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Development of Wireless Master Slave Humanoid Robot Arm

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Abstract:
This paper presents an in-depth mechatronics design methodology for developing a wireless master-slave humanoid robot arm, combining mechanical engineering, electrical system design, and advanced programming to deliver a fully functional robotic system. The primary objective of this work is to develop a safe and reliable solution for executing tasks in environments that are too dangerous or inaccessible for humans such as bomb disposal, volcanic area exploration, and contaminated zones. The development process included a detailed mechanical design of a six-degree-of-freedom humanoid arm, as well as the construction of custom printed circuit boards (PCBs) and power systems. The electrical system integrated multiple microcontrollers, rotary encoders, motor drivers, and solid-state relays, all coordinated through custom-developed control architecture. A key feature of the system is the implementation of a robust wireless communication link, based on the nRF24L01 module, providing real-time control and feedback over distances up to 50 meters. The control algorithms allow the slave arm to precisely mimic the movements of the master arm using master-slave synchronization. After extensive testing, the robot demonstrated reliable performance and responsiveness, confirming the practicality and efficiency of the proposed design. This work not only shows the potential of wireless teleoperation in high-risk scenarios but also contributes a scalable design framework for future robotic applications in hazardous environments.

Keywords:
Robot Arm, Master-Slave, Wireless Robot, Humanoid Robot.

1 Introduction

A robot is an artificial agent that can be either virtual or mechanical, typically realized as an electromechanical machine guided by computer programming to execute tasks autonomously, often displaying movements or behaviors that suggest intent or agency; the term "robot" originates from a Slavic word for "work," historically referring to the labor of serfs, and scientific definitions now emphasize robots as automated devices that mimic human intelligence or as reprogrammable, multifunctional manipulators designed for various tasks. A manipulator, in this context, is a specialized robotic device engineered to handle materials without direct human contact, originally developed for managing hazardous or hard-to-reach substances, but its modern applications now extend to areas such as robot-assisted surgery and space exploration; typically, a manipulator comprises a segmented, arm-like mechanism with sliding or jointed segments that offer multiple degrees of freedom for grasping and moving objects, and in industrial ergonomics, these devices function as lift-assist tools enabling workers to maneuver heavy, hot, or bulky items by reaching into confined spaces for precise removal and placement, with their ability to execute complex motions like pitching, rolling, and spinning further enhancing their versatility and efficiency in diverse manufacturing processes.

1.1 History of Robots and Manipulators

Robotics traces its roots to the ancient world—with early devices such as those created by Ctesibiusand evolved significantly during the Industrial Revolution through breakthroughs in complex mechanics and electricity, ultimately giving rise by the early 20th century to the concept of humanoid machines that paved the way for industrial robots revolutionizing manufacturing without human intervention[1]. Influential works, including Mary Shelley's Frankenstein and Karel Čapek's 1921 play *R.U.R.*, introduced the term "robot" and framed early notions of artificial life, ideas later refined by Asimov's "Three Laws of Robotics"[2],[3]. The field advanced rapidly with key milestones such as Norbert Wiener's Cybernetics in 1948, the debut of UNIMATE in 1961, and the development of computer-controlled robotic arms like the Rancho Arm in 1963, followed by further innovations including mobile robots like Shakey in 1970, sensor-integrated arms in 1974, and the Stanford Cart in 1979, all highlighting an ongoing evolution toward robots with near-human intelligence and movement[4],[5]. Concurrently, significant progress in remote manipulation was achieved in 1945 when Central Research Laboratories developed a remote manipulator for Argonne National Laboratory to handle radioactive materials safely within a sealed chamber; the resulting Master-Slave Manipulator Mk. 8 (MSM-8) enabled researchers to operate normally by manipulating materials through the chamber's side wall design that supplanted earlier methods of overhead manipulation[6], [7]. Notably, Robert A. Heinlein later attributed the concept of remote manipulation to a 1918 *Popular Mechanics* article describing a man with myasthenia gravis who devised lever arrangements to overcome his physical limitations, suggesting that the idea of remote manipulators has deeper historical roots than is commonly recognized[8].

1.2 The Essential Characteristics

A robot must be equipped with sensors such as light, touch, chemical, hearing, and taste sensors to perceive its environment and possess the capability to move either as a whole unit or through articulated parts, thereby navigating its surroundings; a reliable energy source, whether solar, electrical, or battery-powered, is essential for sustained operation, while programming endows the system with the intelligence necessary for task execution, collectively integrating sensing, movement, energy, and intelligence as the defining characteristics of robotics[9]. Equally critical is the design of manipulators, which are classified by their motion characteristics planar manipulators operate with links in parallel planes, spherical manipulators execute movements around a common point in a spherical manner, and spatial manipulators incorporate links with a full range of spatial movements and by their kinematic structures, distinguishing between open-loop (serial) configurations, closed-loop (parallel) systems, and hybrid manipulators that combine elements of both[10]. Furthermore, a comprehensive robotic system integrates several fundamental components that work in unison: a mechanical linkage composed of rigid links, joints, and an end effector for executing specific tasks; actuators and transmissions that convert control signals into physical movements via electric, pneumatic, or hydraulic systems; sensors that provide critical environmental feedback for collision avoidance, object differentiation, and task precision; and a central controllersupported by a user interface and power conversion unit that processes programmed instructions and converts them into actionable signals for the actuators[11].

1.3 Types of Robots and Manipulators

Robots are classified into several types based on their functionality and operating environment[12]. Mobile robots, for instance, navigate autonomously without fixed physical locations, while autonomous underwater vehicles operate beneath the surface without operator input[13]. Service robots perform tasks that are dirty, dull, distant, dangerous, or repetitive, thereby enhancing human well-being outside of manufacturing, and educational robots provide a platform for learning through the design and construction of prototypes. Additionally, collaborative, modular, and manipulator robots are engineered for seamless integration into production environments, adaptability through reconfiguration, and material handling without direct human contact[14]. Manipulators themselves are classified by configuration and application: remote manipulators also known as telefactors or waldo devices enable human operators to control hand-like mechanisms via electronic or mechanical linkages for handling hazardous materials; serial robots, which are the most common type in industry, consist of a series of rigid links connected by motor-actuated joints that typically mimic a human arm with at least six degrees of freedom (although simpler SCARA robots with four degrees of freedom are also prevalent); and parallel manipulators employ closed-loop chains, such as those found in the six-actuator Stewart platform, to achieve higher stiffness and distribute positioning errors among multiple chains[15]. Furthermore, mobile manipulators, which integrate locomotion with manipulation, offer distinct advantages over stationary systems, underscoring the diverse approaches taken to meet specific operational requirements in robotics[16].

1.4 Master-Slave Robots

Master-slave humanoid arms represent a pinnacle of teleoperated robotics, merging the precision of remote manipulation with the dexterity and intuitive control of human movement[17],[18]. Initially developed to protect workers in hazardous environments, these systems have evolved from simple mechanical linkages and cables to sophisticated assemblies integrating electrical, hydraulic, and digital control systems. Modern implementations employ high-fidelity sensors, advanced actuator technologies, and real-time feedback mechanisms including haptic feedback and closed-circuit imaging to closely mimic the operator's movements with remarkable accuracy and responsiveness[19]. This level of control enables intricate tasks across diverse applications, from space exploration and underwater operations to medical surgery and advanced prosthetics. The ongoing development of master-slave humanoid arms not only enhances the safety and efficiency of remote operations but also paves the way for revolutionary advancements in human-machine interaction, promising significant impacts in both industrial and rehabilitative domains[20],[21].

1.5 Problem Statement

Designing a wireless master-slave humanoid robot arm with 6 degrees of freedom (DOF) involves integrating advanced concepts in robotics, control systems, wireless communication, and mechanical design. The proposed system had a configuration as shown in Figure 1that assure a proper process for transferring joint angles from master arm to slave arm.

Figure 1: Master-Slave Proposed System

1.6 Master-Slave Configuration

- Master Device: Typically, a human-operated interface that captures the operator's movements. The master device sends control commands that mimic natural human motion.
- Slave Device: The robotic arm, which replicates the motions commanded by the master. It must interpret incoming commands accurately and move its joints accordingly.
- Control Loop: A real-time closed-loop control system ensures that the slave arm follows the master's input with minimal delay. Feedback from sensors on the slave is critical to adjust and correct the motion

1.7 Master Arm Mechanical Design

The master arm is designed to resemble a human arm, with dimensions based on human anatomy. It consists of a wrist, elbow, and shoulder as shown in Figure 2and is made of an acrylic frame that the user straps to their arm and back. The arm has six joints, each equipped with an encoder that converts its position into an electrical signal. These signals are sent to control panels to generate commands for the movement of the slave joints.

To ensure that the master arm accurately mimics natural human movement, the design process also considered the biomechanical workspace of the human arm. The typical workspace for a human arm shown in Figure 3 includes a spherical volume extending approximately 70 cm from the shoulder center, covering a range of 180° in shoulder flexion, 150° in elbow flexion, and 180° in wrist rotation. These constraints were used to guide the joint positioning, encoder limits, and mechanical range of motion. Incorporating these workspace parameters into the design ensures both ergonomic fidelity for the human user and accurate translation of motion to the robotic slave arm.

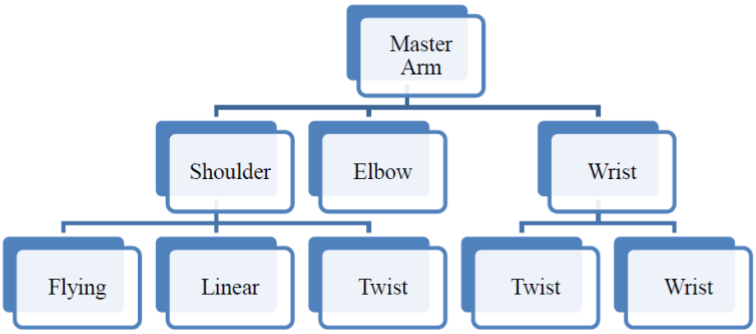


Figure 2: Master Arm Configuration

The CAD design as shown in Figure 4 and Figure 5of the full master arm, intended to be mounted on a human arm, is an intricate and highly detailed process that requires a balance between biomimetic accuracy and mechanical functionality. The design process involves creating precise digital models that replicate the natural curvature, joint positions, and dimensions of a human arm, ensuring ergonomic compatibility and comfort for the user.

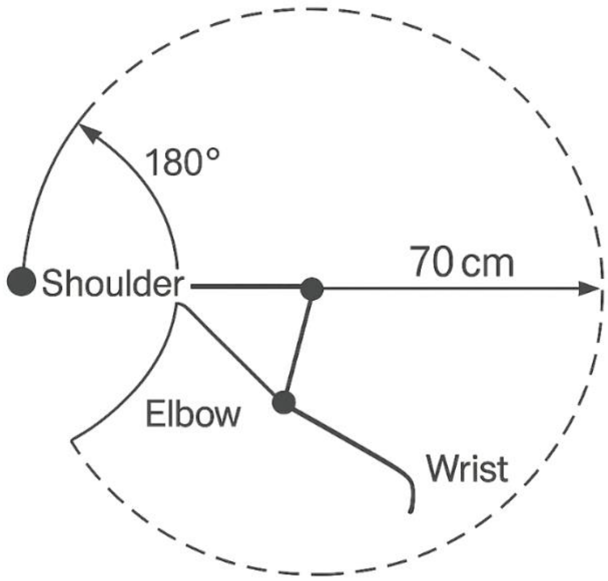


Figure 3: Workspace of Human Arm

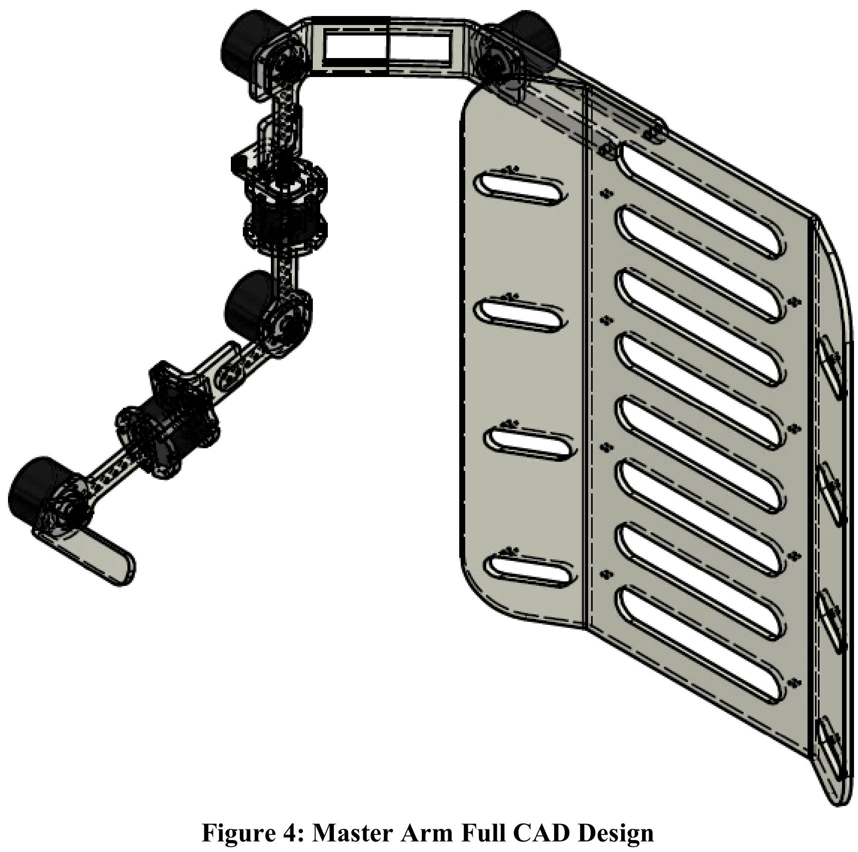


Figure 4: Master Arm Full CAD Design

Emphasizing complexity, the design incorporates multiple modular components, each with integrated encoders and sensors, to accurately capture and translate the nuances of human movement. The assembly is designed with robust structural supports and interlocking mechanisms, which not only ensure durability and stability but also allow for easy maintenance and upgrades. This high level of detail in the CAD model ensures that every joint, from the shoulder to the wrist, is precisely aligned, providing the necessary accuracy for the control system to deliver a seamless and responsive user experience.

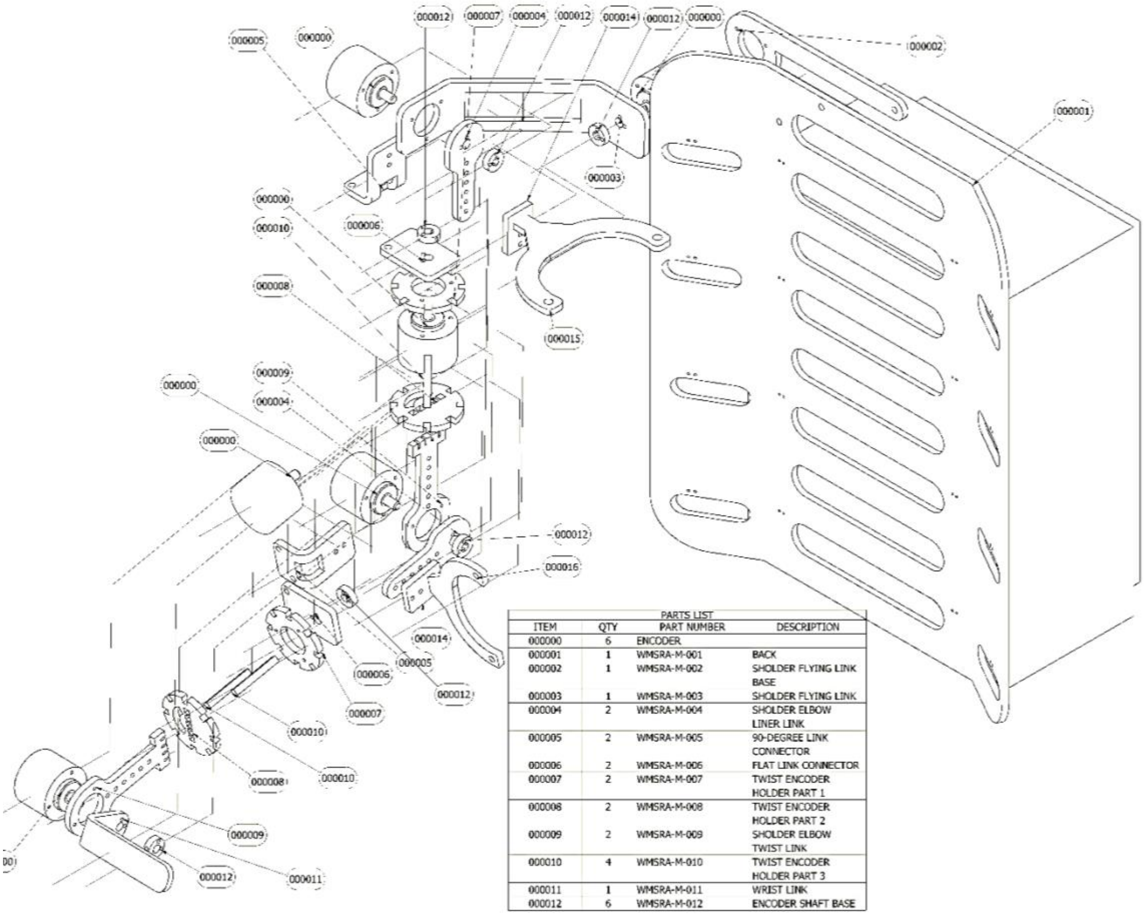


Figure 5: Master Full Mechanical Design CAD Exploded View

1.7.1 Master Shoulder

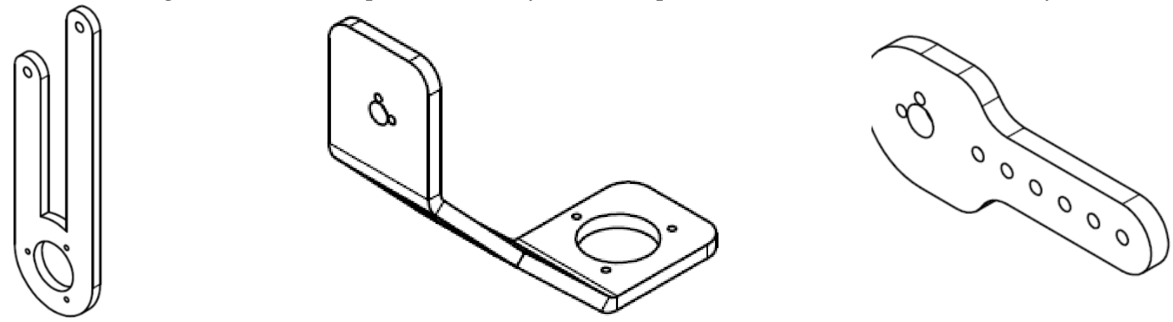
The shoulder part of the master arm is meticulously engineered to replicate the natural movement and stability of a human shoulder. As shown in the schematic inFigure 6, the shoulder mechanism integrates several components including the main joint, connecting supports, and encoder mounting points as shown in Table 1that work together to provide smooth and precise articulation. The accompanying table outlines the dimensions and material specifications for each component, ensuring consistency with human arm proportions and optimal performance. The encoder installed at the shoulder axis converts rotational movements into electrical signals, which are then processed by the control panels to direct the corresponding movements of the slave joints. This detailed design not only enhances the ergonomic function of the master arm but also ensures accurate and reliable motion tracking during operation.

Table 1: Shoulder Parts Description

Joint Name	Design Parts Description	Part Code	Cross Reference
Flying	Shoulder flying link base: It was made, used as a connection between the back of the master and the next part shoulder flying link and used at its end as a joint node for the encoder	WMSRA-M-002	Figure 6(A)
	Shoulder flying link: It was made, used as connection between the pervious part and the next part shoulder elbow linear link, used at its beginning as a joint node for the encoder	WMSRA-M-003	Figure 6(B)
Linear	Shoulder elbow linear link: It was made, adjustable for different arm dimensions and used as connection between the pervious link and 90-degree link connector	WMSRA-M-004	Figure 6(C)
Twist	90-degree link connector	WMSRA-M-005	Figure 6(D)
	Flat link connector	WMSRA-M-006	
	Twist encoder holder part1	WMSRA-M-007	Figure 6(E)

Twist encoder holder part2	WMSRA-M-008	Figure 6 (F)

In addition, the design of the shoulder component emphasizes both durability and ease of maintenance. The modular construction allows for quick replacement of individual parts, if necessary, while the detailed schematic serves as a comprehensive guide for assembly and troubleshooting. This thoughtful approach to design and documentation supports efficient performance testing and calibration, ensuring that the shoulder part consistently meets the precise demands of the master arm system



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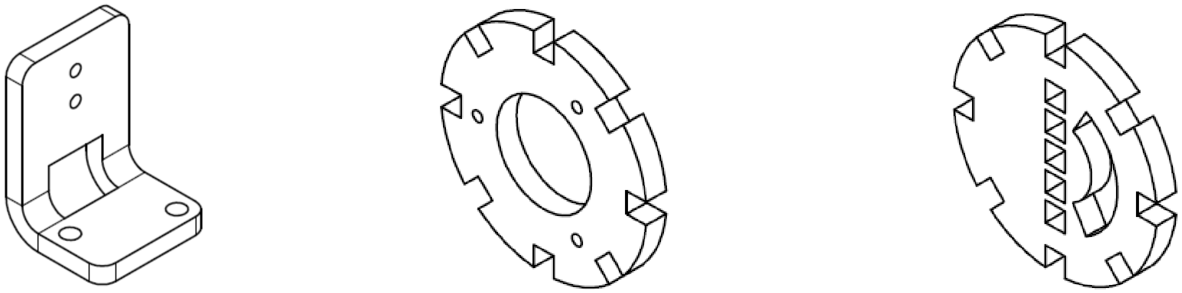
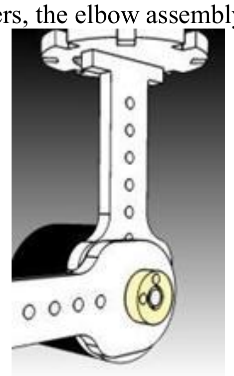


D E F

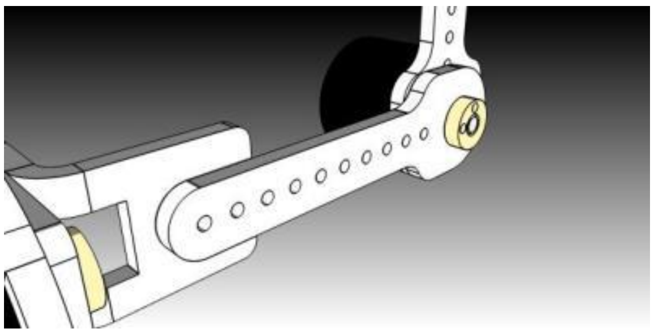
Figure 6: Shoulder CAD Parts

1.7.2 Master Elbow

The elbow assembly of the master arm is designed to provide smooth and precise only one DOF bending motion, closely replicating natural human arm movement. It comprises two main components: the shoulder elbow twist link (WMSRA-M-009) and the shoulder elbow linear link (WMSRA-M-004). As shown inFigure 7, both links are adjustable for different arm dimensions, ensuring a comfortable fit for a wide range of users. The twist link serves as a connection between the twist encoder holder and the shoulder elbow linear link, enabling rotational movements. Meanwhile, the linear link bridges the twist link and the 90-degree link connector, allowing for the necessary extension and flexion at the elbow. By translating mechanical motion into electrical signals via encoders, the elbow assembly ensures that every movement of the master arm is accurately relayed to the slave system.



WMSRA-M-009



WMSRA-M-004

Figure 7: Master Elbow CAD Parts

1.7.3 Master Wrist

The wrist of the master arm is designed with 2 degrees of freedom (DOF) to accurately mimic the complex rotational and flexional movements of a human wrist. This design consists of three main parts that work together to ensure precise motion tracking and secure encoder integration. Each part plays a critical role in aligning and supporting the encoders, allowing them to capture the rotational data of the wrist joints effectively. The first part serves as the wrist encoder house as shown inFigure 8,. The second and third parts as shown inFigure 9is a rotating joint that enables one axis of motion (Wrist Bending Motion). Together, these components ensure that both encoders are correctly aligned with their respective axes of rotation. This setup guarantees that all wrist movements are accurately recorded and transmitted as electrical signals to the control system for responsive and synchronized movement in the slave arm.

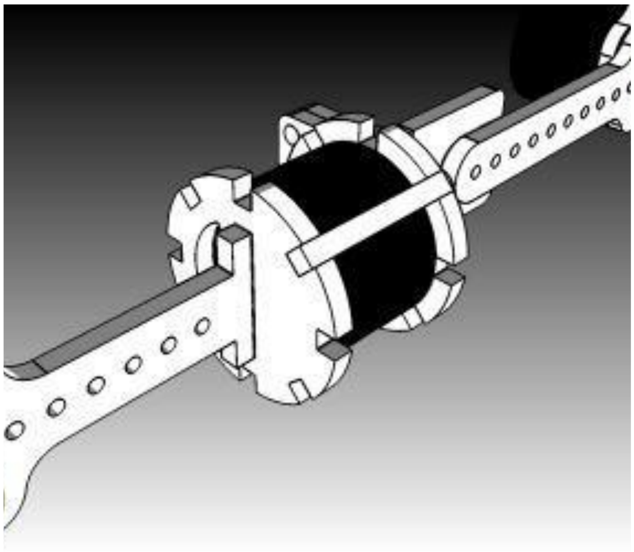
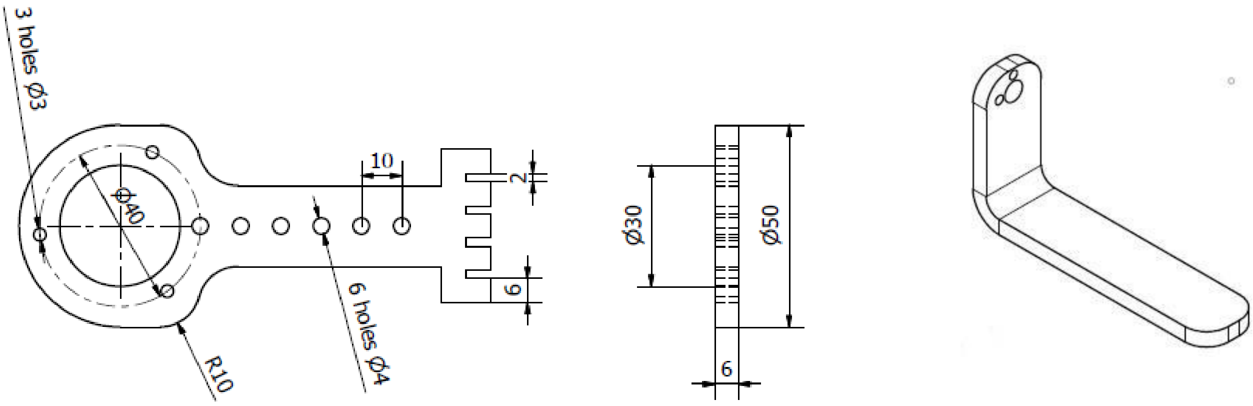


Figure 8: Wrist Twist Encoder House



Wrist Link 1 Wrist Link 2

Figure 9: Wrist Bending CAD Parts

1.8 Slave Arm Mechanical Design

The slave arm is engineered to mimic the appearance and proportions of a human arm, with its dimensions scaled up to accommodate embedded motors, as depicted inFigure 10. It comprises a wrist, elbow, and shoulder, each designed for precise movement and robust performance. The enlarged scale ensures that there is sufficient space within the arm to house the necessary motors and related components, providing enhanced strength and accuracy in motion. Additionally, the slave arm is mounted onto a metal holder that incorporates the slave control panel, facilitating seamless integration and coordinated control with the master arm system.

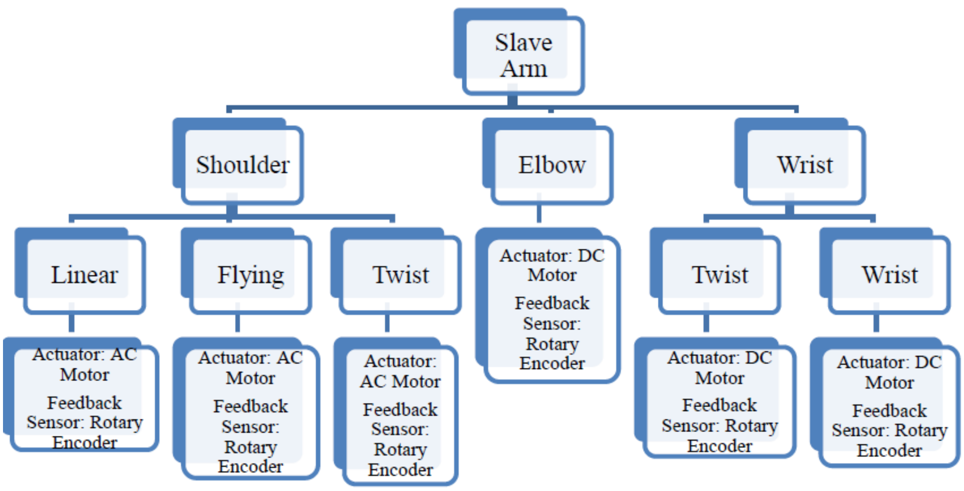


Figure 10: Slave Arm Configuration

Furthermore, the mechanical design of the slave arm emphasizes durability and operational precision. The larger scale not only accommodates powerful motors but also improves the arm's load-bearing capacity, ensuring smooth replication of human-like movements. The embedded motors work in tandem with the control panel to execute commands accurately, while the metal holder provides a stable and secure base for the entire system. This robust construction supports rigorous performance demands and allows for straightforward maintenance and potential future upgrades, making the slave arm both a reliable and adaptable component of the overall system

The slave arm as shown in Figure 11is a sophisticated assembly designed to mirror human arm functionality while accommodating the necessary mechanical components internally. The slave shoulder, with its 3 degrees of freedom (DOF), is driven by three separate motors that allow for a wide range of motion, closely replicating the natural movement of the human shoulder. The elbow features a 1 DOF mechanism powered by a single motor, enabling precise bending and extension. Additionally, the wrist is engineered with 2 DOF, utilizing two motors to handle complex rotational and flexional movements. To integrate these motors within the arm's structure, bevel gears are employed to switch the motion through a 90-degree drive train. This clever use of bevel gears not only optimizes the internal layout of the motors but also ensures that the motion transmitted is smooth and accurately aligned with the design's functional requirements.

As shown in the red parts in Figure 12encoders were strategically placed on every joint, transforming both AC and DC motors into precise servo-position motors. These encoders convert the rotational movements into electrical signals, which are then processed by the control system to ensure accurate positioning of the end effector. This integration significantly enhances the slave arm's precision, allowing it to replicate complex human arm movements with high fidelity and ensuring that every movement is carefully monitored and adjusted in real time.

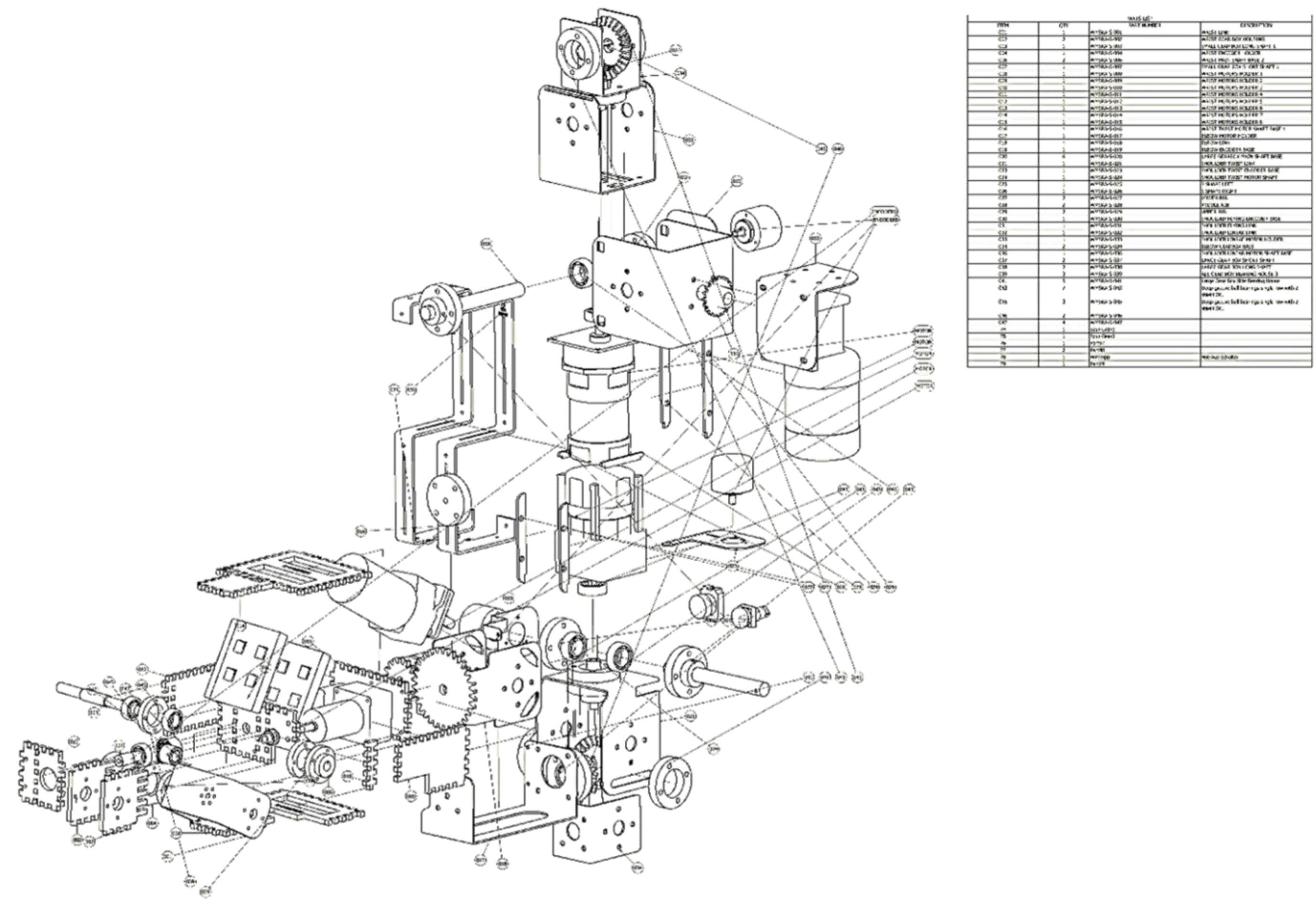


Figure 11: Slave Mechanical Design CAD Exploded View

The blue parts in the CAD model are fabricated from stainless steel, a material chosen for its superior strength, excellent corrosion resistance, and high durability. These properties ensure that the parts can withstand significant stresses and perform reliably under demanding conditions, also green ribs were added to strengthen the parts which is critical for robust stress analysis. Additionally, stainless steel's ductility and toughness allow for precise and effective bending during the manufacturing process. Initially, the components are accurately cut using a laser CNC machine, which guarantees exact dimensions and clean edges. Following the cutting process, the parts are then formed using a bending machine, ensuring that they maintain structural integrity and meet the design specifications while taking full advantage of stainless steel's capabilities.

The wrist structure is constructed from acrylic, a material chosen for its lightweight properties and ease of manufacturing. This choice minimizes the overall mass of the wrist assembly while still providing adequate strength for the intended application. Acrylic is also well-suited for precise fabrication, making it ideal for streamlined production processes. Its ease of machining and cost-effectiveness contribute to a design that is both efficient and reliable, ensuring that the wrist mechanism can be produced quickly and with high quality.

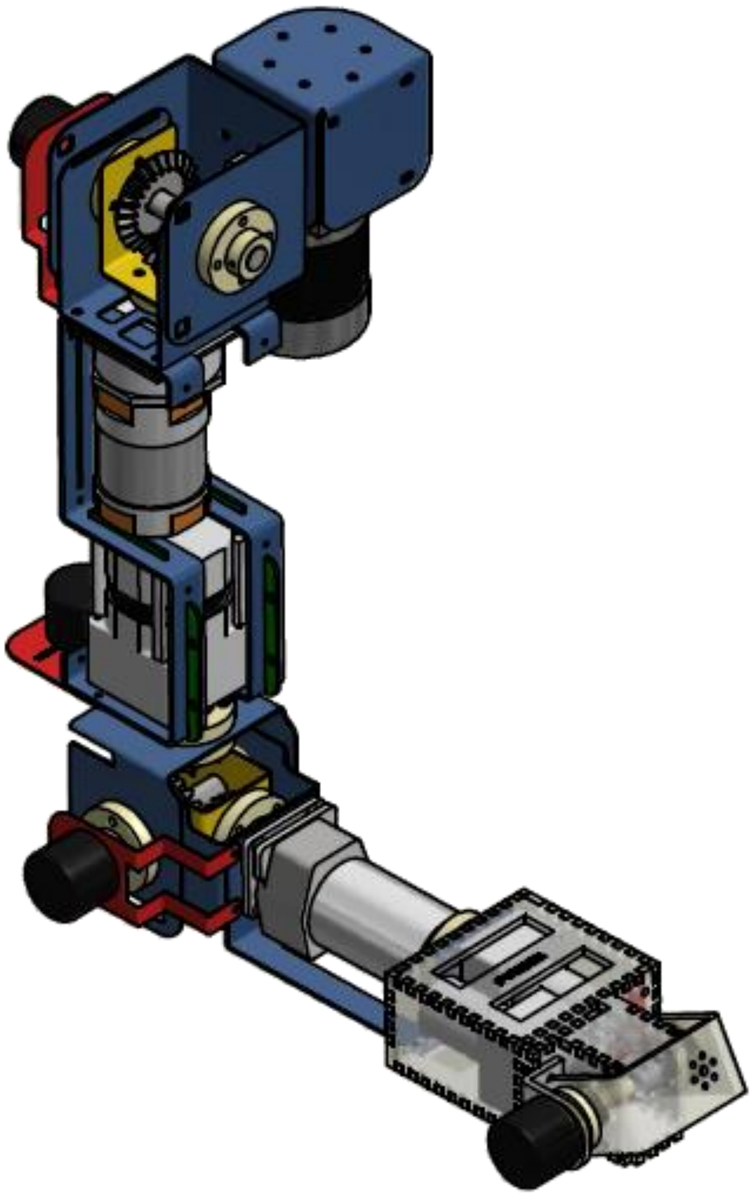


Figure 12: Slave Arm Full CAD Design

The slave robot arm is designed with a 6-DOF configuration, comprising a 3-DOF shoulder, a 1-DOF elbow, and a 2-DOF wrist. The mechanical structure is primarily constructed from stainless steel and acrylic components, chosen for their specific properties in supporting the arm's functionality.

1.8.1 Slave Shoulder

The shoulder joint enables 3 degrees of freedom through a combination of linear and rotational (Flying and Twist) movements as shown in a detailed description in Table 2andTable 3.

Table 2: Shoulder Linear Motion Components

Part Name	Description	Cross Reference
Shoulder Linear Motor Holder	This component (part no. WMSRA-S-033) is fabricated from stainless steel sheet metal and serves as the housing for the AC linear motor, which facilitates linear movement in the shoulder. The use of stainless steel ensures structural integrity and durability to withstand the motor's operational forces.	Figure 13 (A)
Shoulder Linear Link	The shoulder linear link (part no. WMSRA-S-032), also made from stainless steel sheet metal, connects the shoulder flying link to the linear motor holder. This connection is crucial for translating the linear motion of the motor to the adjacent joint.	Figure 13(B)

Figure 13: Slave Shoulder CAD Components

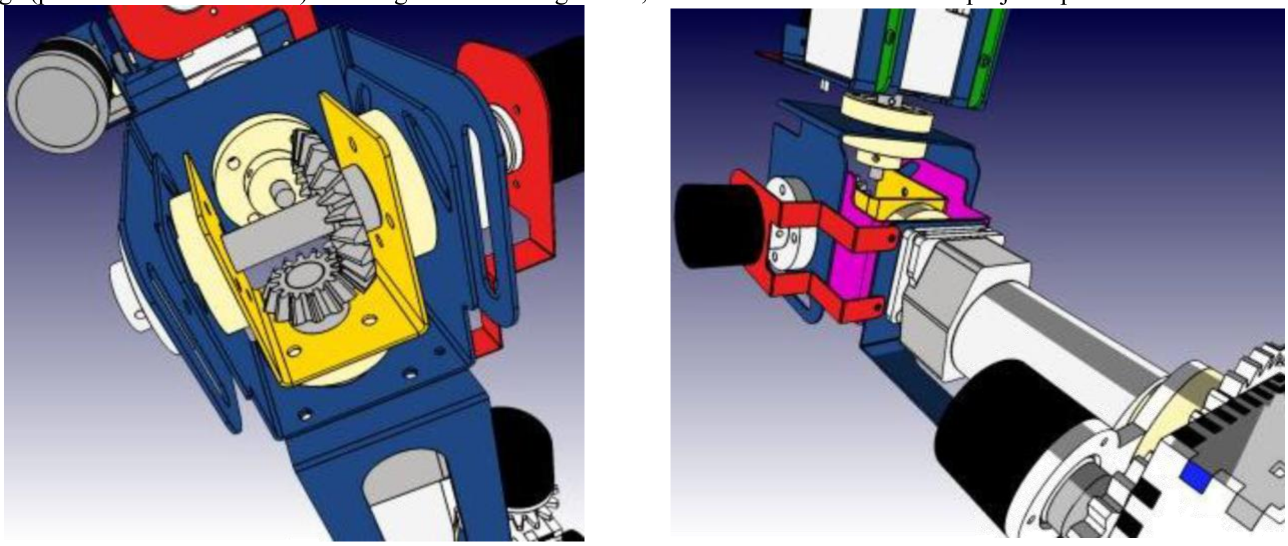
Table 3: Shoulder Flying Motion Components

Part Name	Description	Cross Reference
Shoulder Flying Link	This link (part no. WMSRA-S-031), constructed from stainless steel sheet metal, connects the S-shaped structures to the shoulder gearbox housing. It acts as a pivotal component in the shoulder's rotational movement	Figure 13(C)
Shoulder Gearbox	The gearbox assembly is crucial for altering the torque and speed of the rotational motion. It consists of several parts	Figure 13(D)
Shoulder Gearbox Base	(part no. WMSRA-S-035) A stainless steel sheet metal component that forms the base for the bevel gear module	
Bevel Gear Module	(part no. WMSRA-S-047) A gear from scrap, integrated into the gearbox to transmit rotational motion between non-parallel axes.	
Large Gearbox Shafts	(short: part no. WMSRA-S-037; long: part no. WMSRA-S-038) Machined from stainless steel, these shafts are essential for transmitting torque within the gearbox.	
Bearing Houses	(side: part no. WMSRA-S-041, aluminum; front: part no. WMSRA-S-042) These lathe-machined housings support the bearings, ensuring smooth rotation of the shafts. The use of aluminum for the side bearing house suggests a focus on weight reduction where feasible	
Large Gear Box Main Shaft Base	(part no. WMSRA-S-020) This lathe-machined component provides a base for the gearbox's main shaft.	
Ball Bearings	(part no. WMSRA-S-043) Specifically, SKF 6003 bearings are used, selected based on load calculations to ensure operational reliability	
Shoulder Flying Encoder Base:	(part no. WMSRA-S-030) Made from stainless steel sheet metal, this base supports the encoder, which is used to measure the angular position of the joint.	Figure 13 (E)
AC Motor Holder Assembly	This assembly supports the two AC motors responsible for the twist and flying motions of the shoulder	Figure 13 (F)
S-Shaped Components	(left: part no. WMSRA-S-025; right: part no. WMSRA-S-026) Stainless steel sheet metal parts that are likely to provide structural support and shape to the motor housing	
Ribs	(lower: part no. WMSRA-S-027; middle: part no. WMSRA-S-028; upper: part no. WMSRA-S-029) These stainless-steel metal ribs reinforce the structure, maintaining rigidity	

The twist motion of the shoulder joint is facilitated by a set of interconnected components that ensure both power transmission and accurate feedback. An encoder holder (part no. WMSRA-S-048) shown in Figure 13 (H) is employed to transfer the rotational motion from the motor shaft to the encoder shaft, which is crucial for providing precise position feedback for control purposes. The shoulder twist link (part no. WMSRA-S-021) shown inFigure 13 (G), constructed from stainless steel sheet metal, serves as the connection between the elbow link and the shoulder twist encoder base. This encoder base (part no. WMSRA-S-023), also made from stainless steel sheet metal, rigidly supports the encoder, ensuring accurate measurement of the twist motion. The torque generated by the motor is transmitted through a lathe-machined stainless steel shoulder twist motor shaft (part no. WMSRA-S-024). This shaft is, in turn, supported by a lathe-machined base (part no. WMSRA-S-022) as shown in Figure 13 (I).

1.8.2 Slave Elbow

Elbow joint incorporates a gearbox mechanism shown inFigure 14(A) to effectively manage torque and speed. This gearbox is constructed upon a stainless-steel metal base (part no. WMSRA-S-034) that provides a foundation for the bevel gear module. The bevel gear module itself (part no. WMSRA-S-047) is a salvaged component. Torque is transmitted through stainless steel lathe-machined shafts (short: part no. WMSRA-S-037; long: part no. WMSRA-S-038), which are supported by lathe-machined bearing houses (side: part no. WMSRA-S-041; front: part no. WMSRA-S-042). The gearbox assembly also includes an aluminum lathe-machined base for the main shaft (part no. WMSRA-S-020). To ensure smooth and efficient rotational movement, SKF 6003 ball bearings (part no. WMSRA-S-043) are integrated into the gearbox, with their selection based on project-specific load calculations.

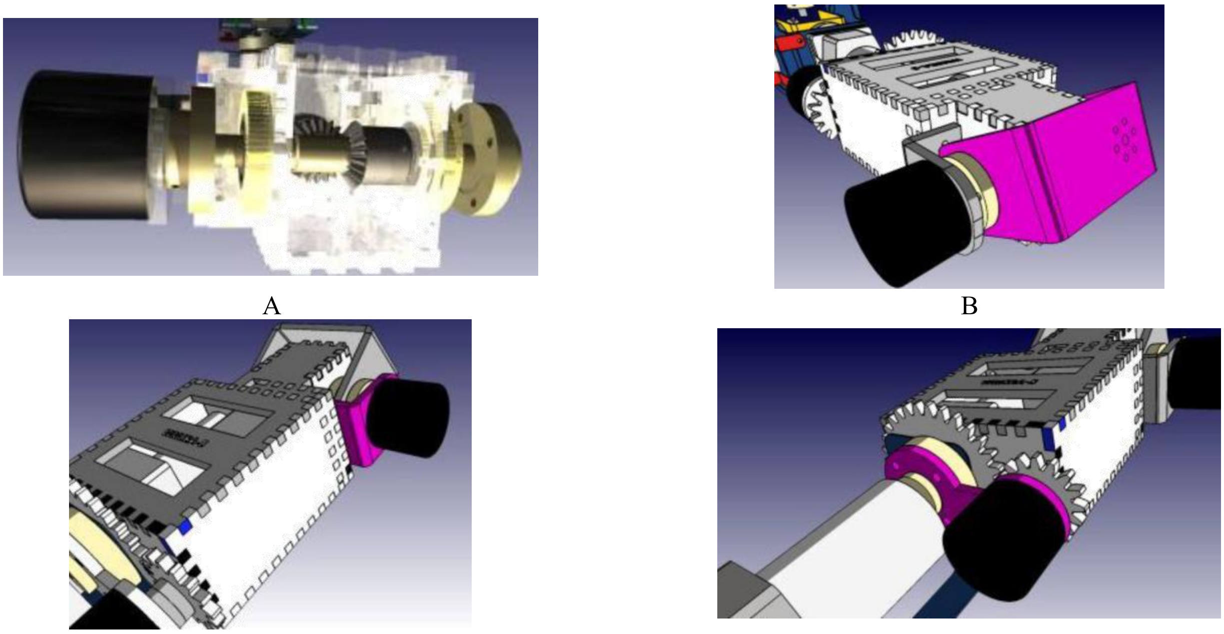


A B

Figure 14: Slave Elbow CAD Design

The joint's mechanical structure includes several key components that facilitate its movement and control. The elbow link (part no. WMSRA-S-018) as shown in Figure 14(B), manufactured from stainless steel sheet metal, provides a crucial connection between the elbow motor holder and the gearbox base, transmitting the rotational force. Additionally, an elbow encoder base (part no. WMSRA-S-019), also made from stainless steel sheet metal, serves to connect the elbow encoder to the elbow motor holder, ensuring accurate measurement of the elbow's angular position. The elbow motor holder (part no. WMSRA-S-017), constructed from stainless steel sheet metal, functions as the mounting structure for the motor, securing it in place within the arm assembly

1.8.3 Slave Wrist



A B

C D

Figure 15: Slave Wrist CAD Components

The wrist joint is designed to provide two degrees of freedom, enabling the robot arm to achieve complex orientations. A wrist link (part no. WMSRA-S-001)Figure 15(B), constructed from acrylic, is utilized, potentially to prioritize weight reduction at the end effector. The gearbox housing assembly Figure 15(A) includes a wrist gearbox housing (part no. WMSRA-S-002), also made from acrylic, which encloses the bevel gear module (part no. WMSRA-S-046), a salvaged gear component. The transmission of torque within the wrist is facilitated by gearbox shafts, specifically a small gear box long shaft (part no. WMSRA-S-003) and a small gear box short shaft (part no. WMSRA-S-007), both machined from stainless steel. These shafts are supported by a lathe-machined small gear box bearing house (part no. WMSRA-S-039), and the assembly incorporates a lathe-machined wrist main shaft base (part no. WMSRA-S-006). SKF 6021 ball bearings (part no. WMSRA-S-044) are used to ensure smooth rotational movement.

An acrylic wrist encoder holder (part no. WMSRA-S-004) and a wrist twist encoder base (part no. WMSRA-S-005) provide mounting and connection for the encoder, with the latter connecting the encoder to the acrylic wrist motor box shown in Figure 15 (C,D). The wrist motor box itself is an acrylic housing that contains several motor holders (part nos. WMSRA-S-008 to WMSRA-S-015) and a wrist twist motor base (part no. WMSRA-S-016). Finally, an encoder timing belt gear (part no. WMSRA-S-048) is employed to transmit motion from the motor to the encoder.

1.9 Master Arm Control Panel Electrical Design

The control panel of the master robot arm incorporates a variety of electronic components shown in Table 4 that collectively enable precise user control, real-time feedback, and wireless communication. At the heart of the system lies the Arduino Mega, which serves as the main controller, orchestrating signal processing and data communication between inputs and outputs. Supporting it are multiple Arduino Nano boards distributed across the panel, each dedicated to handling input signals from rotary encoders, optimizing modularity and signal integrity. The rotary encoders, sourced from HanyoungNux, are key input devices that detect angular movements of the user's arm or fingers, translating mechanical motion into electrical signals that are sent to the Arduino boards for interpretation. To power the entire setup, a 12V battery supplies electrical energy, while a PCB board—custom manufactured—organizes and connects the components for a clean and reliable layout.

Table 4: Master Control Panel Electrical Components

Part No.	Partname	Quantity	Notes
WMSRA-M-027	ControlPanel	1	
WMSRA-M-028	ArduinoMega	1	Arduinocompany
WMSRA-M-029	Battery(12v)	1	
WMSRA-M-030	PCBBoard	3	Manufactured
WMSRA-M-031	Rf(code:nRF24L01)	1	
WMSRA-M-032	Emergencystopswitch	1	
WMSRA-M-033	LCD	6	
WMSRA-M-034	ON/OFFSwitch	1	
WMSRA-M-035	USBhub	1	
WMSRA-M-036	Rotaryencoder	2	HanyoungNuxcompany
WMSRA-M-037	ArduinoNano	2	Arduinocompany
WMSRA-M-038	Rotaryencoder	2	HanyoungNuxcompany
WMSRA-M-039	ArduinoNano	2	Arduinocompany
WMSRA-M-040	Rotaryencoder	2	HanyoungNuxcompany
WMSRA-M-041	ArduinoNano	2	Arduinocompany

Additional supporting components enhance functionality and safety. A wireless RF module (nRF24L01) enables real-time communication between the master and slave units, allowing commands to be transmitted without physical connections. Visual feedback is delivered through six LCD screens, which can display sensor data, system status, or connection feedback. Safety is ensured via an emergency stop switch, allowing the system to be quickly deactivated during faults or accidents. A standard ON/OFF switch provides basic power control, while a USB hub facilitates programming and data transfer between the microcontrollers and a computer. Together, these components form an integrated, responsive, and user-safe control interface essential for operating the master arm in a master-slave humanoid robot system.

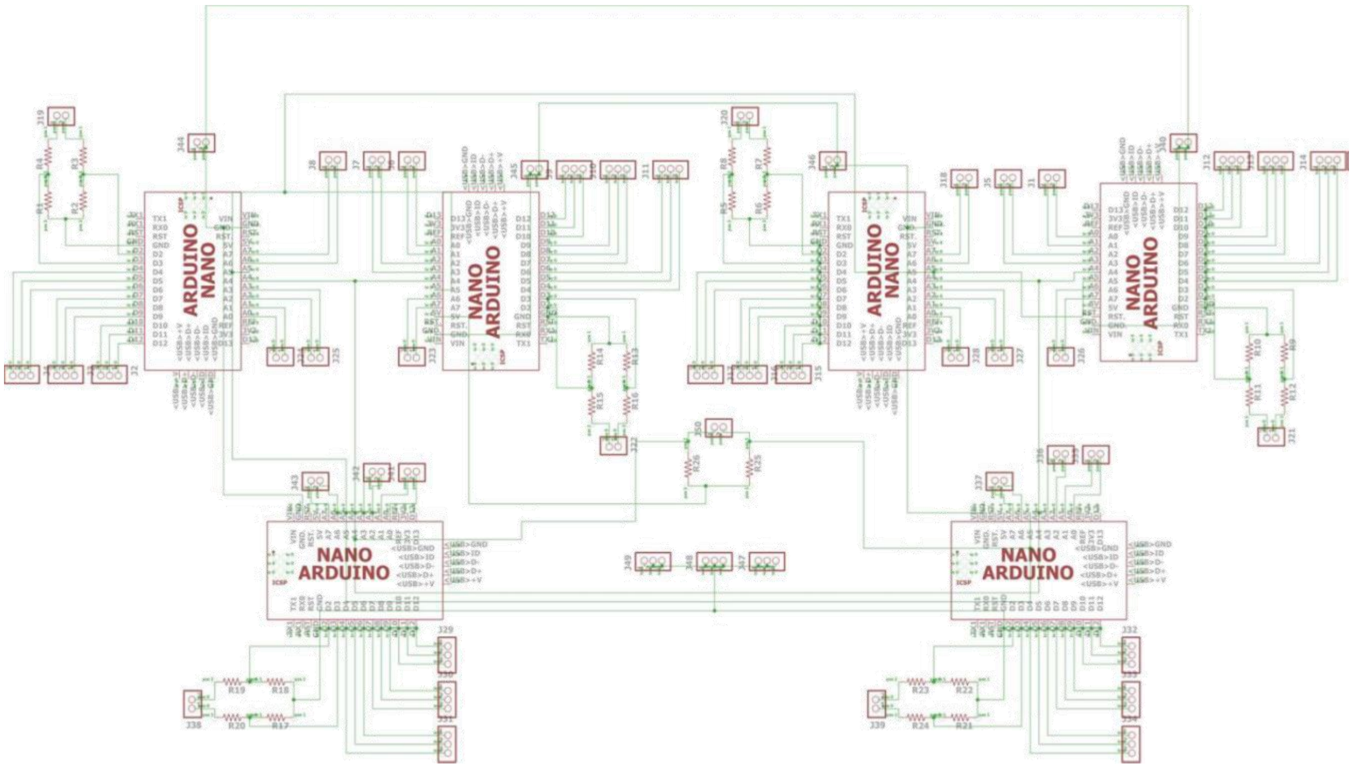


Figure 16: Master Control Panel Schematic Circuit

Designing the PCB (Printed Circuit Board) for the control panel of the master robot arm is a critical step in ensuring the system's reliability, compactness, and ease of integration. The PCB shown inFigure 16 and Figure 17serves as the physical and electrical foundation where all essential components such as Arduino boards, rotary encoders, the RF module, and power supply interfaces are systematically arranged and connected. The design process began with mapping out the circuit schematic using specialized software like Eagle or Altium Designer. This involved assigning the correct pin connections for each Arduino Nano and Mega, aligning signal paths from the rotary encoders, and providing appropriate voltage regulation and filtering circuits for stable operation. Care was taken to minimize noise and cross-talk, especially for the analog signals and communication lines like the nRF24L01 module, which is sensitive to interference.

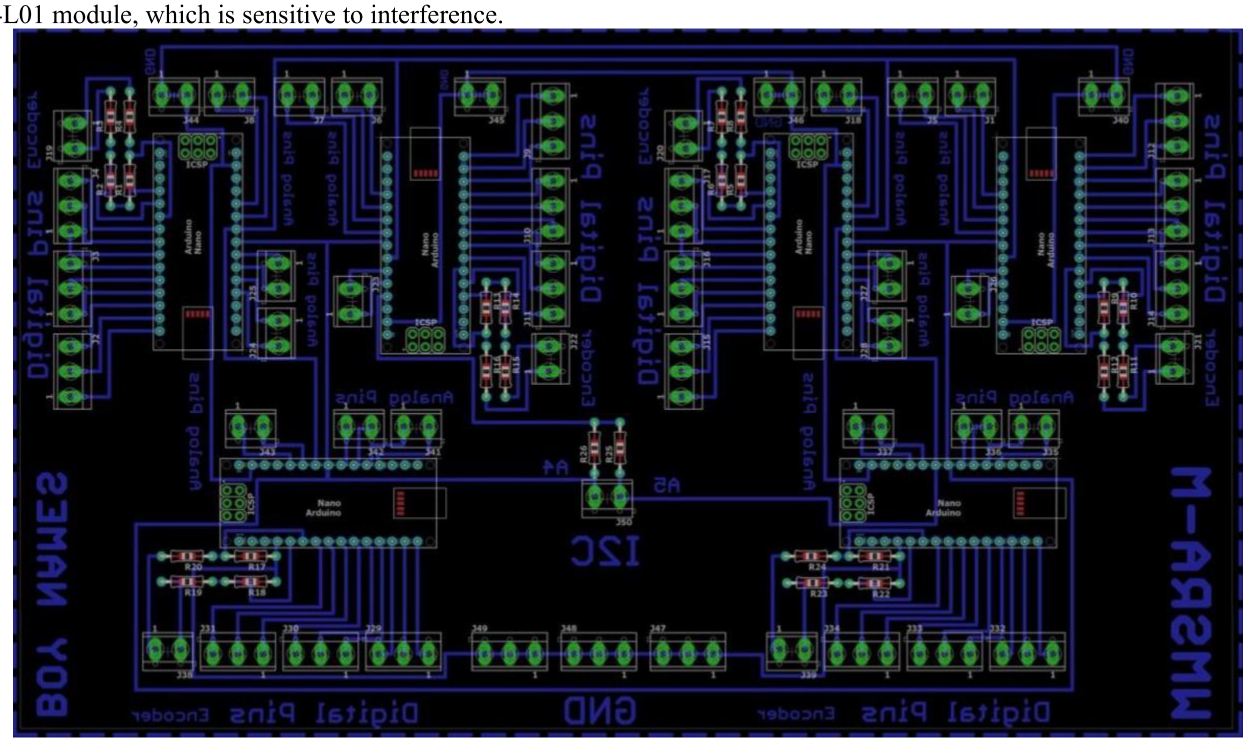


Figure 17: Master Control Panel PCB Design

Special attention was given to the power distribution layer to handle the 12V input and efficiently step it down where necessary. The layout was optimized to reduce wire clutter, shorten trace lengths for critical signals, and improve heat dissipation. Ground planes were implemented to ensure signal stability, and decoupling capacitors were added near microcontroller pins to stabilize voltage levels. The result was a set of three manufactured PCBs each tailored to handle a subset of inputs and outputs ensuring modularity and ease of troubleshooting. These boards not only helped maintain a neat and professional building but also significantly enhanced the performance and maintainability of the master control panel by securely hosting and interconnecting all the electronic components.

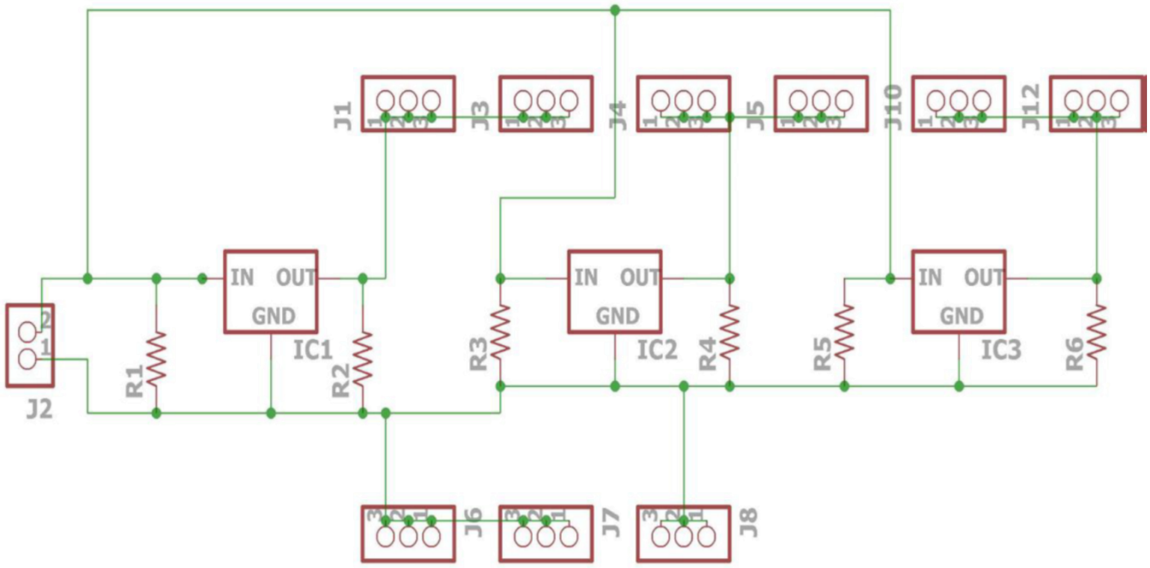


Figure 18: Schematic Design of PCB Power Converter Board

In the design of the PCB for the master robot control panel, one of the key functions was to regulate power from the main 12V battery to the appropriate voltage levels required by sensitive components as shown inFigure 18. To achieve this, the board was equipped with an LM7805 voltage regulator, a widely used linear regulator that converts 12V DC input to a stable 5V DC output. This 5V line is essential for powering components such as the LCD screens, which require a regulated 5V input to operate reliably and display data clearly. The LM7805 was placed strategically on the PCB, with appropriate input and output capacitors to filter out voltage spikes and ensure a smooth DC supply.

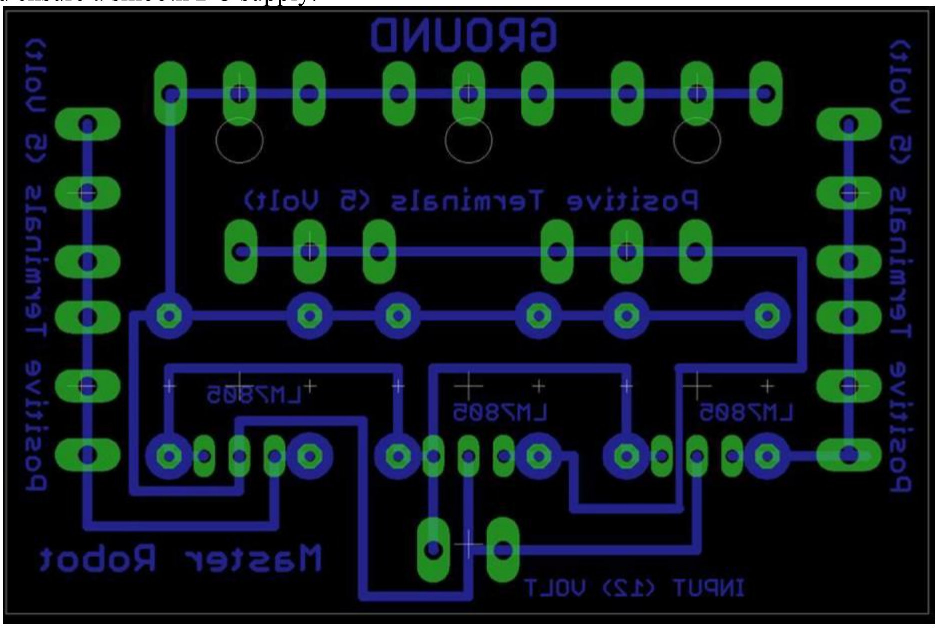


Figure 19: Design of PCB Power Converter Board

The regulator circuit was integrated into the power section of the PCB layout as shown inFigure 19, with thermal considerations in mind such as adding a heatsink or providing enough copper area around the LM7805 to dissipate heat during operation. This design choice ensured that the LCDs received a clean and consistent voltage, protecting them from fluctuations that could damage the displays or affect their readability. By incorporating this voltage regulation directly into the PCB, the design minimized external wiring, improved overall safety, and enhanced the system's compactness and reliability.

1.10 Slave Arm Control Panel Electrical Design

The control panel of the slave robot arm features a comprehensive set of electrical components shown inTable 5 designed to receive wireless commands from the master arm and precisely replicate the operator's movements. Central to this system is the Arduino Mega, which acts as the main processing unit, handling input from the RF module and distributing control signals to actuators. Multiple Arduino Nano boards are deployed to manage localized control tasks, such as reading position feedback from rotary encoders installed at various joints (wrist, elbow, and shoulder). These encoders, supplied by HanyoungNux, provide real-time angular position data to ensure accurate motor response and smooth motion. The RF module (nRF24L01) enables wireless communication with the master unit, ensuring synchronized and responsive control. Supporting user interaction and monitoring, six

LCD screens display operational parameters, while push buttons and an ON/OFF switch allow for manual control and safe power management.

Table 5: Slave Control Panel Electrical Components

Part No.	Partname	Quantity	Notes
WMSRA-S-001	Controlpanel	1	
WMSRA-S-002	Arduinomega	1	Arduinocompany
WMSRA-S-003	PowerSupply(5-12-24)Volt	3	
WMSRA-S-004	Motordriver	3	Cytroncompany
WMSRA-S-005	Resistor1.5kohm	12	
WMSRA-S-006	Resistor1k ohm	12	
WMSRA-S-007	PCBBoard	4	Manufactured
WMSRA-S-008	Rf(code:nRF24L01)	1	
WMSRA-S-009	Electricalwires	-	
WMSRA-S-010	LCD	6	
WMSRA-S-011	Pushbuttons	13	
WMSRA-S-012	ON/OFFSwitch	1	
WMSRA-S-013	USBhub	2	
WMSRA-S-014	RotaryEncoders	2	HanyoungNuxcompany
WMSRA-S-015	Arduinonano	2	Arduinocompany
WMSRA-S-016	WristDcmotors	2	
WMSRA-S-017	Rotaryencoder	1	HanyoungNuxcompany
WMSRA-S-018	Arduinonano	1	Arduinocompany
WMSRA-S-019	ElbowDcmotor	1	
WMSRA-S-020	Rotaryencoder	3	HanyoungNuxcompany
WMSRA-S-021	Arduinonano	3	Arduinocompany
WMSRA-S-022	ShoulderflyingAc motor	1	
WMSRA-S-023	ShouldertwistAc motor	1	
WMSRA-S-024	ShoulderlinearAcmotor	1	
WMSRA-S-025	SolidStateRelay-SSR	6	Egatsand Alkscompany
WMSRA-S-026	capacitor	3	

To drive the robot's mechanical motion, the panel integrates a combination of DC motors (for the wrist and elbow) and AC motors (for shoulder motions including flying, twisting, and linear movements). These are powered by a set of three power supplies (5V, 12V, and 24V) tailored to meet the voltage needs of different components. Motor drivers from Cytron are employed to regulate the direction and speed of the DC motors, while Solid State Relays (SSRs) from Egats and Alks control the AC motors with electrical isolation for safety. The use of manufactured PCBs ensures organized circuit layouts, with resistors and capacitors integrated to manage signal conditioning and noise suppression. USB hubs facilitate firmware updates and data exchange, and electrical wiring interconnects all elements within the compact control panel. Together, these components form a robust and flexible system that allows the slave robot arm to mimic the master arm's movements with high precision and responsiveness.

Designing the PCB for the slave robot arm control panel as shown in Figure 20was a critical step in ensuring efficient electrical connectivity, signal integrity, and compact integration of various components. Given the complexity of the system with multiple sensors, motor drivers, relays, and microcontrollers, the PCB design had to be modular and carefully segmented. The layout process began with circuit schematics for each functional block: power management, signal processing, motor control, and communication. Each Arduino Nano and rotary encoder was assigned to its own section with dedicated traces to minimize interference. Special attention was paid to motor control circuits, where higher currents are involved. Wider traces and proper grounding techniques were used to handle the load safely, especially for the Cytron motor drivers and the Solid-State Relays (SSRs) that control AC motors.

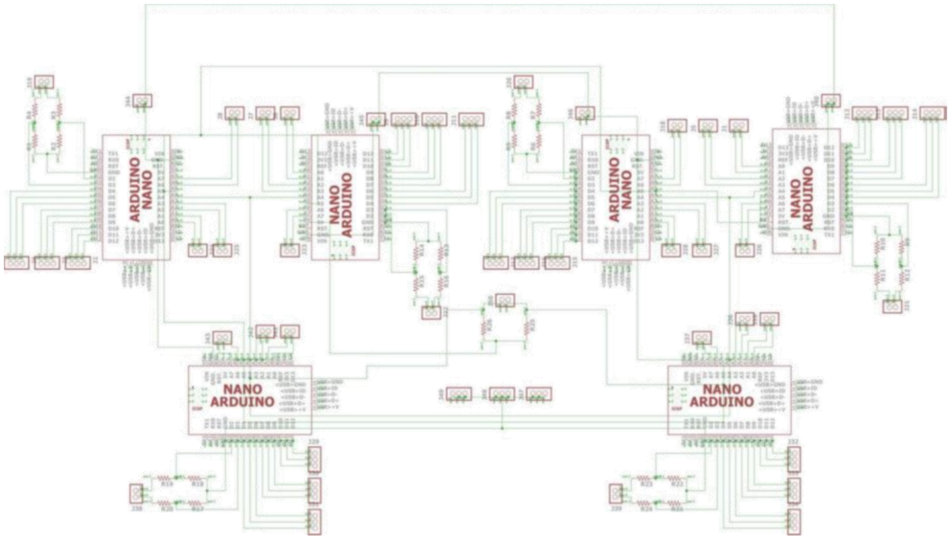


Figure 20: Control Panel Schematic Circuit

Power distribution was a key focus area in the PCB design as shown inFigure 21. The board was engineered to accommodate inputs from three different power supplies (5V, 12V, 24V), each routed through appropriate filtering and regulation components to provide clean power to sensitive devices like the RF module (nRF24L01) and LCDs Resistors and capacitors were placed strategically across the board to manage signal stability, debounce input signals from push buttons, and filter noise from motor circuits. Multiple PCBs (four in total) were fabricated to separate control logic, power handling, and interface components, reducing the risk of overheating or cross-talk between high-power and low-power sections. The result was a neatly organized and reliable electrical system that supports the smooth operation and accurate response of the slave arm, while also allowing easy maintenance and future upgrades.

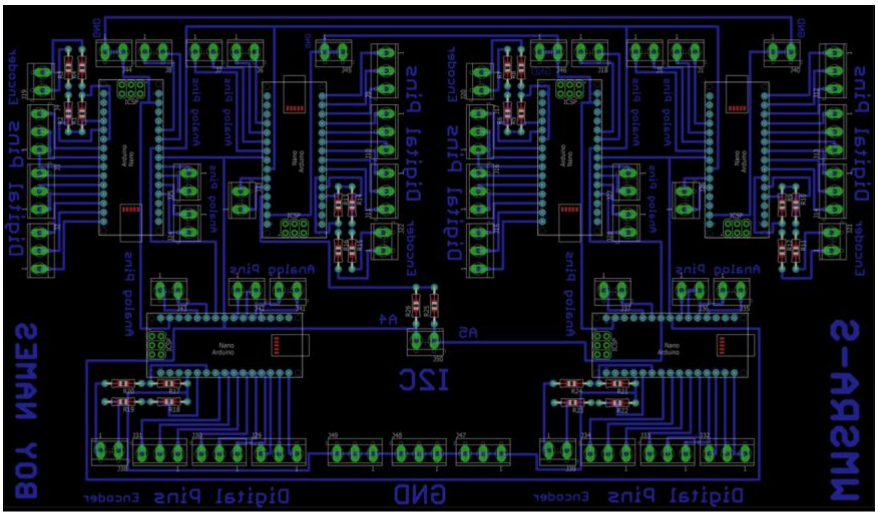


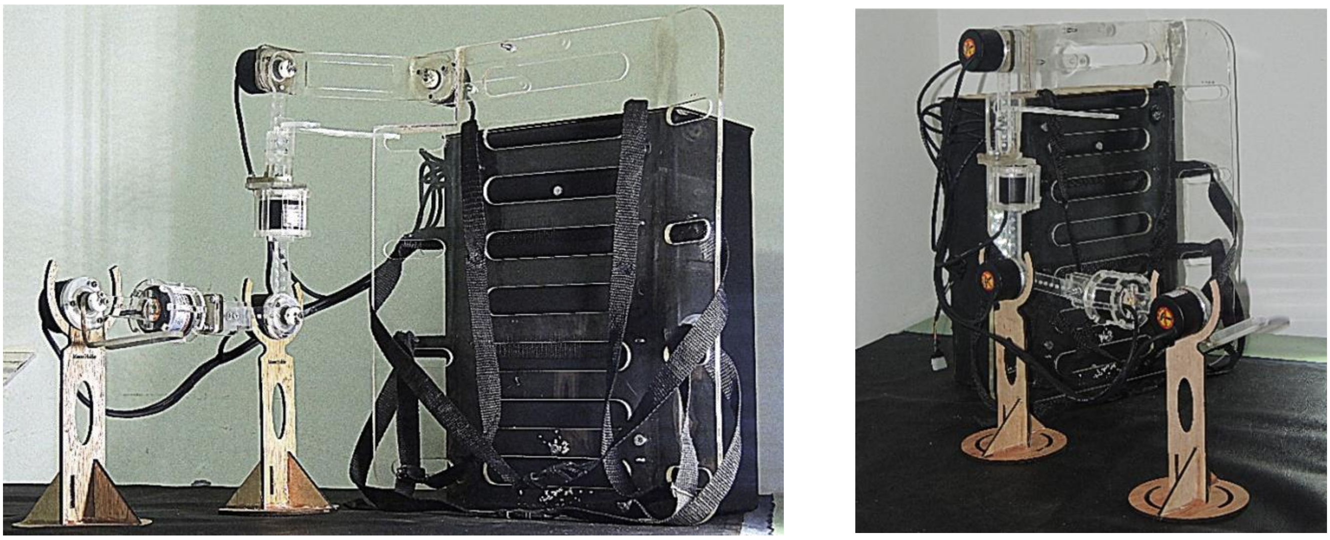
Figure 21: Slave Control Panel PCB Design

2 Experimental Implementation

The experimental implementation phase was conducted to evaluate the real-world performance and functionality of both the master and slave arms after the design and fabrication stages. This phase aims to verify the accuracy, responsiveness, and synchronization of movement between the master arm worn by the user and the slave arm driven by motors. The master arm, equipped with encoders on each joint, was tested for its ability to capture and transmit precise human arm movements. Simultaneously, the slave arm, with embedded motors and gear mechanisms, was assessed for its capability to replicate those movements accurately. Through a series of controlled tests, the system’s motion fidelity, structural integrity, and control reliability were analyzed to validate the effectiveness of the overall design and ensure seamless interaction between the human operator and the robotic system.

2.1 Master Implementation

The experimental implementation of the master arm involved mounting the acrylic structure onto the user's arm and back to ensure proper alignment with natural human joints. The arm was tested for comfort, stability, and range of motion, verifying that the design allowed for natural and unrestricted movement across all six joints shoulder (3 DOF), elbow (1 DOF), and wrist (2 DOF). Encoders were installed at each joint to capture precise angular positions and convert them into electrical signals. During testing, these signals were transmitted to the control panel, where they were processed to generate real-time commands for the corresponding slave arm movements.

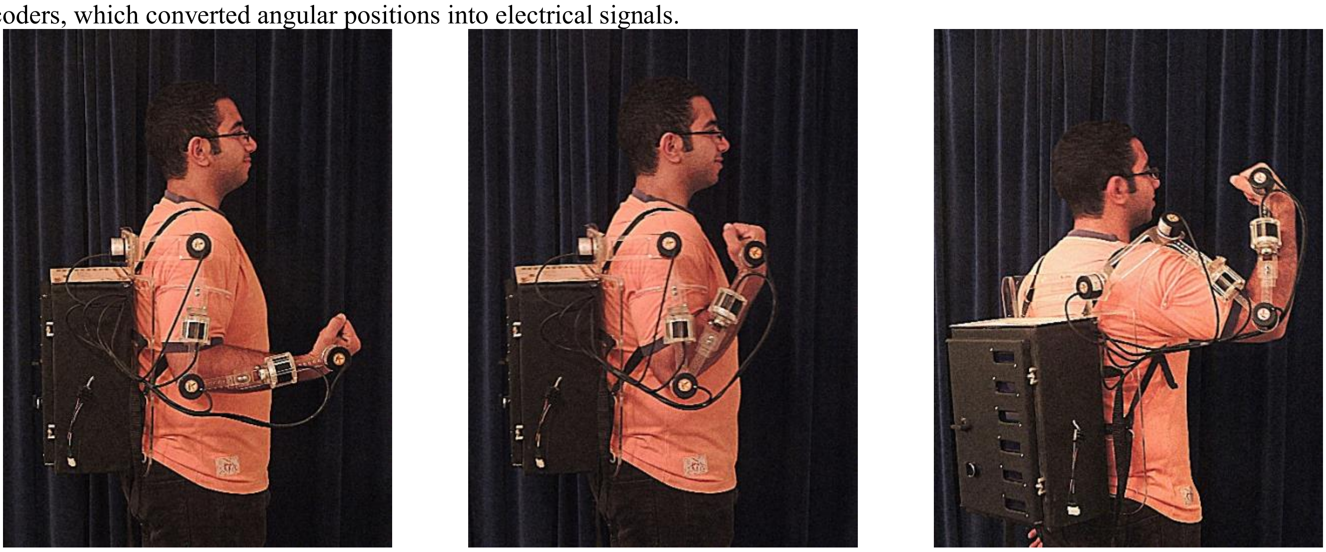


A B

Figure 22: Master Arm Experimental Implementation

As shown in Figure 22the system was calibrated to ensure accuracy in motion tracking, and various arm motions such as reaching, bending, and rotating were performed to evaluate responsiveness and fidelity. The results showed that the master arm successfully captured human movements with minimal latency and high repeatability. This confirmed the effectiveness of the encoder placements and the overall mechanical design in delivering a reliable interface between human motion and robotic control.

During testing, the master arm was worn by a human user as shown in to assess its movement capability and functional performance in a real-use scenario. The arm was designed to follow natural human motion, and its structure, made from lightweight acrylic, ensured user comfort and mobility. Once strapped to the user's arm and back, the master arm accurately tracked the movement of the shoulder, elbow, and wrist through six degrees of freedom. Each joint's rotation was captured by dedicated encoders, which converted angular positions into electrical signals.

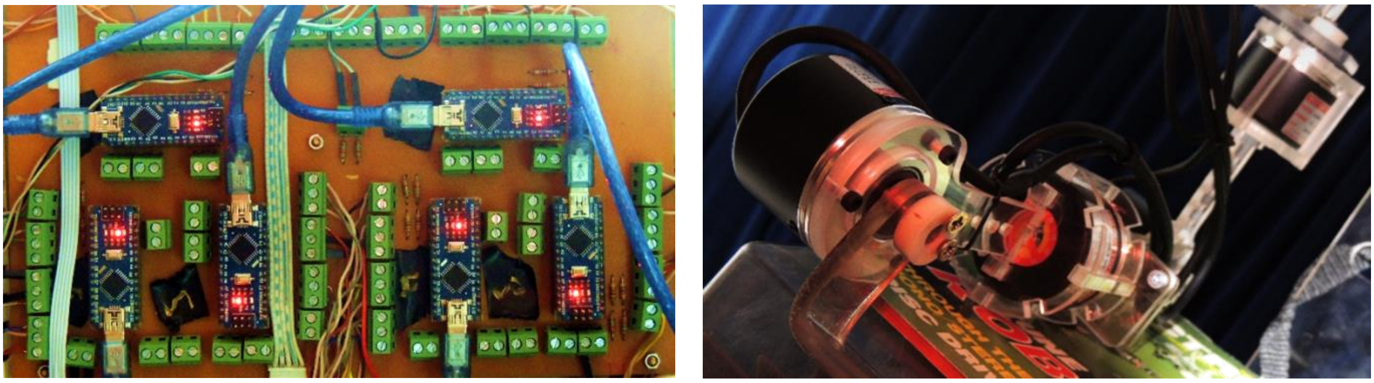


Position A **Position B** **Position C**

Figure 23: Master Arm Human Movement Testing

These signals were sent in real time to the control system to command the slave arm. The user was able to perform various tasks such as lifting, reaching, and rotating the arm, simulating operations the system is intended for such as teleoperation, robotic-assisted manipulation, or remote handling in hazardous environments. The smooth and intuitive movement of the master arm allowed the user to control the slave arm naturally, with minimal learning curve, proving the effectiveness of the design in practical applications.

Despite the overall effectiveness of the master arm, some limitations were observed near the boundaries of its workspace as in Figure 23Position (C) . As the user's arm approached the extreme ends of its natural range, particularly in full extension or extreme rotation mechanical constraints within the master arm's structure began to restrict smooth movement. These limitations were primarily due to the physical length of the linkages and the range of motion of the joints, as well as potential misalignment between the user's arm and the encoder axes at extreme positions.



A B

Figure 24: Master Electrical Control Panel

The implementation of the master control panel as shown in Figure 24was a critical step in enabling the translation of human motion into digital control signals. To handle the data acquisition from the six encoders one for each degree of freedom in the master arm six Arduino Nano microcontrollers were used. Each Arduino Nano was dedicated to reading the signal from a specific joint encoder, ensuring parallel and uninterrupted data collection for all six joints: three at the shoulder, one at the elbow, and two at the wrist.

The microcontrollers were programmed to read the analog or digital output from their respective encoders, convert the readings into position data, and transmit them to the main control system via serial communication. This distributed approach allowed for efficient data handling, minimized processing load on a single microcontroller, and reduced latency in real-time operation. The master control panel, integrating all six Arduinos, served as the central hub for collecting, organizing, and relaying joint position data, enabling accurate and responsive control of the slave arm.

2.2 Slave Implementation

The manufacturing process of the slave arm began with the selection and procurement of raw materials, primarily stainless-steel sheets. Stainless steel was chosen for its strength, corrosion resistance, and suitability for supporting mechanical loads during operation. High-quality sheets with suitable thickness were sourced to ensure durability and reliability. These sheets formed the core structural elements of the slave arm, especially the blue-colored components shown in the CAD model. Before fabrication, detailed technical drawings were prepared to guide the manufacturing process, ensuring precision and adherence to the design specifications.

A B

C D

Figure 25: Slave Manufacturing Process

Once the material was acquired, the fabrication process began with laser CNC cutting. This method was selected for its high accuracy, clean cuts, and efficiency in handling complex geometries. All required parts were cut from the stainless-steel sheets according to the CAD files, ensuring perfect fit and alignment during assembly. After cutting, the components were transferred to a bending machine as shown in Figure 25 (A,B), where specific parts were shaped to the required angles and curves. This step was critical for forming the three-dimensional structure of the arm and ensuring that mounting points for motors, bearings, and other hardware aligned correctly.

In parallel with the fabrication of structural parts, all standard mechanical and electronic components were sourced as in Figure 25 (C,D). These included fasteners, bearings, gears (particularly bevel gears for the drivetrain), encoder mounts, and high-torque electrical motors. Motors were selected based on the required torque and speed for each joint's degree of freedom, and their compact form allowed them to be integrated inside the arm. Electronic components such as encoders, wires, connectors, and control boards were also procured. Great care was taken to ensure compatibility between all electrical and mechanical components to avoid issues during installation and operation.

The final stage involved the detailed assembly of the slave arm as shown in Figure 26. Each fabricated part was cleaned, checked for dimensional accuracy, and then assembled using bolts and precision fittings. Motors were mounted inside the structure and linked to the joints using bevel gear systems, allowing motion transmission at 90 degrees in accordance with the compact design. Encoders were installed on each joint to provide real-time feedback to the control system. Electrical wiring was routed neatly through the structure to avoid interference or entanglement. Once fully assembled, the arm was mounted onto a metal base that housed the slave control panel. Calibration and testing followed to ensure that each joint responded correctly to input signals from the master arm, confirming that the system operated reliably and precisely.


A


B

Figure 26: Slave Arm Final Assembly

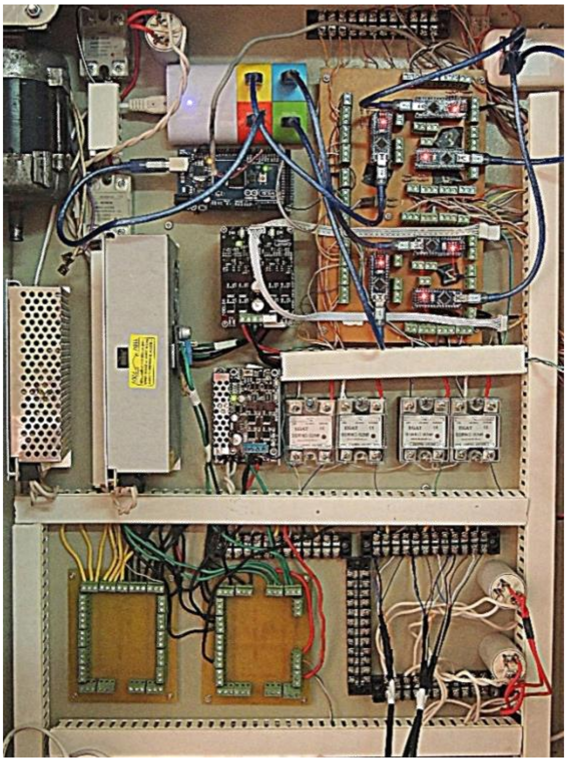


Figure 27: Slave Control Panel

The implementation of the slave control panel as shown in Figure 27 was a vital component in the integration and functionality of the slave arm system. The control panel served as the central processing and power distribution unit responsible for receiving position data from the master arm, processing it, and generating accurate control signals to drive the motors embedded within the slave arm. The design of the panel focused on modularity, ease of maintenance, and efficient communication with both the master system and the actuators. At the core of the slave control panel was a microcontroller unit that received real-time position data from the master arm via serial communication. This unit was programmed to interpret the incoming signals, map them to the corresponding joint positions, and generate PWM or motor driver control signals accordingly. To manage the six motors (corresponding to the slave arm's 6 DOF), motor driver modules were included and appropriately connected to handle the required current and voltage for each motor. Heat sinks and ventilation were also considered to ensure thermal stability during continuous operation.

In addition to the motor drivers, the panel incorporated encoder feedback lines to continuously monitor the actual position of each joint. This closed-loop feedback system enabled the control panel to correct any deviation in real-time, ensuring high precision and synchronization with the master arm. A power supply unit, capable of delivering stable and sufficient current to all motors and electronics, was installed within the panel. Circuit protection components such as fuses and relays were added to safeguard the electronics and motors from overloads or short circuits. The physical layout of the control panel was compact and organized within the metal holder attached to the slave arm base. Components were mounted on a perforated board or chassis with labeled wiring for easy troubleshooting and future upgrades. Once fully assembled, the system was tested for responsiveness, stability, and accuracy. The slave control panel successfully ensured smooth execution of commands from the master arm, completing the human-to-robot teleoperation system with a robust and efficient electronic control backbone.

3 Software and Testing Results

The control system is divided into two main parts: the master arm and the slave arm. Each system uses a combination of Arduino Nano and Arduino Mega boards for efficient data handling and control. On the master side, six Arduino Nanos are connected to the arm's joints. Each Nano reads encoder data from one joint, converts it into angle values, and sends this data via serial communication to a central Arduino Mega. The Mega collects and checks all the incoming data, synchronizes it, and then sends a unified control command to the slave arm.

On the slave side, each Arduino Nano controls one joint, reading encoder feedback and adjusting motor movements in real-time. These Nanos receive target positions from the Mega and use onboard algorithms, possibly with PID control, to correct joint positions. Each Nano also sends feedback back to the Mega, which acts as the main controller.

Figure 28 shows the main loop logic used in the Arduino Nano on the master side, where encoder values are read, processed into angle metrics, and sent to the Mega. The communication is handled using a simple protocol like comma-separated values or JSON-like structures, ensuring accurate and continuous data transfer.

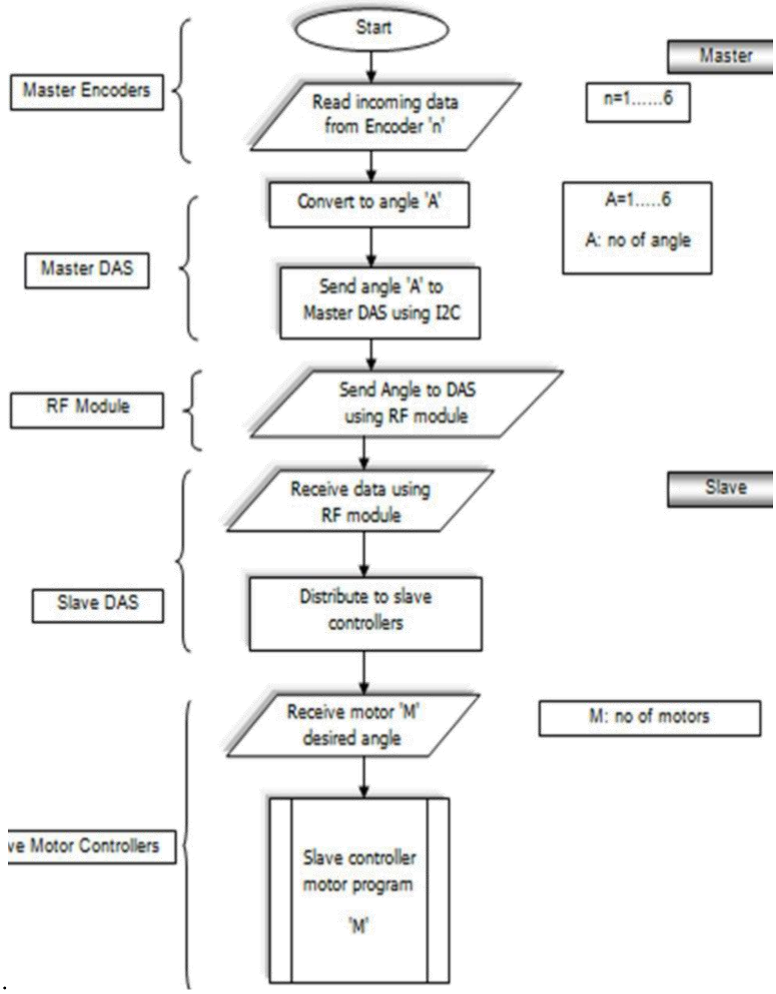


Figure 28: Master Software Flowchart

Figure 29 illustrates the role of the Arduino Mega on the slave side, where it receives data from the Nanos, checks for errors, and sends final motor commands. It ensures all joints are synchronized and accurately follow the master arm's movements.

Overall, the system uses distributed processing (Nanos for local control) and centralized coordination (Megas for communication and synchronization). This setup improves real-time performance, accuracy, error management, and makes the system easy to upgrade or debug—ideal for precise robotic teleoperation.

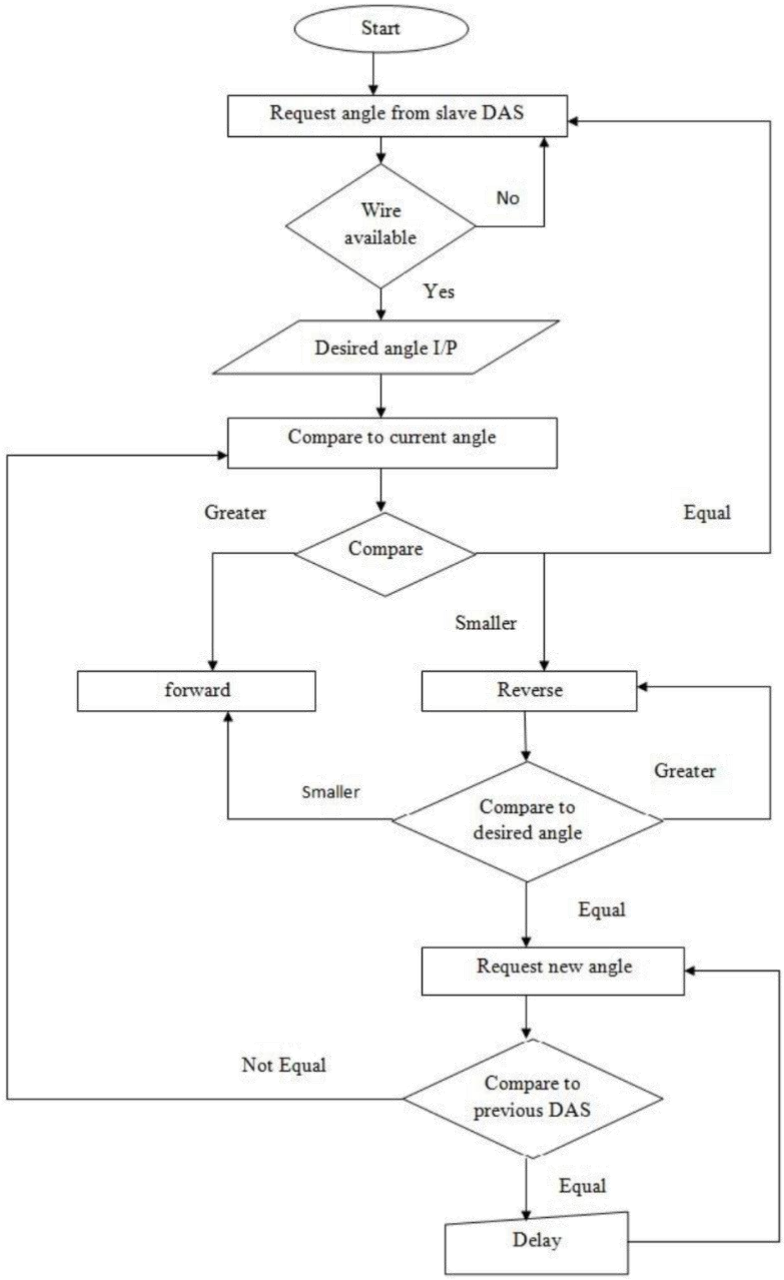


Figure 29: Slave Software Flowchart

4 Conclusions

In conclusion, the paper has reached a significant milestone by demonstrating a functional wireless master-slave robotic arm with 6 DOF despite the many challenges encountered. Through diligent design, construction, and testing, the system successfully achieved the core objectives of capturing and transmitting human arm movements for accurate teleoperation, even though compromises in the specifications were necessary. The complexity of the human arm inspired innovative solutions such as embedding motors in the slave arm and leveraging available electrical components within tight budget constraints. However, limitations in resources, manufacturing inaccuracies, and the use of suboptimal electronic components inevitably impacted the overall efficiency and precision of the arm. Each difficulty encountered ranging from mechanical design limits and component quality to manufacturing errors provided valuable insights that have informed the project's evolution.

Based on our experience, we recommend several directions for future work. Firstly, the implementation of a remotely operated vehicle (ROV) platform to house the slave arm may offer enhanced stability and operational flexibility. Additionally, developing a complementary slave arm for the left hand would move the project closer to replicating a full bi-manual system, thereby expanding its range of practical applications. Addressing resource and manufacturing constraints through advanced components such as high-precision gearboxes, special order electronic servo motors, absolute rotary encoders, heat-treated steel parts, HSC modules, and specialized GSM wireless modules could further improve accuracy and reduce weight. Future efforts should focus on overcoming these limitations to refine the system's overall performance and enable its transition from a prototype into a scalable, high-precision teleoperation solution.

List of Abbreviations

Abbreviation	Definition
WMSRA	Wireless Master Slave Robot Arm
PCB	Printed Circuit Board
SSRs	Solid State Relays

Declarations

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