Dual Humanoid Robotic Hand System for Real-Time

Speech-to-Sign Language Translation

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Descriptive Abstract

Communication between deaf and hearing individuals remains a significant challenge. One major contributing factor is the limited proficiency in sign language among hearing populations, often due to a perceived lack of necessity to acquire it. This study explores the design and development of a dual humanoid robotic hand system to translate natural speech into sign language in real time through the integration of natural language processing, simulation, and an optimised power system. Through an iterative design and development process, the proposed system aims to bridge the communication gap between deaf and hearing communities.

Contents

Deafness is a physical disability characterised by partial or complete loss of hearing, and it can significantly affect an individual's ability to communicate with others. Individuals who are deaf often rely on visual forms of communication, such as sign language, lip-reading, and written text. However, they face numerous challenges in daily life, including barriers to communication, limited access to education and employment opportunities, and social isolation due to the lack of widespread proficiency in sign language among hearing people.

These challenges are further exacerbated by the lack of tools for effective, real-time translation and a low incentive from the hearing community to learn sign language. The global prevalence of hearing loss has increased in recent years, making this issue more significant. In fact, according to the World Health Organization, over 430 million people worldwide require rehabilitation for disabling hearing loss, a number projected to rise to over 700 million by 2050 (World Health Organization, 2026).

Robotics is an emerging field with high potential in supporting individuals with disabilities due to its wide integration of sensing technologies, artificial intelligence, and mechanical ingenuity. According to Nanavati et al. (2024), assistive robotic systems can improve independence in daily activities for individuals with disabilities by up to 60% in controlled environments. Therefore, our research attempted to explore robotics in combination with natural language processing (NLP) software as a solution to translate natural speech to sign language.

This report focuses on the contributions and work completed by Hashem Altajar. It reflects an independent account of the design and development process and has been prepared with a commitment to academic integrity and originality.

1. Communication Barriers Between Deaf and Hearing Individuals

1.1 Limited Incentive to Learn Sign Language

A key factor contributing to the communication barriers between the deaf and hearing communities is the limited incentive for learning sign language. Since spoken language is most dominantly used in social, educational, and professional environments, many people do not face the need to learn sign language, as they do not perceive it as a necessary skill. As a result, sign language is commonly overlooked and further burdens the communication gap for deaf people. According to Mitchell and Young (2023), approximately 2.8% of the U.S. population speaks American Sign Language. This small proportion highlights the low incentive for U.S. citizens to learn sign language.

As illustrated in Figure 1, the number of deaf people in the global population represents a constant but minority level of the total population. Roughly 0.12% of the global population has complete hearing loss. This implies that because of the minority status of the deaf population, particularly among younger generations, sign language is often overlooked in education and social development, leading to limited awareness.

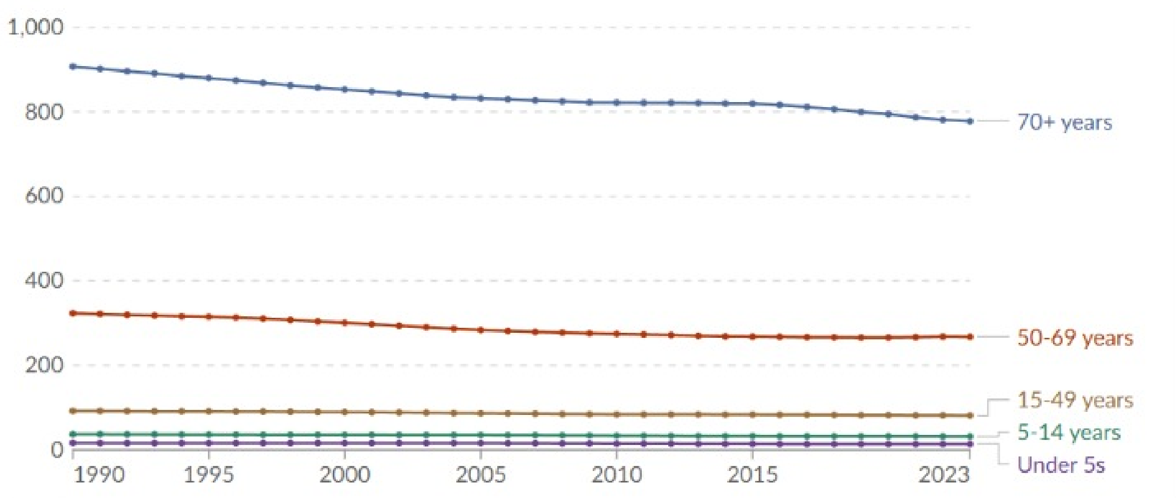

Figure 1: Number of people with complete hearing loss, per 100,000 people in the global population.

Note. From Global Burden of Disease (2025).

1.2 Regional Sign Language Differences

An additional communication barrier that exacerbates the communication gap between hearing and deaf individuals is regional differences in sign languages across the globe. According to National Geographic (2024), there are over 300 different types of sign languages. Not only can it be difficult for deaf individuals to communicate with hearing people, but they may also face challenges when communicating with other deaf individuals. This diversity makes it difficult to educate hearing individuals about sign language on a global scale. It also highlights the need for accessible technology that can quickly recognise multiple spoken languages and translate them in real time into the appropriate sign language.

2. Dual Robotic Hand System for Sign Language Translation

2.1 Literature Review

Several robotic arm systems have been previously designed to facilitate speech-to-sign language communication. Alabbad et al. (2022) successfully proposed and developed a robot-based system using the Pepper robot capable of two-way translation between Arabic Sign Language (ArSL) and spoken language.

Adeyanju et al. (2022) proposed a modular robotic hand built with locally sourced materials and coupled with an Android application for speech recognition. The device successfully translated spoken input into ASL letters and numbers, with an accuracy rate of 78.4%. This work emphasises the accessibility of low-cost, speech-to-sign robotic systems, particularly for educational and assistive contexts.

Al-Khulaidi et al. (2019) introduced SignBot, a robotic hand powered by servo motor arrays to replicate Malaysian Sign Language. The robot executed pre-programmed motion sequences in response to speech input, demonstrating the practicality of robotic systems for language bridging. Although limited to predefined motions, SignBot illustrates early efforts toward embodied robotic signing.

2.2 Project Objective and Impact

The objective of this project is to develop a robotic system that implements two human-like arms that translate natural speech to American Sign Language (ASL). Minimally viable communication is the current goal for this project, with basic numerical and alphabetical translation the first fundamental step. ASL is chosen due to its simplicity and widespread use with its own grammar and structure, and conveying it through human-like robotic arms allows for more accurate, expressive, and intuitive signing compared to text-based or screen-dependent alternatives.

The underlying impact of the robotic system is bridging the gap in communication between hearing and deaf people. Specifically, the project aims to translate spoken languages from around the world into the corresponding sign languages used by their communities. The project's capability can be further explored for its software utility in the quick real-time translation of any language to its sign language.

2.3 Project Planning and Management

Table 1: Members and Task Distribution

<table>
<tr><th>Name</th><th>ID</th><th>Distinguished Tasks</th><th>Common Tasks</th></tr>
<tr><td>Hashem Altujar</td><td>202432940</td><td>Simulation, Robotic Hand Assembly, Power System Design</td><td rowspan="4">Documentation</td></tr>
<tr><td>Abdullah Omar Siddiqui</td><td>202453040</td><td>Robotic Hand Assembly, Power System Design</td></tr>
<tr><td>Abdulrahman Omar Siddiqui</td><td>202450780</td><td>Robotic Hand Assembly, 3D Design, Power System Design</td></tr>
<tr><td>Ali Naeem Al Shaikh Ahmed</td><td>202179050</td><td>Jetson Nano Configuration, Pipeline Software Development</td></tr>
</table>

Table 1 highlights the distinctive and common tasks assigned to each team member. Members were assigned roles based on previous experience as well as their respective majors.

The overall system pipeline was divided into five stages, as shown in Figure 2: Audio Capture, Speech-to-Text Synthesis, Text Normalisation, ASL Mapping, and Sign Synthesis. During audio capture, speech is captured at a continuous stream, using a push-to-talk mechanism with a "STOP" keyword for control. The captured speech is then processed by a speech-to-text (STT) module on the Jetson, initially constrained to a limited vocabulary such as letters and numbers. This stage is followed by text normalisation, where each letter is cleaned and standardised. For example, the letter "W" would be translated as the letter itself rather than the phrase "double u." Each character or number is represented by predefined joint configurations for the robotic arms in a JSON format. Finally, the sign synthesis stage generates smooth, human-like motions by transitioning between poses with controlled speed and timing, ensuring readability.

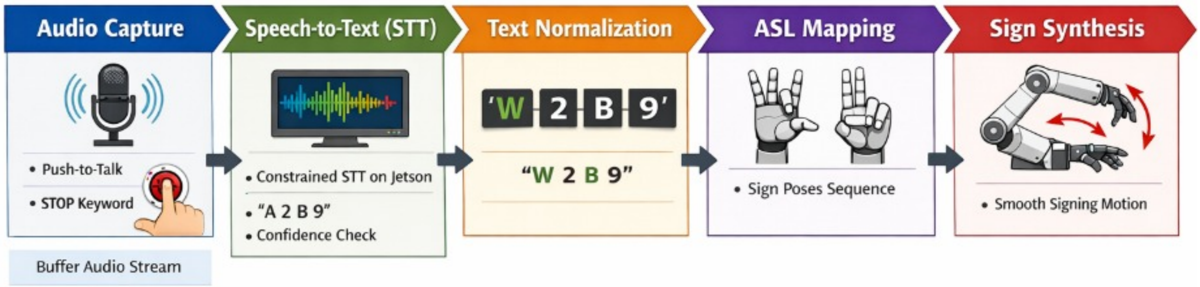

Figure 2: Natural Speech to Sign Language Translation Pipeline

2.4 Market and Engineering Requirements

Table 2: Market and Engineering Characteristics

Engineering	**Marketing**
Economy: <3500 SAR in Cost	**Target Market:** Educational institutions, research labs, and hobbyists interested in affordable AI-enabled robotics.
Weight: Medium weight (<15 kg)	**Usability:** Easy to install, operate, and maintain with minimal technical expertise required.
Performance: Fast Response; Accurate with a high degree of freedom (90% or higher); clearly understandable	**Market Differentiation:** Offers dual-arm manipulation and AI processing (Jetson Nano) at a lower cost and weight compared to similar systems.

Table 2 highlights the key engineering and marketing aspects of the proposed dual humanoid robotic arm system, including its low cost (under 3500 SAR), midweight design (under 15 kg), and high-performance motor-driven operation for accurate, real-time speech-to-sign language translation. It also outlines the target market, ease of use, and the system's differentiation through its dual-arm capability and AI-based processing.

2.5 Initial Iterative Design

2.5.1 3D Design

The first 3D design of the prototype was conceived during the early stages of the development period. The design was fully outsourced from the online website GrabCad, and can be shown in Figure 3.

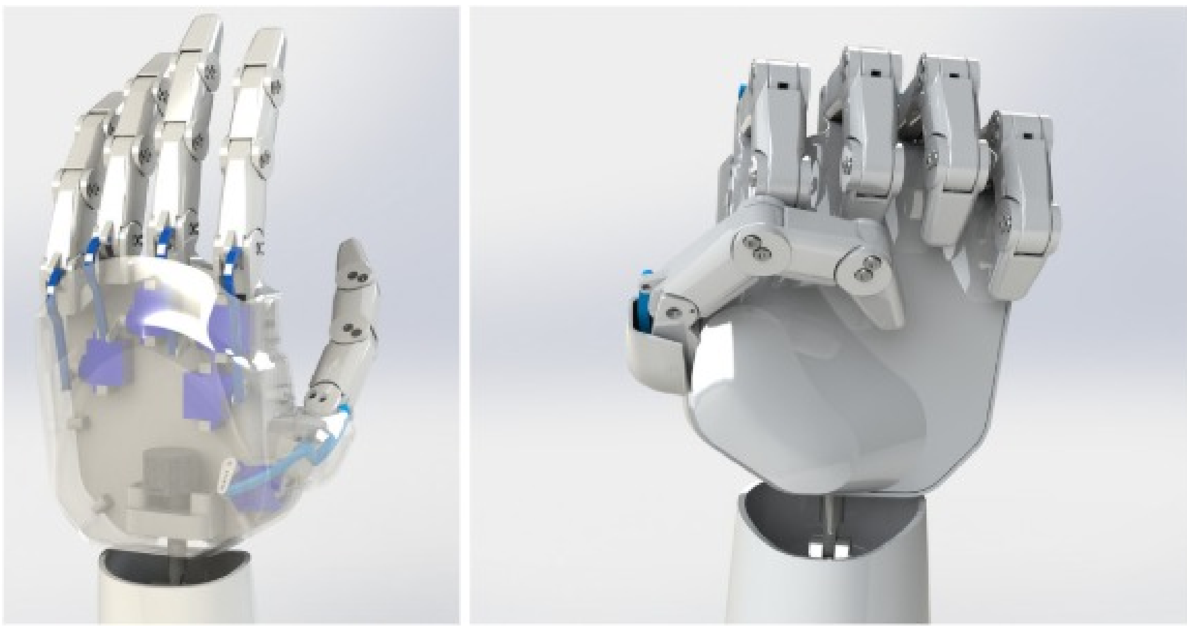

Figure 3: Initial Robotic Hand Design

Note. From Nurman Turkic (2020).

2.5.2 Assembly

Figure 4 showcases the assembly of the printed components for the first design. The overall assembly was performed equally by all members of the team.

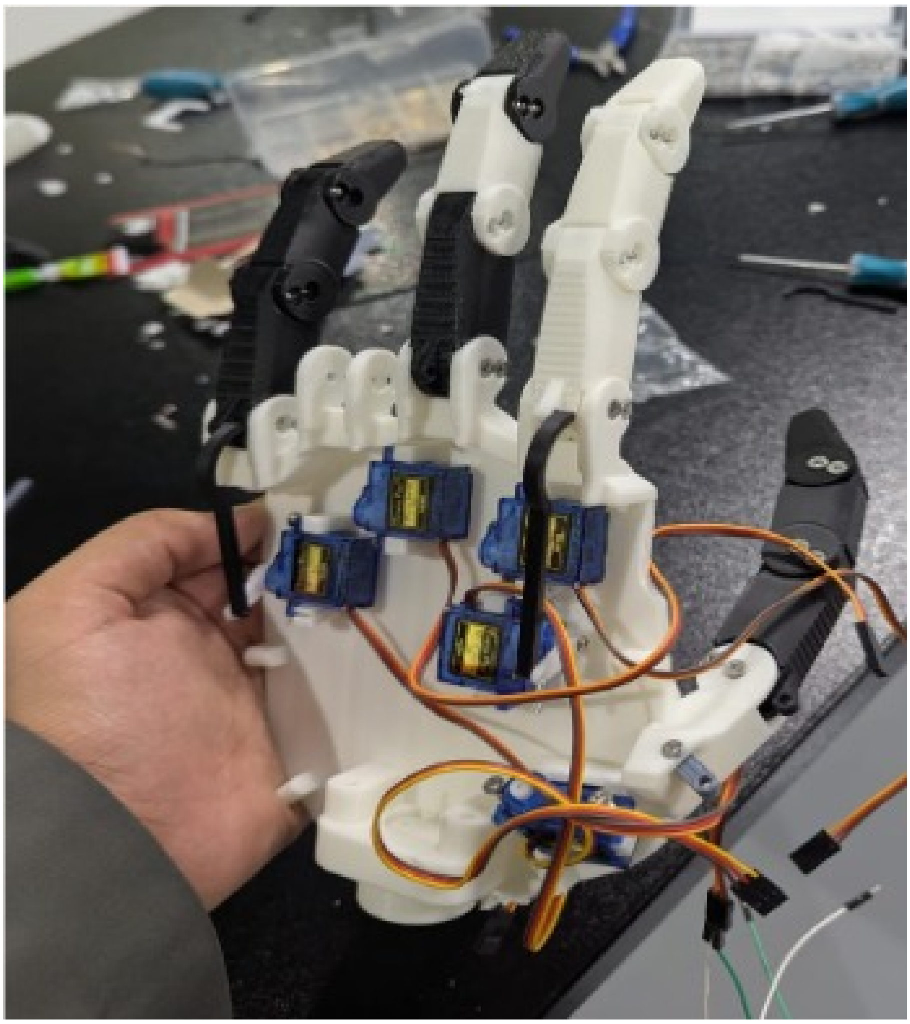

Figure 4: Initial Robotic Hand Design

2.5.3 Design Challenges

Upon assembly and testing, multiple design flaws were documented:

- Disproportionately large component sizes that were inaccurate in comparison to the average human hand size.
- The plastic rods used for finger rotation are attached to the fingers very rigidly without screw holes, and they break very often, as shown in Figure 5.

Figure 5: Initial Robotic Hand Design

Note. From Nurman Turkic (2020).

- Screw holes were very flimsy and unstable, which led to frequent drilling, broken parts, and thus more reprints that cost a lot of time.
- The SG90 servo motors frequently broke due to their insufficient power output.
- Plastic components for rotating the fingers were highly rigid and introduced a lot of unnecessary friction that damaged the servos.
- The thumb component had misaligned screw holes that prevented the attachment of the servo motors.

2.5.4 Future Improvements

- Finger rotation using a combination of strings attached to stronger servos effectively reduces the risk of damaged components and provides for faster, power-efficient rotation.
- Align the servos on the forearm of the robotic hand to save space and allow for an additional servo motor to be attached to the palm for thumb rotation.
- Utilise stronger servos with a higher torque output.

2.6 Second Iterative Design

2.6.1 Components

Table 3: Components and Pricing

Component Name	Quantity	Price (SAR)
20 kg Digital Servo Motor	×12	65
150 kg Digital Servo Motor	×4	150
380 kg Servo Drivers	×4	115
PCA9685 Servo Driver	×2	50
DC-DC Variable Buck Converters	×3	30
NVIDIA Jetson Nano Orin	×1	1,100
	TOTAL COST	**3,130 SAR**

2.6.2 Simulation

The dual-arm robotic system was simulated using MuJoCo to evaluate the kinematic structure and motion behaviour before physical testing. The model was constructed using imported STL mesh files representing the shoulder, bicep, elbow, forearm, palm, and finger components. Each arm was organised as a hierarchical body structure, beginning from the shoulder base and extending through the bicep, elbow, forearm, palm, and fingers. Hinge joints were assigned to each moving segment to represent the rotational degrees of freedom required for arm lifting, bicep motion, forearm rotation, thumb movement, and finger curling.

The fingers were modelled using multiple hinge joints connected through tendons and equality constraints to ensure coordinated curling motion. Motor actuators were assigned to the major arm joints, while position actuators were used for the finger tendons to simulate controlled finger flexion. Joint limits, damping, and force constraints were included to prevent unrealistic movement and to better approximate the behaviour of the physical prototype.

The simulation was mainly used to verify joint placement, motion ranges, actuator behaviour, and the overall coordination between both robotic arms. In some testing views, the STL meshes were hidden to allow clearer observation of the joint markers and kinematic structure. This helped identify alignment issues and confirm that the simulated motion followed the intended mechanical design. Figures 6-8 show one arm of the simulation translating the first three letters of the alphabet.

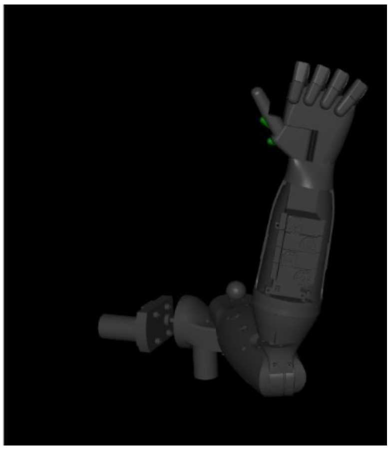

Figure 6: Letter A

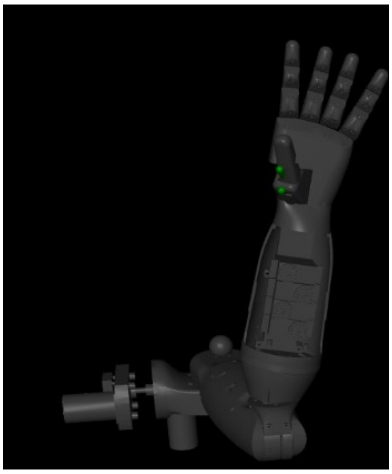

Figure 7: Letter B

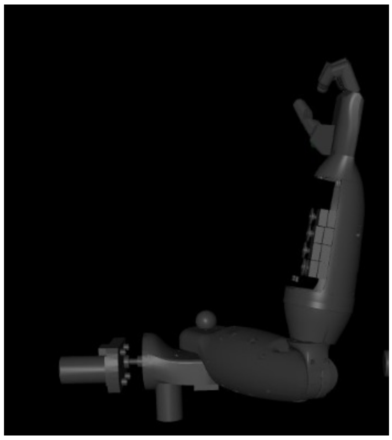

Figure 8: Letter "C"

2.6.3 Hardware Architecture

The hardware architecture of the robotic system utilises a three-branch parallel connection from a 16 V DC power supply. Two of these branches are connected to DC-DC buck converters: one steps down the voltage to 5 V to power the two PCA9685 servo driver boards, while another provides 12 V for the 150 kg servos. The third branch supplies power directly to the 380 kg servo motors.

The PCA9685 servo drivers generate PWM control signals, which are received from the Jetson Orin Nano. The Jetson acts as the central controller, managing and distributing commands to each servo group. All components share a common ground to ensure stable operation and reliable signal referencing. It is important to note that the PCA9685 boards provide control signals only, while the servos are powered directly from the dedicated power lines. Figure 9 illustrates the overall system connections.

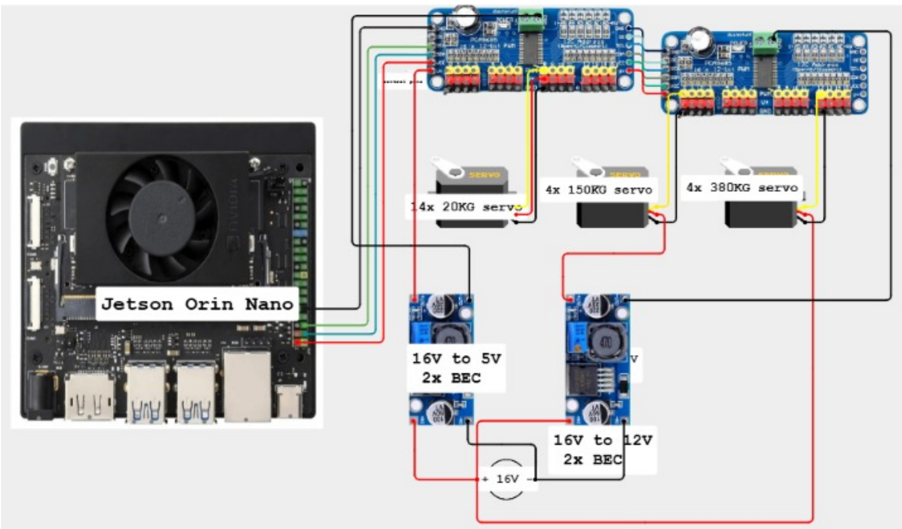

Figure 9: Hardware Architecture Wiring Diagram

2.6.4 3D Design

Taking the first design's flaws and improvements into consideration, the second iterative design yielded much more positive results. Figure 10 showcases various components' CAD models and their overall assembly. The new design incorporated a system of fishing line strings wrapped around a set of motors. Rotation of the motors results in the components contracting and relaxing.

Each arm is equipped with six 20 kg servos located in the forearm, where five motors control the rotation of individual fingers and the sixth controls thumb rotation. Two 150 kg servos are positioned on the biceps to manage the contraction and relaxation of each arm. An additional two 150 kg servos are mounted externally and connected to the biceps via bicycle cables, enabling up to 180-degree rotation of the bicep mechanism. Finally, two 380 kg servos are mounted externally at the shoulders to control the raising and lowering of the entire arm, which explains the requirement for a higher supply voltage.

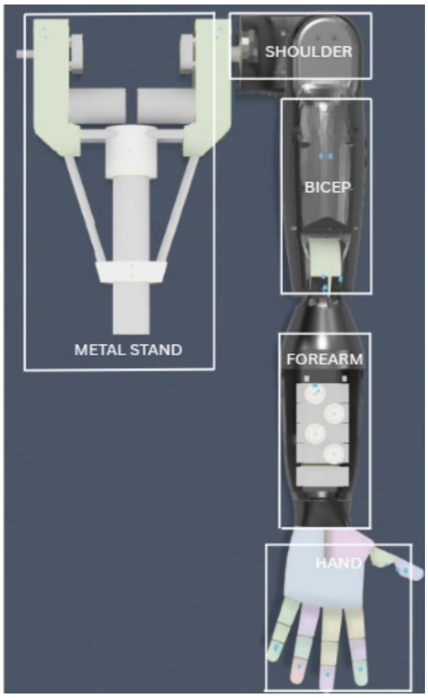

Figure 10: Initial Robotic Hand Design

The design was partially inspired by an existing model available online (Ryonicle, 2025), with additional modifications and enhancements developed by Abdulrahman Siddiqui to optimise speed and power consumption. Specific modifications include the biceps: the original design used an externally mounted motor, whereas the modified design attaches the motor directly to the bicep, as shown in Figure 11, allowing rotation of the bicep and reducing mechanical complexity compared to an external motor connected via a string.

Figure 11: *Enhanced Bicep Design*

2.6.5 Assembly

The assembly process consists of three stages: mechanical assembly of the arm structure, installation of servomotors and cable mechanisms, and integration of the power and control systems.

The mechanical assembly begins with the base of the robotic arm system. A solid base requires it to be mobile and stable. Mobility is crucial for a system that weighs an estimated 15 kg for the convenience of transportation and demonstration. The conceived base can be observed in Figure 12: a 1.6-metre steel pipe with a diameter of 10 cm is attached to the rolling base of a moveable office chair. A 3D-printed, mountable part is attached to the top of the metal pipe, with four thin, long metal rods inserted through the 3D part. The two 380 kg servo motors can then be attached to the top of the pipe, allowing the mounting of the two robotic arms.

Figure 12: Robot Base (left) and 3D-mounted parts with steel pipes (right).

After the construction of the base comes the construction of the robotic arms themselves. The robotic arms can be divided into four parts: Hands, Forearm, Bicep, and Shoulder. The hands consist of five fingers that relax and contract by the servo motor pulling the fishing line strings attached to the fingers. Each finger consists of three plastic parts that are held together via fishing lines inserted through. The pulling and relaxing of the fishing line using the servo causes contraction and relaxation of the fingers. An additional motor is attached at the centre of the hand for rotating the thumb. The hand can be observed in Figure 13.

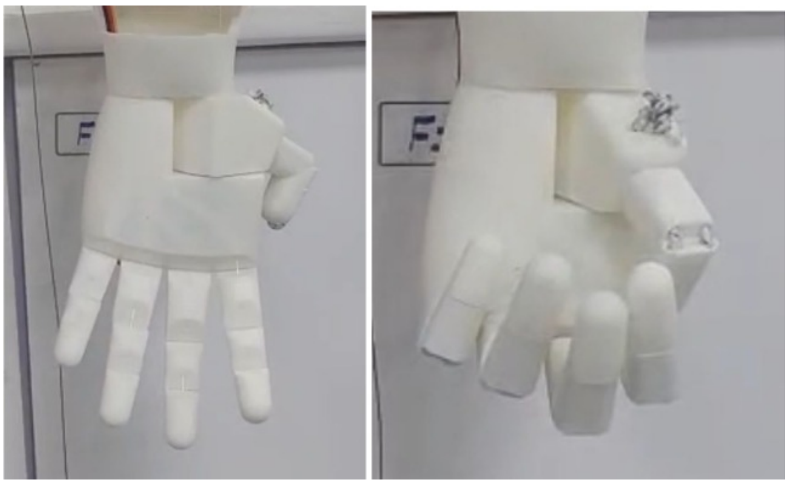

Figure 13: Robot Hand Assembly: Open (Left) and Closed (Right).

The next component is the forearm. The forearm contains five screwed servos responsible for the finger movements. Circular servo heads are designed for the winding of the strings, where a 180-degree rotation causes the strings to be wound tighter and, therefore, bend the finger using tension. The forearm and servo head design can be observed in Figure 14.

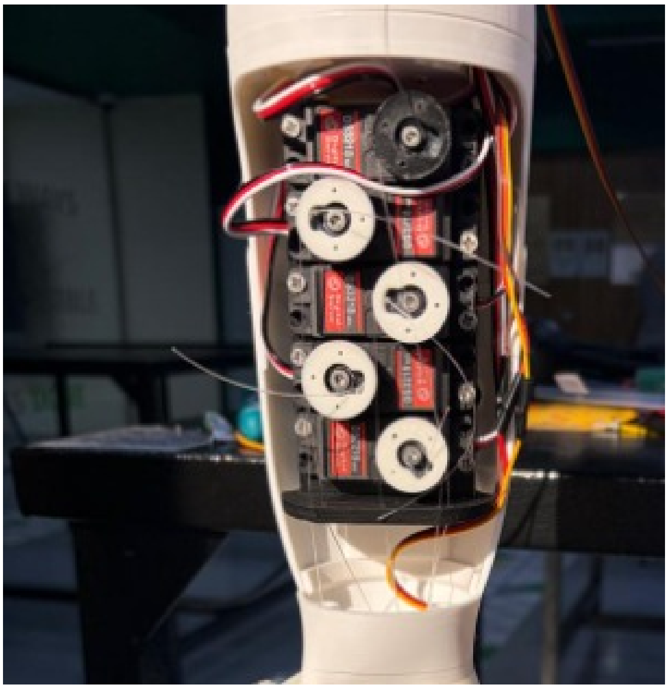

Figure 14: Forearm

The bicep is the intermediate component attached between the forearm and the shoulder. It contains three servo motors: one (20 kg) located at the bottom of the bicep responsible for the rotation of the forearm, one (120 kg) at the top of the bicep responsible for the rotation of the entire arm, and another (120 kg) located externally responsible for the curling of the bicep, made possible by using brake cables that loop around the joint connecting the bicep and the forearm. The bicep can be observed in Figure 15.

Figure 15: Bicep: Relax (Top Left) and Curled (Top Right)

For the shoulder, its implementation was straightforward. Each arm contains two 380 kg servos attached to the shoulder component of the robot, one for forward rotation and another for sideways rotation. When initially testing the sideways rotation of the arm, the force applied to the shoulder joint was very high and caused the part to lose stability and break off. The issue was fixed later on by printing the same shoulder components with higher infill density and using deeper, stronger screws. The shoulder forward and sideways rotation can be observed in Figure 16.

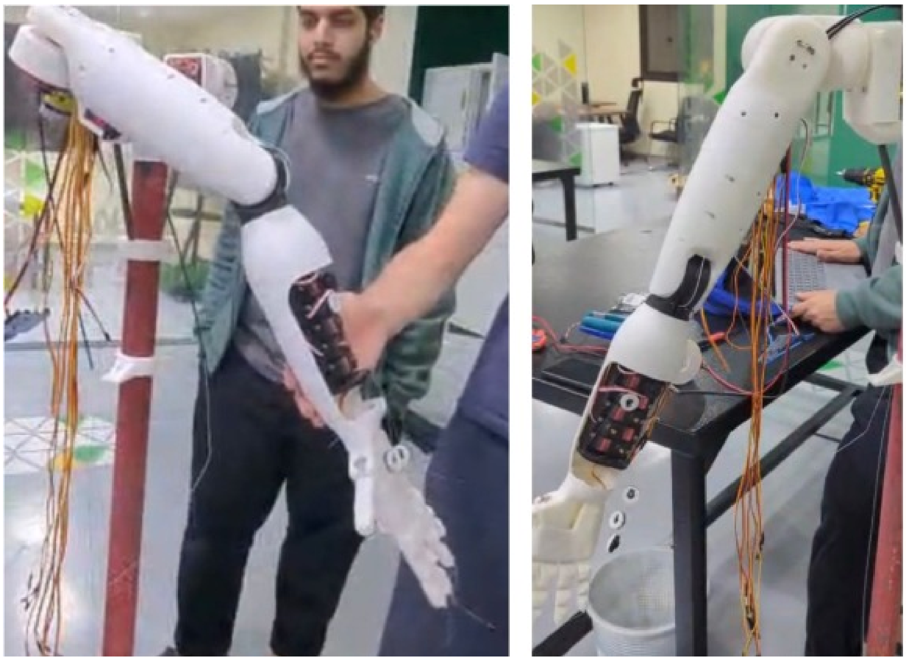

Figure 16: Shoulder: Forward Rotation (Left) and Sideways Rotation (Right)

The power and control system integration proved to be the most challenging stage of the design process due to the varying voltage requirements of the different motor groups. Each set of servos operates at a distinct voltage level, requiring a parallel power distribution system supported by multiple DC-DC buck converters.

The 20 kg servos, which are responsible for forearm movement and finger articulation, operate at 5 V and are connected directly to the PCA9685 servo drivers. In this configuration, both control signals and power are supplied through the PCA boards, with two 5 V buck converters used to ensure stable and sufficient current delivery, one dedicated to each arm.

The 150 kg servos, which control the contraction and relaxation of the bicep as well as contribute to the rotation of the arm, require a higher operating voltage of 12 V. These servos are connected to the PCA9685 drivers for PWM control, but are powered externally via a 12 V buck converter rather than through the PCA itself. To maintain proper signal referencing and stable operation, they share a common ground with both the PCA drivers and the 5 V servo system.

The 380 kg servos, responsible for the shoulder's lateral and forward lifting motions, require the highest power and were initially intended to be controlled through the PCA9685 while being powered externally. However, during testing, this configuration led to significant overcurrent issues, causing the buck converter to shut down repeatedly.

Additionally, an early testing oversight further impacted the system's reliability. The system was left ungrounded overnight, allowing excessive charge build-up and damaging several electronic components, requiring their replacement. Despite installing new components, similar overcurrent issues persisted when attempting to drive the 380 kg servos through the regulated setup, reinforcing the need for a direct power connection.

3. Conclusion

This project presented the design and development of a dual-arm robotic system intended to translate natural speech into American Sign Language (ASL). The work primarily focused on the mechanical design, assembly, and simulation of the robotic arms to achieve coordinated, human-like motion suitable for sign language representation.

The final system successfully demonstrated full mechanical actuation across all joints. Both robotic arms were capable of executing coordinated movements, including finger articulation, forearm rotation, bicep motion, and shoulder positioning. During initial testing, all motors operated simultaneously across both arms, confirming the effectiveness of the mechanical design and actuator integration.

However, subsequent testing revealed critical limitations in the power distribution system. Specifically, overcurrent issues caused the DC-DC buck converters to shut down under load, particularly when driving the higher-torque servos. This prevented sustained operation of the full system and highlighted the challenges associated with managing high-current requirements in multi-actuator robotic platforms. Additionally, earlier grounding issues led to component damage, reinforcing the importance of proper electrical design and system protection.

While the mechanical and hardware aspects of the system were successfully developed and validated, the full software integration—particularly the speech-to-sign translation pipeline—was not completed within the project timeline. As a result, a complete end-to-end demonstration of real-time speech translation was not achieved. Nevertheless, the robotic system provides a functional foundation, with all necessary degrees of freedom and actuation capabilities required for future integration of the software pipeline.

In conclusion, the project demonstrates the feasibility of a dual-arm robotic platform for sign language representation at a mechanical level. Despite challenges in power management and incomplete software integration, the system establishes a strong basis for future work, where improved electrical design and fully implemented control software can enable complete, real-time sign language translation.

4. Recommendations

To further develop and enhance the dual-arm robotic translation system, several improvements are recommended:

1. Use high-current rated DC-DC converters.
2. Implement a proper grounding system for the robot to remove residual charges.
3. Complete the speech-to-text and NLP pipeline.

4. Expand beyond basic alphanumeric translation to full ASL words and sentences.
5. Develop a bimodal translation system capable of interpreting both American Sign Language (ASL) and natural speech through the integration of camera-based vision and audio processing.
6. Test with deaf users or sign language experts and evaluate readability.

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