + l_4)$ which is $0.5r_M$ or 0.35m.

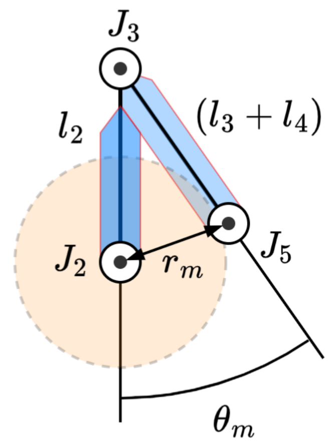


Figure. 3: Representation of the minimal radius r_m caused by the members l_2 and $l_3 + l_4$ and their resulting minimum angle θ_m

The wrist angle should be at least ±135°. With such range of motion, it is possible to cover the entire linear workspace, from one side to another, without having to change the arm configuration during motion. A last mention is given to the joint J_1 which, as seen in figure 2a, causes the dead zone behind the arm. In fact, it is more of a constraint of the chair in and of itself. The joint J_2 restricts the lower movement as seen in figure 2b. However, with the help of the base joint J_b, this limitation is overcome. Based on these constraints and the requirements, the Denavit Hartenberg parameters are calculated from the configuration of figure 1a and the orientation of the axis shown in figure 4. All parameters, including range of motion, are presented in the table I.

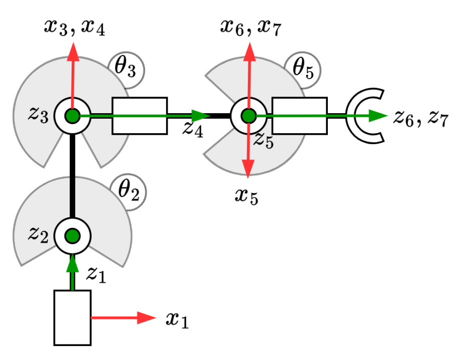


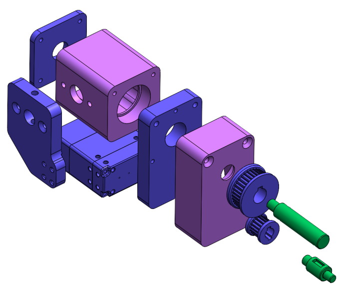
Figure. 4: Orientation of the axis of the joints J_1 to J_6

B. *Choice of Joint Materials*

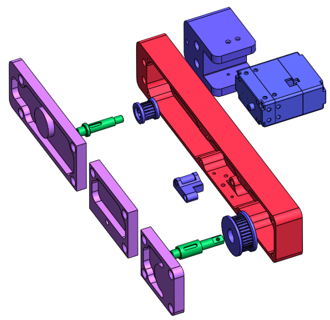
All shafts are machined out of a mild steel labeled 12L14. Most of the longer parts and other parts that require higher levels of yield strength are made of *Delrin* acetal. It is a

TABLE. I: Denavit Hartenberg parameters of the robot arm

Joint ID	$\mathbf{a}_i$ $[m]$	$\mathbf{b}_i$ $[m]$	α_i $[°]$	θ_i $[°]$
1	0	0.2	90	[-90:150]
2	0.35	0	0	±120
3	0	0	90	±150
4	0	0.35	90	±180
5	0	0	90	±135
6	0	0.2	0	±180



(a) 3rd robot link and 4th joint



(b) 4th robot link and 5th joint

Figure. 5: Main components of the 3rd and 4th link. In red are parts made out of *Delrin* acetal, In blue are 3D printed parts and in purple are parts that are currently made out of *Delrin* acetal, but can be switched to 3D printing without severe modifications. The green parts are the shafts.

rigid plastic capable of resisting the bearing loads while being lighter than metal. All other parts are 3d printed out of nylon using selective laser sintering (SLS). The usage of 3D printing is advantageous in term of a good strength-to-weight ratio, its rapid prototyping capability and the ability to design more complex part, which are more difficult to make with conventional machining.

Compared to fused deposition modeling (FDM) and stereolithography (SLA) printing, SLS printing has a more homogeneous and precise results. It gives the possibility of making the required timing pulleys with custom hub designs.

Other than the arm's casing and the shafts, most of the parts are 3D printed as shown in figure 5a and 5b. It is in stark contrast from its predecessor, which mainly used 6061-T6 aluminum for its structure [14].

C. Actuator Technologies and power transmission

The robot arm is powered by two distinct types of actuators. For joints J_1 through J_3, a brushless DC motor with a continuous load capacity of 0.5 Nm is used. The nominal load for joint J_3 is calculated to be 8 Nm, while joints J_1 and J_2 each have a nominal load of 16.5 Nm. To suffice these load requirements, a reduction is needed. A custom planetary gearbox with a 1:5 reduction ratio is used for joints J_3, while a double-stacked planetary gearbox with a 1:25 reduction ratio is used for joint J_1 and J_2. All primary components of the gearbox are fabricated from SLS Nylon.

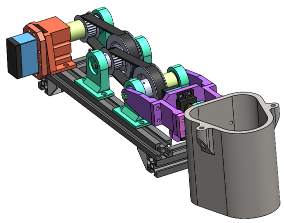
For joints J_4 through J_6, a custom servo motor, termed the *OmniServo*, is utilized. This servo motor, developed by the *IngReadapt* research laboratory, incorporates a compact brushed DC motor and features a high 1:172 gear ratio. The *OmniServo* enables position control with continuous rotation by the utilization of an absolute encoder.

To minimize required torque, the motors for joints J_3 through J_5 are offset from their respective axes of rotation. In these instances, power transmission is achieved using timing pulleys, with a 1:3.5 reduction ratio for joints 4 and 5, and a 1:1 reduction for joint 3. For long belt distances, a tensioner is included to ensure proper tension and efficient power transfer.

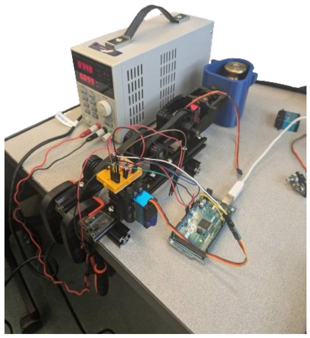
D. Motor testing

As the *OmniServos* are custom assembled, it is important to evaluate them for their torque performances and thermal characteristics. For this case, a test bench is assembled. It is a direct comparison for the joint J_5 and the wrist (J_6). As illustrated in figure 6a, the motor is mounted on an aluminum extrusions base. It drives a timing belt system with a double reduction of 25:48 each. The use of timing belts is to replicate the characteristics of the robot arm, since timing belts will be present in the design. The final pulley drives the joint which raises and lowers the wrist. A second motor attached to the wrist turns the final shaft. Connected to the final shaft is a container made for placing calibrated weights. With the use of a power supply, a current sensor and a thermistor, shown in figure 6b, it is possible to acquire the drawn current of the motor and its temperature. For dynamic testing, such as cycles of raising and lowering the payload, the test bench is modified to link the payload directly to the motor with a bar, as illustrated in figure 7

The test bench is initially calibrated via the use of FT6335m servomotors from *Feetech*, since their torque values are known. Then, two types of tests can be done: A static load for an extended period of time and a dynamic load raised and lowered multiple time. An example of a static and a dynamic test's results are shown in figure 8a and 8b respectively. From there, the characteristics of the *OmniServo* can be tested. It helps to evaluate the potential of the custom made servo motors for the arm joints. A similar test bench, excluding timing pulleys, is planned for the brushless motors.



(a) CAD design



(b) Setup of the test bench with the sensors and power supply.

Figure. 6: Static test bench of the servomotors and power transmission

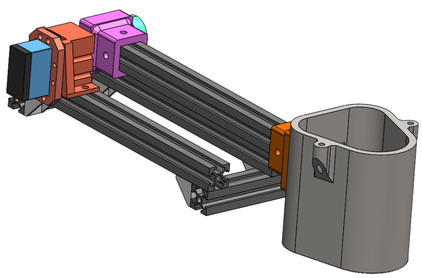


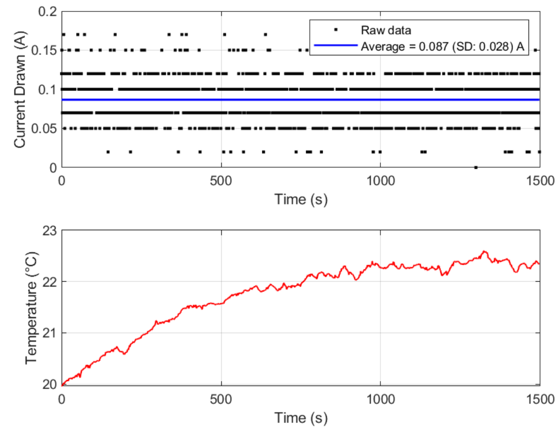
Figure. 7: CAD design of the dynamic test bench

E. Current Design

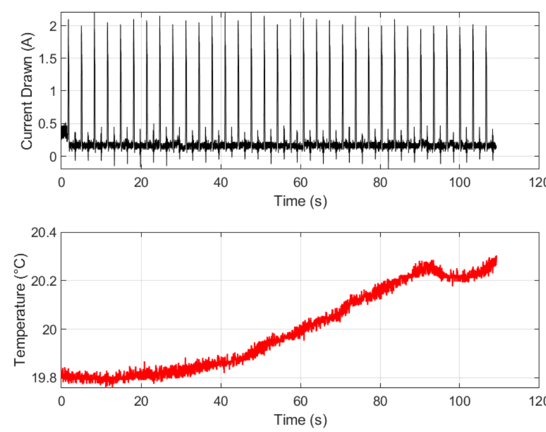
The design of the robot arm, from joints J_4 to J_6, is illustrated in Figure 9a. It represents the current progress of the robot arm, as the forearm's results are critical for the design of the rest of the arm. These joints incorporate the *OmniServos* for actuation. Specifically, joints J_4 and J_5 feature a 1:2 belt reduction ratio, which has been selected based on the torque requirements for these joints. In contrast, joint J_6 is directly driven without any reduction.

IV. Conclusion

This project aims to develop a low-cost assistive robotic arm capable of effectively manipulating common household objects. Based on the established requirements, the kinematic chain of the arm has been calculated, torque requirements have been determined, and the design for joints J_4 to J_6 has been completed and assembled, as shown in Figure 9b. The next phase of the project will involve the continuation of the design, including the design of the BLDC actuators, and of the fabrication and assembly. Once assembled, motion control will be programmed, and testing will be conducted in collaboration with physical medicine and rehabilitation (PM&R) professionals. Additionally, a torque-limiting mechanism is being considered for certain joints to enhance compliance, allowing the arm to fold against hard surfaces to prevent damage. However, it is crucial that the arm maintains its position when holding an object, even in the absence of power. Overall, SIARA Version 2 demonstrates significant potential to build upon the initial proof of concept, meeting the critical requirements of weight and cost.



(a) Static testing results. The motor was bearing a load of 0.9kg for 25 minutes.



(b) Dynamic testing results. The motor was moving a load of 0.1kg for 100 cycles.

Figure. 8: Current drawn and temperature of the *Feetech* ft6335m servomotor for static and dynamics loads.

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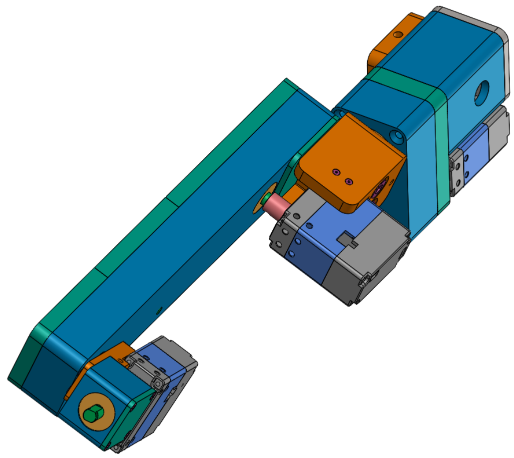
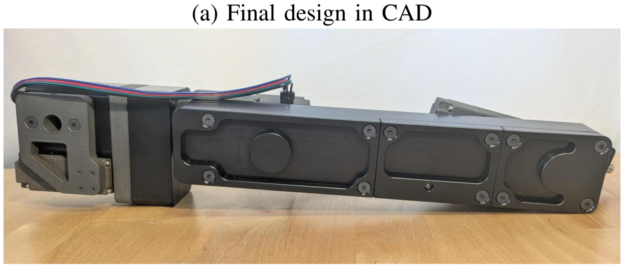


(a) Final design in CAD



(b) Side view of the current assembly

Figure. 9: Complete assembly of the robot arm from joint J_4 to J_6.

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