Designing of Control System for IIRI

M.Tech. Thesis

By

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DISCIPLINE OF ASTRONOMY, ASTROPHYSICS, AND SPACE ENGINEERING

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Designing of Control System for IIRI

A THESIS

Submitted in partial fulfillment of the
requirements for the award of the degree
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Gautam Arora

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Designing of Control System for IIRI** in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** and submitted in the **Discipline Of Astronomy, Astrophysics, and Space Engineering, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2022 to May 2024 under the supervision of Dr. Narendranath Patra, Assistant Professor.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

20-05-2024

Signature of the student with date
(Gautam Arora)

This is to certify that the above statement made by the candidate is correct to the best ofmy/our knowledge.

20.05.2024
Signature of the Supervisor of M.Tech. thesis (with date)
(Dr. Narendranath Patra)

Gautam Arora has successfully given his/her M.Tech. Oral Examination held on **26-04-2024.**

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Abstract

This thesis pioneers a groundbreaking approach to enhance motion and speed control in astronomical observations through the design and implementation of a novel system utilizing the Raspberry Pi 4B and Raspberry Pi Pico W. The proposed system aims to replace the existing control infrastructure of the IIT Indore Radio Interferometer, addressing its limitations and introducing a cutting-edge solution for precision radio astronomy. Leveraging the computational capabilities of the Raspberry Pi 4B, the system orchestrates the Raspberry Pi Pico W to generate PWM waves, finely regulating the motion of an AC servo motor. This innovative configuration enables unparalleled precision in telescope pointing accuracy and tracking capabilities. The integration of these components, a Raspberry Pi-based control system coupled with Raspberry Pi Pico for PWM signal generation, not only marks a significant departure from conventional approaches but also presents an unexplored avenue for achieving unprecedented levels of control in astronomical observations. The outcomes of this research promise to contribute to the advancement of radio astronomy instrumentation, setting the stage for a new era of precision and adaptability in the pursuit of unraveling the mysteries of the cosmos.

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Chapter 1 : Introduction

1.1 Motivation and Purpose

In the vast expanse of the cosmic tapestry, radio astronomy stands as a powerful tool for unraveling the mysteries of the universe. At the heart of this exploration is the sophisticated instrumentation employed by observatories, such as radio telescopes, to capture and analyze celestial signals. In this context, the thesis at hand delves into the realm of cutting-edge technology, focusing on the development of a robust control system tailored for the Radio Astronomy facility at the Indian Institute of Technology (IIT) Indore.

As the pursuit of understanding the cosmos becomes increasingly intricate, the importance of precision and efficiency in observational instruments cannot be overstated. The IIT Indore Radio Astronomy facility, with its state-of-the-art radio telescope, is positioned at the forefront of this scientific endeavor. However, to harness the full potential of this powerful tool, a meticulously designed control system is imperative. This thesis aims to address the intricate challenges posed by the operation of a radio telescope, offering a comprehensive solution that enhances the accuracy, reliability, and overall performance of IIT Indore's radio astronomy endeavors.

The need for this system arises due to the fact that the current system has become unreliable and cannot be used for scientific research purposes. As the offset in the pointing of the telescope changes with time and usage, the use of the interferometric system becomes exponentially difficult, as it requires precision both in time and space from the incoming signal. Hence it was decided to make a replacement for the current system and replace it with the new system that we are currently making and working on in this thesis. This new system aims to rectify the current problems and set the motion for the scientific endeavor. The new system will offer both cheap and precise functioning of the astronomy site, such that it can be implemented to various other similar facilities without causing them to have to spend ginormous amounts of money for it.

As we embark on this journey at the intersection of technology and astrophysics, the research presented herein strives to make meaningful contributions to the broader scientific community. By marrying theoretical insights with practical applications, the thesis seeks to lay the foundation for a new era of precision and reliability in radio astronomy observations, pushing the boundaries of our understanding of the cosmos.

Through a synthesis of engineering principles, signal processing techniques, and astronomical expertise, this thesis endeavors to contribute to the refinement of control systems within the realm of radio astronomy. By delving into the specific requirements of IIT Indore's Radio Telescope, the research explores the intricacies of celestial signal acquisition, data processing, and system optimization. The ultimate goal is to empower the radio astronomy community with a control system that not only meets the unique demands of IIT Indore's facility but also serves as a valuable model for advancements in radio astronomy instrumentation globally.

1.2 Control Systems

Control systems are the orchestrators behind the seamless functioning of complex devices and processes, serving to regulate and manage dynamic systems across various industries. At their core, these systems are designed to command, monitor, and adjust the behavior of a given system to achieve desired outcomes. In the context of engineering and technology, control systems are fundamental in maintaining stability, accuracy, and efficiency. They rely on a combination of sensors, actuators, and feedback mechanisms to continuously assess and modify the system's performance in response to changing conditions. Whether applied to industrial processes, transportation systems, or scientific instruments like radio telescopes, control systems are indispensable in optimizing operations, enhancing reliability, and ensuring precision in the face of dynamic and often unpredictable environments. The field of control systems engineering continually evolves, driven by the need to address new challenges and leverage emerging technologies, making it a critical component in the advancement of modern technological landscapes.

1.3 Radio Antenna’s

Radio antennas, distinctive in their design and functionality, serve as the sensory organs of radio telescopes, capturing and decoding celestial radio waves. Their uniqueness lies in their ability to detect signals across a broad spectrum, providing astronomers with insights into the cosmic phenomena that emit radio frequencies. The structure of radio antennas, tailored for this specific purpose, exhibits characteristics that set them apart from other types of antennas.

Figure 1.1 Image of GMRT Antenna

Unlike antennas designed for specific frequency bands, radio antennas are engineered to detect a wide range of radio frequencies emanating from celestial sources. This broad sensitivity allows them to capture signals associated with various astrophysical processes, from synchrotron radiation to molecular spectral lines, providing a comprehensive view of the cosmos.

A prominent structural feature of many radio antennas is the use of parabolic reflectors. These dish-shaped structures are adept at focusing incoming radio waves onto a central feed or receiver. The parabolic shape ensures that signals arriving from different angles are reflected toward a common focal point, enhancing the antenna's sensitivity and resolution. Large parabolic reflector antennas, often found in radio telescopes, are particularly effective in capturing weak signals from distant celestial objects.

The structure of radio antennas showcases versatility and adaptability. Arrays of smaller antennas, spread over a region, can collectively function as a powerful instrument. This flexibility allows astronomers to tailor their observational setups based on specific scientific goals, from studying pulsars and galaxies to mapping the cosmic microwave background.

1.3.1 Precision:

Precision in radio antennas is paramount for accurate and detailed observations of celestial objects. The ability to precisely point the antenna at specific coordinates in the sky is crucial for capturing signals with the desired accuracy. This precision is influenced by various factors, including the mechanical design of the antenna, the control system, and environmental conditions. Achieving high precision ensures that radio telescopes can effectively gather data, whether for mapping distant galaxies or tracking the motion of pulsars.

1.3.2 Torque Required for Movement:

The movement of radio antennas, especially in large parabolic reflectors, demands torque to overcome resistance and ensure accurate positioning. Torque requirements are influenced by the size and weight of the antenna, as well as the friction and resistance within the mechanical components. High-precision motors and gear systems are often employed to provide the necessary torque for smooth and controlled movement. The torque must be finely tuned to avoid overshooting or undershooting the target position, ensuring precision in observational tasks.

1.3.3 Speed of Movement:

The speed at which a radio antenna can be moved is a factor that affects the efficiency of observations. While precision is crucial, achieving efficient coverage of the sky or rapid response to transient astronomical events necessitates a balance between precision and speed. Control systems and motors must be designed to allow for both slow, precise movements for targeted observations and faster movements for surveying or tracking dynamic celestial phenomena.

In summary, precision, torque, moment of inertia, and speed are interconnected mechanical considerations in the design and operation of radio antennas. Achieving the delicate balance between these factors ensures that radio telescopes can perform with the required accuracy and efficiency, allowing astronomers to explore the universe with unprecedented detail and insight. the uniqueness of radio antennas lies in their ability to capture a wide spectrum of radio frequencies and their distinctive structural features, such as parabolic reflectors and versatile feed systems. These design elements empower radio antennas to unveil the secrets of the universe, offering astronomers a sophisticated tool to explore the cosmos in the radio frequency domain.

1.4 Technological Standards

Several state-of-the-art radio astronomy sites worldwide are at the forefront of technological innovation, advancing our understanding of the universe. Notable among them are:

1. **Atacama Large Millimeter/submillimeter Array (ALMA), Chile:** ALMA, located at an altitude of 5,000 meters in the Atacama Desert, is a collaborative effort involving international partners. With an array of 66 high-precision antennas, ALMA observes in millimeter and submillimeter wavelengths, enabling groundbreaking studies of star formation, galaxy evolution, and the early universe. Its advanced technology includes ultra-precise antennas, sophisticated receivers, and powerful correlators.
2. **Very Large Array (VLA), United States:** Situated in New Mexico, the VLA is an iconic radio telescope array comprising 27 antennas arranged in a Y-shaped configuration. The VLA's technological prowess lies in its ability to combine signals from its widely distributed antennas, providing high-resolution images of celestial objects. Recent upgrades, known as the VLA Sky Survey (VLASS), enhance its survey capabilities.
3. **Square Kilometre Array (SKA), Global Project:** While still in the construction phase, the SKA represents an ambitious global project that will consist of thousands of antennas distributed across sites in Australia and South Africa. SKA aims to be the world's most powerful radio telescope, enabling breakthroughs in various fields, including cosmology, dark matter, and gravitational waves.

1.5 Giant Meter Radio Wave Telescope (GMRT)

GMRT, situated near Pune, India, is one of the world's leading radio astronomy facilities. Its array consists of 30 fully steerable parabolic dishes spread across a 25-kilometer baseline. The antennas operate in the frequency range of 150 MHz to 1.5 GHz, allowing for a diverse range of observations.[1]

1.5.1 Technological Features:

1. Large Antenna Array: GMRT's 30 antennas, each 45 meters in diameter, are arranged in a Y-shaped configuration, providing a

unique hybrid array that combines the advantages of both filled and unfilled aperture synthesis.

2. Frequency Coverage: GMRT's wide frequency coverage allows astronomers to study a variety of celestial phenomena, including pulsars, galaxies, and cosmic microwave background radiation.
3. Advanced Receivers: GMRT employs sophisticated receivers capable of handling a wide range of frequencies, providing flexibility in observational targets and research goals.
4. Correlator Technology: The facility is equipped with a powerful and flexible correlator that combines signals from different antennas, allowing for high-resolution imaging and sensitivity.
5. Pulsar Observations: GMRT has made significant contributions to pulsar research, with its sensitive receivers enabling the detection of pulsars and the study of their properties.

1.5.2 System Architecture and Components*[2]*[3][4]

1. Antenna Mount: The GMRT antennas are mounted on alt-azimuth mounts, allowing movement in two axes - azimuth (parallel to the horizon) and elevation (normal to the horizon). The mount is designed to support the weight of the large antennas (over 80 tons) and ensure stable movement.
2. Servo System: The servo system is a closed-loop position feedback control system consisting of dual drives with counter-torquing mechanisms to eliminate non-linearities. It includes components like position loop amplifiers (PLA), rate loop amplifiers (RLA), current loop amplifiers (CLA), and servo amplifiers.[5]
3. Servo Motors: Specialized DC brush type permanent magnet motors are used for precise position, velocity, and torque control. These motors have specific electrical and mechanical characteristics to meet the demands of rapid acceleration and deceleration.
4. Gear Reducers: Gear reducers are employed to increase torque and reduce the speed of the motors to match the load requirements of the antennas. Planetary gearboxes are typically used due to their bi-directional energy flow and low backlash characteristics.
5. Position Sensors: Optical encoders, specifically absolute shaft encoders, are used to provide highly accurate angular position feedback. This ensures precise control over the antenna's pointing direction without relying on homing procedures after power loss.
6. Digital Controller: The control system is managed by a digital controller based on an Intel 8086 processor running at 8 MHz. The

controller processes position data from encoders, computes errors, applies compensations, and generates control signals for the servo amplifiers.

1.5.3 Control System Operation

1. Closed-Loop Control: The servo system operates on negative feedback principles to minimize position errors. Position, velocity, and current feedback loops work together to accurately track and position the antennas.
2. Position Control: The position control involves nested feedback loops (position loop, velocity loop, and current loop) to achieve precise and stable antenna movement. Each loop is responsible for specific aspects of control, such as reducing back-lash and improving transient response.
3. Operational Commands: The control system responds to various operational commands sent from a central control station via optical fiber links. Commands include move, track, hold, stop, and reset, enabling remote operation and control of the antennas.

1.5.4 System Integration and Reliability

1. Integration: The control system is integrated with other subsystems of the GMRT, such as data acquisition systems, to facilitate coordinated observations and data collection.
2. Reliability: Redundant and fail-safe mechanisms are implemented to ensure system reliability and safety. This includes motor brakes, error detection, and protection against over-current and over-speed conditions.

1.5.5 Scientific Contributions:

GMRT has played a pivotal role in various astronomical discoveries, including the detection of rare and exotic celestial objects. Its contributions span pulsar astronomy, galactic studies, and cosmological research. GMRT's ability to operate at low frequencies positions it uniquely for studying the least explored regions of the radio spectrum.

In conclusion, GMRT stands as a technological marvel in the field of radio astronomy, contributing significantly to our understanding of the cosmos. Its advanced capabilities, innovative design, and scientific achievements make it a key player in the global landscape of state-of-the-art radio astronomy facilities.

1.6 Problem Statement

The existing control system employed by the IIT Indore Radio Interferometer is currently experiencing operational challenges that compromise its effectiveness in facilitating cutting-edge radio astronomy research. The current system has some issues in the pointing accuracy, reliability of pointing, variable offset, and low precision that arises due to these issues. These shortcomings underscore the critical necessity of replacing the current control system with a redesigned infrastructure. The replacement system must address the deficiencies of the existing setup and be specifically tailored to the unique specifications of the Radio Interferometer. This imperative redesign aims to ensure optimal functionality, reliability, and adaptability, thereby positioning the Radio Interferometer at the forefront of contemporary radio astronomy research. The new system that we aim to make is cheaper, and more precise than the current system because of the use of the FPGA's and implementation of cheaper substitutes to the costly parts while maintaining the quality.

This imperative redesign aims to ensure optimal functionality, reliability, and adaptability, thereby positioning the Radio Interferometer at the forefront of contemporary radio astronomy research.

Chapter 2 : Literature Review

2.1 Radio Astronomy

Radio astronomy holds a unique and indispensable position in the realm of observational astronomy, offering unparalleled insights into the universe that complement and, in some cases, surpass the capabilities of other branches. The importance of radio astronomy stems from its ability to unveil celestial phenomena beyond the reach of traditional optical astronomy, providing a distinct perspective on the cosmos.

One of the key advantages of radio astronomy lies in its capacity to penetrate cosmic dust clouds, enabling the study of celestial objects that emit predominantly in radio wavelengths. This capability allows astronomers to investigate regions where visible light is obscured, revealing the hidden facets of our galaxy and the broader universe. Additionally, radio astronomy excels in the observation of non-thermal processes, such as synchrotron radiation, providing crucial information about high-energy astrophysical phenomena.

The utilization of radio waves for astronomical observation offers several advantages over optical astronomy. Radio telescopes can operate day and night, unaffected by atmospheric conditions that often limit observations in the optical spectrum. Moreover, radio waves can traverse interstellar distances without significant absorption or scattering, allowing astronomers to study objects located at vast distances from Earth.

Radio astronomy's distinctive capabilities have led to groundbreaking discoveries that have reshaped our understanding of the cosmos. Pioneering observations, such as those of the cosmic microwave background radiation, have provided critical evidence supporting the Big Bang theory and elucidating the early moments of the universe. The discovery of pulsars, rotating neutron stars emitting periodic radio pulses, was another milestone that originated from radio astronomy, opening new avenues for the study of extreme astrophysical environments.

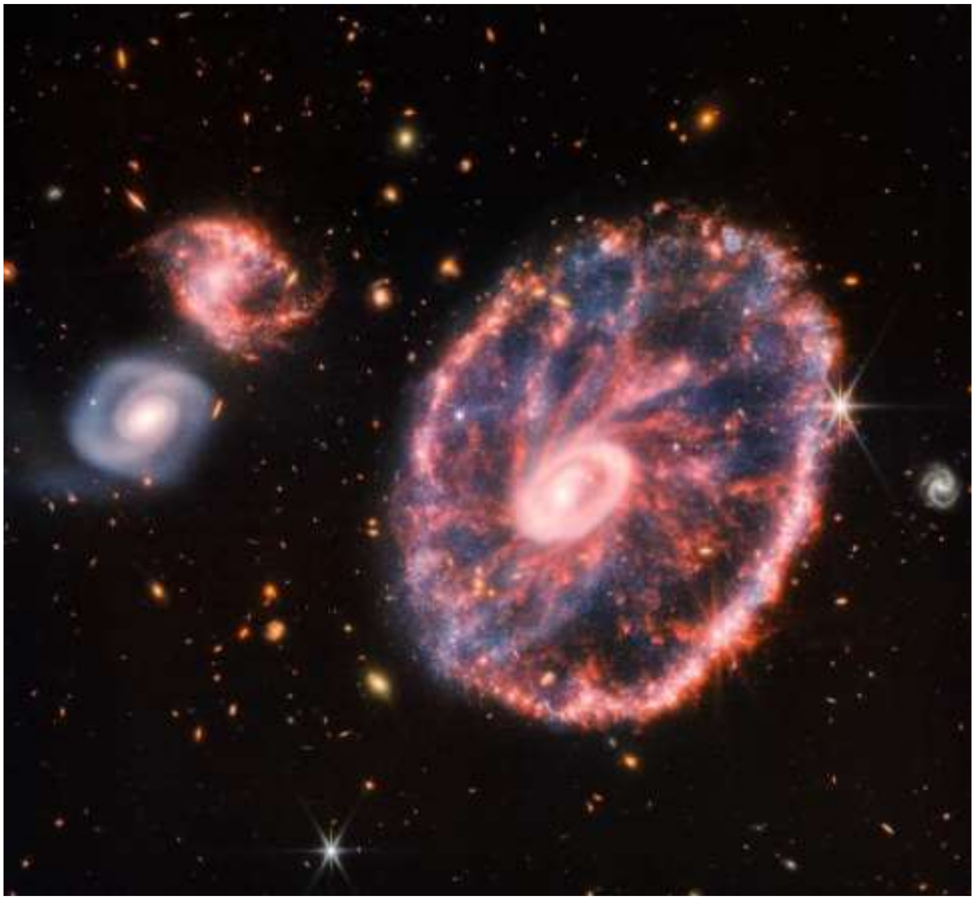


Figure 2.1 Image of a galaxy, Published by NASA on their website

Furthermore, radio astronomy plays a pivotal role in the exploration of extraterrestrial intelligence, as radio waves are considered a potential means of communication across interstellar distances. Ongoing efforts to detect radio signals from other civilizations underscore the unique contributions of radio astronomy to the search for extraterrestrial life.

In summary, the importance of radio astronomy lies in its ability to uncover celestial phenomena inaccessible to other branches of astronomy. Its versatility, capacity to penetrate obscured regions and unique observational advantages make it an indispensable tool for unraveling the mysteries of the universe, contributing to transformative discoveries that have reshaped our cosmic narrative.

2.2 Control Systems

Control systems are engineering structures or processes designed to manage and regulate the behavior of dynamic systems. They are employed in various fields to maintain desired outputs or performance by adjusting inputs. These systems are crucial for achieving stability, precision, and reliability in complex processes and technologies.

Control systems find applications in a wide range of industries, including manufacturing, aerospace, automotive, robotics, and more. In manufacturing, for example, control systems regulate the temperature, pressure, and other variables in industrial processes. In aerospace, they are essential for stabilizing aircraft during flight. In robotics, control systems dictate the movements and actions of robotic arms.

The importance of control systems lies in their ability to ensure that a system or process behaves predictably and efficiently. They enable automation, reduce human intervention, and enhance overall system performance. Control systems contribute to maintaining consistency, accuracy, and safety in various applications.

Several algorithms are used in control systems, with the Proportional-Integral-Derivative (PID) controller being one of the most common. PID controllers adjust the system output based on proportional, integral, and derivative terms to minimize error and achieve desired performance. Other algorithms include state-space control, fuzzy logic control, and model predictive control, each tailored to specific applications and system requirements. These algorithms play a crucial role in determining how a control system responds to changes in the environment or inputs, ensuring effective regulation and optimization of the controlled process.

Pulse Width Modulation (PWM) techniques, an integral part of control systems theory, play a pivotal role in achieving variable output signals. PWM is widely employed in motion control applications, offering precise control over motor speed and position. Understanding the intricacies of PWM is essential for designing systems that demand fine-grained control, such as those in radio astronomy instrumentation.

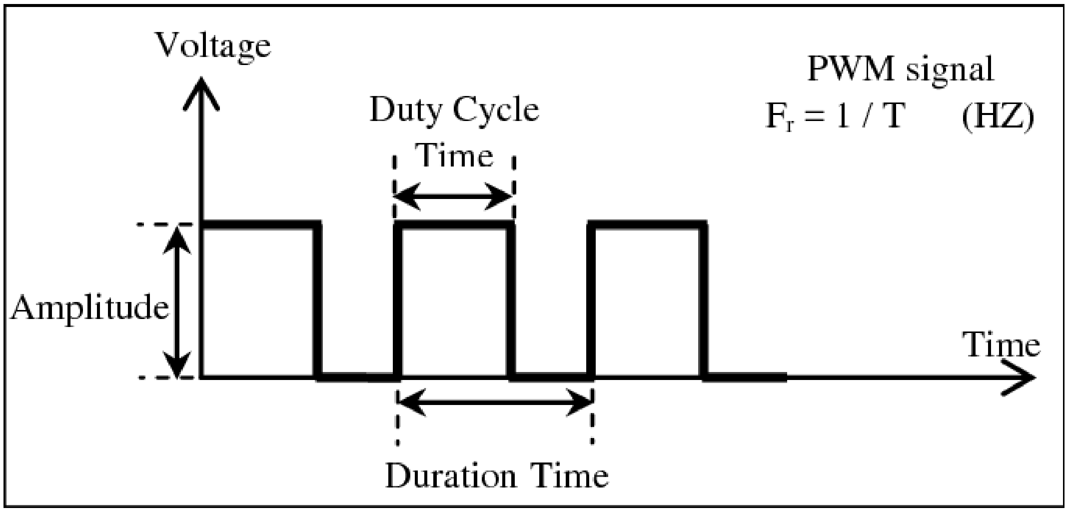


Figure 2.2 PWM Signal

2.2.1 Open Loop Systems

In an open loop control system, the output has no influence on the control action. The control action is determined solely by the input command. Here's how it works:

- Input: A reference input signal or setpoint is provided to the system.
- Controller: The controller generates a control signal based solely on the input signal, without any feedback from the output.
- Plant/Process: The control signal is applied to the plant or process being controlled.
- Output: The output of the system is not directly measured or monitored to adjust the control action.

Advantages of Open Loop Control Systems:

- Simplicity: Open loop systems are often simpler and less expensive to implement since they don't require feedback sensors or complex control algorithms.
- Fast Response: Since there is no feedback loop, open loop systems typically have faster response times.
- Stability: They are generally more stable since there is no possibility of instability due to feedback.

Disadvantages of Open Loop Control Systems:

- Lack of Accuracy: They are less accurate compared to closed loop systems because they do not correct for disturbances or errors in the system.
- No Adaptability: Open loop systems cannot adapt to changes in the system or environment since they do not have feedback.
- Sensitivity to Disturbances: They are sensitive to disturbances and uncertainties since there is no mechanism to compensate for them.

2.2.2 Closed Loop Control System:

In a closed loop control system, the output is continuously monitored and compared to a reference value, and corrective action is taken to minimize the difference between the output and the reference value. Here's how it works:

- Input: A reference input signal or setpoint is provided to the system.
- Controller: The controller compares the output of the system to the reference input and generates a control signal based on the error between them.
- Plant/Process: The control signal is applied to the plant or process being controlled.
- Feedback: The output of the plant is measured and fed back to the controller to adjust the control signal.
- Output: The output of the system is continuously adjusted based on the feedback to minimize the error between the output and the reference input.

Advantages of Closed Loop Control Systems:

- Accuracy: Closed loop systems are more accurate since they continuously correct for errors and disturbances.
- Adaptability: They can adapt to changes in the system or environment since they have feedback.
- Reduced Sensitivity: They are less sensitive to disturbances and uncertainties since they can compensate for them.

Disadvantages of Closed Loop Control Systems:

- Complexity: Closed loop systems are often more complex and expensive to implement due to the need for feedback sensors and more advanced control algorithms.

- Slower Response: They typically have slower response times compared to open loop systems due to the additional processing required for feedback.
- Potential for Instability: Closed loop systems can be prone to instability if not properly designed, especially if there are delays or nonlinearities in the system

2.3 Hardware

2.3.1 Raspberry Pi 4B

The Raspberry Pi 4B stands as a powerful single-board computer (SBC) that has revolutionized the landscape of affordable and versatile computing. Born out of the Raspberry Pi Foundation's commitment to promoting computer science education and facilitating accessible computing solutions, the Raspberry Pi 4B combines enhanced processing capabilities with a compact form factor, making it a preferred choice for various applications.[6]

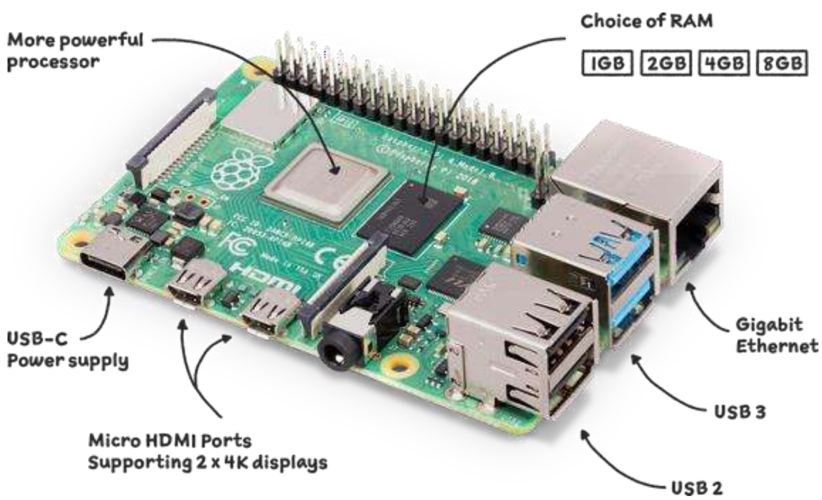


Figure 2.3 Raspberry Pi 4B[7]

Processing Power:

The Raspberry Pi 4B is equipped with a quad-core ARM Cortex-A72 processor, providing significant computational power for a wide range of tasks. With clock speeds up to 1.5 GHz, this SBC can handle diverse workloads, from basic computing tasks to more complex applications.

Memory and Connectivity:

One of the notable features of the Raspberry Pi 4B is its memory capacity and connectivity options. The SBC is available with variants offering up to

8GB of LPDDR4 RAM, allowing for smoother multitasking and improved performance. Additionally, it includes USB 3.0 ports, Gigabit Ethernet, and support for dual-band wireless networking, providing robust connectivity options for various peripherals.[6]

Video Capabilities:

The Raspberry Pi 4B supports dual-monitor configurations with dual micro-HDMI ports, each capable of driving a 4K display. This feature enhances its applicability in projects requiring high-definition video output, making it suitable for media centers, digital signage, and educational purposes.

General-Purpose Input/Output (GPIO):

The GPIO pins on the Raspberry Pi 4B facilitate interfacing with the physical world, enabling the connection of sensors, actuators, and other hardware components. This capability makes the SBC a valuable tool for embedded systems, IoT (Internet of Things) projects, and educational activities that involve hands-on electronics.

Operating Systems:

Raspberry Pi 4B supports various operating systems, including Raspbian (now known as Raspberry Pi OS), Ubuntu, and others. This flexibility allows users to choose the most suitable operating system for their specific applications, ranging from desktop computing to dedicated server tasks.

In conclusion, the Raspberry Pi 4B stands as a versatile and accessible computing platform with significant processing power, robust connectivity options, and a rich ecosystem. Its impact spans a wide range of applications, from educational initiatives to DIY projects and industrial applications, solidifying its position as a transformative force in the world of single-board computing.

2.3.2 Raspberry Pi Pico W

The Raspberry Pi Pico W represents a compact and cost-effective microcontroller developed by the Raspberry Pi Foundation, extending the organization's commitment to fostering education and innovation in the realm of embedded systems and programming. Introduced as an evolution of the original Raspberry Pi Pico, the Pico W retains the Pico's core features while integrating wireless connectivity, further expanding its utility in IoT (Internet of Things) projects and other applications.

Figure 2.4 Raspberry Pi Pico W[8]

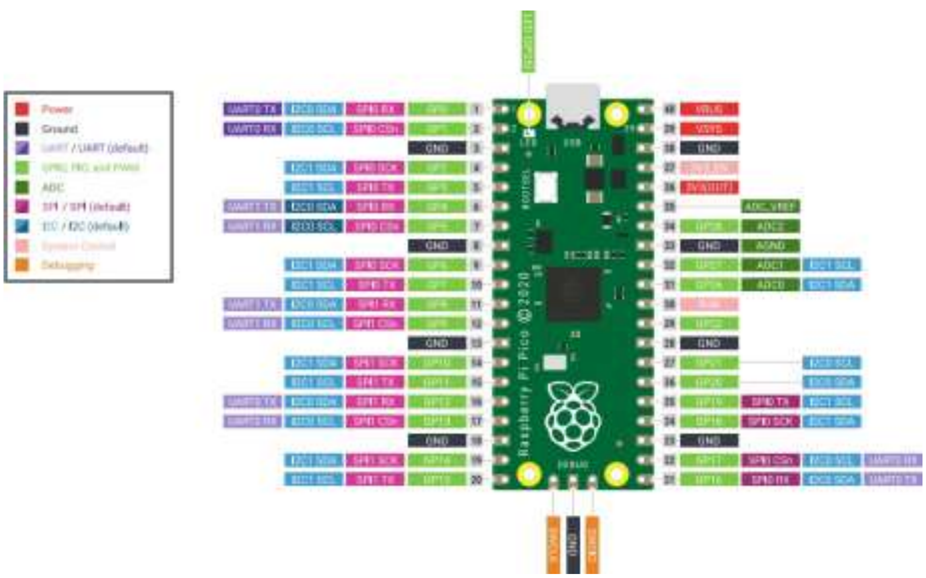


Figure 2.5 Raspberry Pi Pico W pinout diagram[9][8]

Microcontroller Architecture:

The heart of the Raspberry Pi Pico W is its microcontroller, a dual-core Arm Cortex-M0+ processor. This microcontroller is optimized for low-power applications, making it well-suited for battery-operated devices and embedded systems. The dual-core design enhances multitasking capabilities, allowing simultaneous execution of multiple tasks with efficiency.[10][8]

Wireless Connectivity:
A notable feature that distinguishes the Pico W from its predecessor is its integrated wireless connectivity. With built-in support for Wi-Fi and Bluetooth Low Energy (BLE), the Pico W enables seamless communication with other devices and networks. This capability is particularly advantageous in IoT scenarios, where remote monitoring, control, and data exchange are essential.

GPIO Pins and Hardware Flexibility:
Similar to the original Pico, the Pico W retains the GPIO (General-Purpose Input/Output) pins, providing the flexibility to interface with various sensors, actuators, and other external components. This versatility allows developers to create custom electronic circuits and connect the Pico W to a wide range of peripherals.

Programmability and Development Environment:
The Raspberry Pi Pico W supports the MicroPython programming language, making it accessible to both beginners and experienced developers. MicroPython facilitates rapid prototyping and experimentation, enabling users to write code efficiently and test ideas quickly. Additionally, the Pico W is programmable using the C programming language through the Raspberry Pi Pico C/C++ SDK, providing advanced users with greater control over their projects.[11]

Energy Efficiency and Low Power Consumption:
Designed with energy efficiency in mind, the Pico W is well-suited for battery-powered applications and projects that prioritize minimal power consumption. This feature makes it an excellent choice for IoT devices that require long battery life and the ability to operate in remote or off-grid locations.

In summary, the Raspberry Pi Pico W microcontroller offers a compelling combination of wireless connectivity, GPIO flexibility, programmability, and energy efficiency. As a versatile tool for both beginners and experienced developers, the Pico W empowers a wide range of projects, from educational endeavors to real-world IoT applications, contributing to the ongoing evolution of embedded systems and DIY electronics.

2.3.3 Servo Motor and Servo Motor Driver
The servo motor to be used in the project is an AC Servo motor. The model's name of the motor is ECMA-C10807SS.

Below is the pictorial representation of the naming convention used for the servo motor.

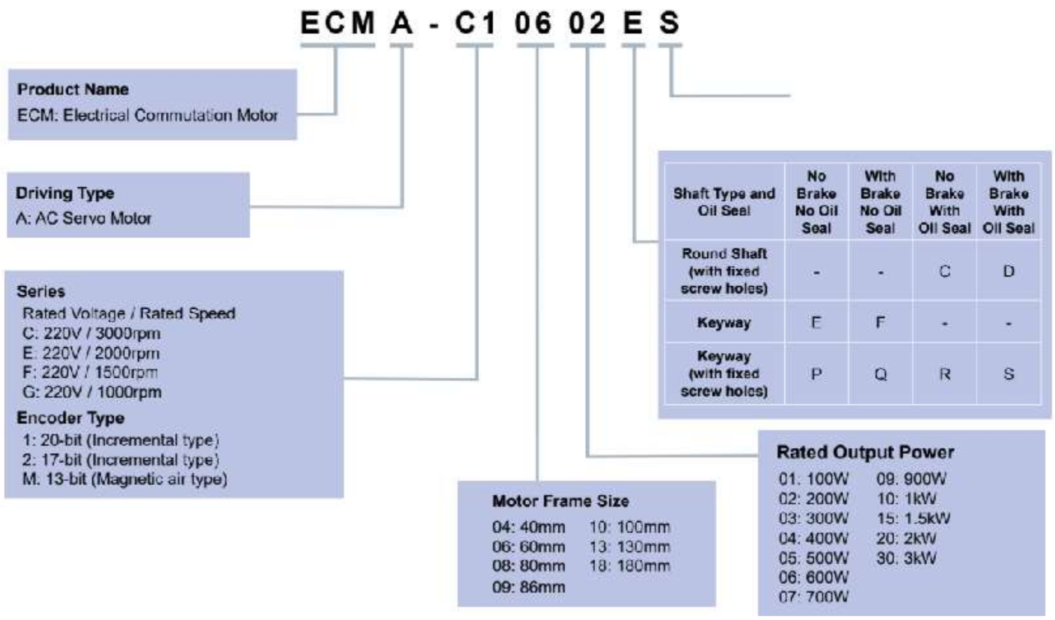


Figure 2.6 Naming Convention for Servo Motor

Given the above image, we can clearly deduce a few properties about the servo motor, like its power rating, encoder type, size, rated output power, and shaft type and oil seal. These properties are listed below:

- Driving Type: AC Servo Motor
- Series: 220V/3000rpm
- Encoder Type: 20-bit incremental type
- Frame Size: 80mm
- Rated Output Power: 700 W
- Shaft type and Oil seal: With break with oil seal

2.3.4 L298N Motor Driver

The L298N operates by using pulse-width modulation (PWM) signals to control the speed of DC motors and by controlling the direction of current flow to control the rotation direction. It consists of two H-bridge circuits, each capable of driving a single motor.

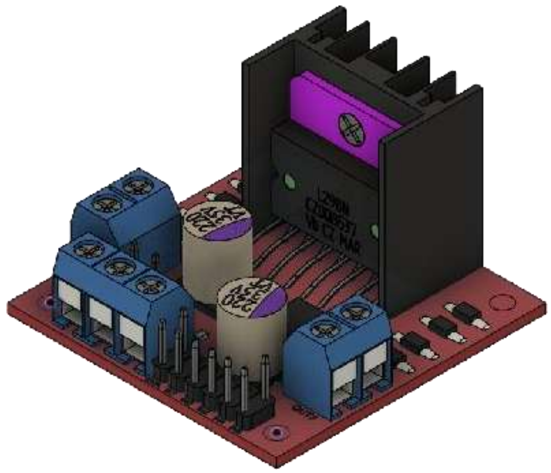


Figure 2.7 L298N Motor Driver

Features:

- **Dual H-Bridge Configuration:** The L298N has two H-bridge circuits, allowing control of two motors independently.
- **High Current Capability:** It can handle relatively high currents, typically up to 2A per channel (with proper heat sinking).
- **Voltage Compatibility:** The L298N is compatible with a wide range of input voltages, typically from 5V to 35V, making it suitable for various motor types. Built-in Diodes: It includes built-in protection diodes (known as "flyback diodes") to protect against voltage spikes generated by the motors during operation.
- **Logic Compatibility:** The control inputs of the L298N are compatible with both TTL and CMOS logic levels, making it easy to interface with microcontrollers and other digital control circuits.

Applications:

- **Robotics:** The L298N is commonly used in robotic platforms for controlling the movement of wheels or other actuators.
- **Automation:** It finds applications in automated systems where precise motor control is required, such as conveyor belts and industrial machinery.
- **Education and Prototyping:** The simplicity and availability of the L298N make it popular for educational purposes and rapid prototyping in electronics projects.

Chapter 3 : Methodology

In this work, we have tried to look into an alternative method to control the radio interferometry site of IIT Indore. The method is as follows:

3.1 Software

The software part can be divided into four sub sections to begin with:

1. Communication
2. Pointing
3. Velocity Profiling
4. Tracking

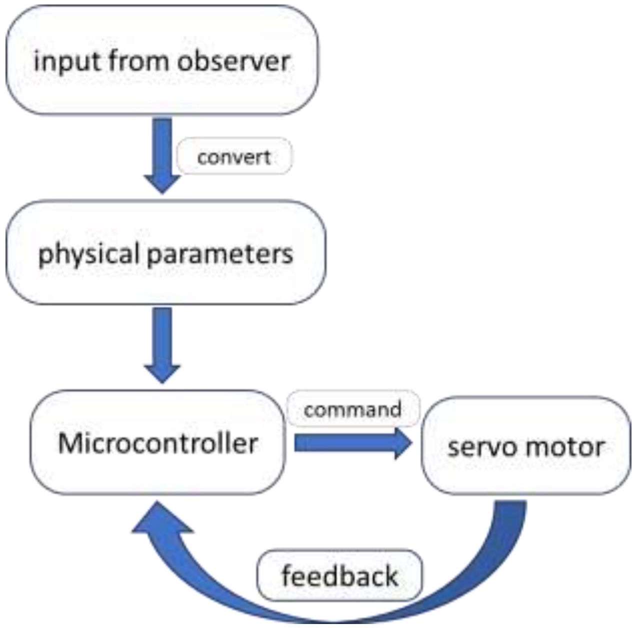


Figure 3.1 The flow chart regarding software functionality

3.1.1 Communication

The communication part entails the communication between the two raspberry Pi's that will serve as the main computing power for the antenna as well as the antenna control site, which will use it so send the messages and commands to the antenna for various purposes.

The communication protocol used for this purpose needs to be carefully chosen such that it not only serves the purpose but also is fast and reliable. The communication protocols that were mainly look into for this purpose were two:

1. UDP (User Datagram Protocol)
2. TCP (Transmission Control Protocol)

Feature	TCP	UDP
Connection Type	Connection-oriented	Connectionless
Reliability and order of delivery	Reliable, ordered, error-checked	Unreliable, unordered
Flow Control and Congestion Control	Implemented	Not implemented
Header Size and Overhead	Larger header size	Smaller header size
Use Cases	File transfer, web browsing, email	Real-time applications (streaming, gaming, VoIP)
Pros	Reliable data delivery, error checking, ordered transmission	Low overhead, faster transmission, less complexity
Cons	Higher overhead, potentially slower for time-sensitive application	Lack of reliability and ordered delivery may not be suitable for applications that require data integrity

Both of these protocols are widely used and are pillars of communication, but for our purpose, we had to choose the one that not only is reliable but also can send messages to all the antenna dishes at the same time, and receive their replies as well. This kind of messaging is known as multicasting, and only one of the above protocols is used for such purpose, that is UDP. The UDP protocol is the only one of these two that can talk to multiple senders at the same time. Hence, we will be using the UDP protocol for the project thus far. The question of reliability can be addressed by having a private network over which the data is sent and since our system is going to be a private system, we can have assurance of safe and reliable data transfer.

3.1.2 Pointing

The pointing problem is the one which can be addressed relatively easily. The pointing is achieved by using the degree by which we have to move the system and calculating the number of pulses required for the rotation thus needed. By doing so, now we just need to make PWM pulses and send them to the servo motor and driver system, to point the telescope to the desired coordinates.

3.1.3 Velocity Profiling

Velocity profiling is the technique used by various control engineers and engineers in general, to give the system in question a smooth transition between it being stationary and moving. The velocity profile is generally provided keeping a few factors in mind which are listed below:

1. **Precision Requirements:** Given that a radio telescope demands high precision for accurate observations, the velocity profile should prioritize smooth and controlled movements. Minimizing abrupt changes in velocity is crucial to prevent disturbances that could affect the telescope's pointing accuracy.

2. **Low Acceleration and Deceleration:** Large and bulky systems, like a radio telescope, are sensitive to acceleration and deceleration forces. The velocity profile should feature low acceleration and deceleration rates to avoid mechanical stress, vibrations, and potential misalignment of the telescope's components.

3. **Smooth Transitions:** Ensuring smooth transitions between different velocity states is essential. The profile should be designed to eliminate jerky movements, reducing the risk of mechanical wear and maintaining the stability of the telescope during motion.

4. **Adaptive Velocity Control:** Incorporate an adaptive velocity control system that can adjust the velocity profile based on the telescope's current state, payload, and environmental conditions. This allows for real-time optimization and ensures consistent performance under varying circumstances.

5. **Dynamic Response:** Evaluate the dynamic response of the system to changes in velocity. The velocity profile should be designed to achieve the desired velocities promptly without introducing overshooting or oscillations that could compromise the telescope's pointing accuracy.

6. **Energy Efficiency:** Optimize the velocity profile for energy efficiency, as large and bulky systems may have significant power requirements. Minimizing unnecessary acceleration and deceleration helps conserve energy and reduce overall operational costs.

7. **Payload Considerations:** Consider the sensitivity of the radio telescope's instruments. Gentle acceleration and deceleration are crucial to prevent disturbances in the equipment and ensure the integrity of observational data.

8. **Control System Precision:** Ensure that the control system is capable of precise regulation of the telescope's velocity. Implement feedback mechanisms and sensors that can monitor and adjust the motion in real-time, compensating for any deviations from the desired profile.

9. **Environmental Adaptability:** Account for external factors such as wind loads and temperature variations that may affect the telescope's motion. The velocity profile should be adaptable to environmental conditions to maintain performance under different circumstances.

Taking the above parameters in consideration it was determined that the acceleration and deceleration time of the motor to reach its maximum velocity will be kept as 10 seconds and the overall motor profile will follow a trapezoidal approach. The lower limit of the velocity was determined using the specifications of Raspberry Pi Pico W, which states that the minimum frequency of PWM waves that can be generated using the method being used is 8Hz. While the upper limit of the velocity is determined using the calculations below:

Sky Tracking Velocity

- Sky moves $15''/s$
- motor moves 360º per 10,000 pulses
- gear ratio of antenna is 158:1

$$158 * 1000 * x/36 \; Pulses = x^\circ$$

$$1580/1296 * x \;\; Pulses = x''$$

$$1'' = \; 1580/1296 \, pulses$$

- to track sky we will need, 18.287Hz of frequency

Peak Velocity

- The peak velocity of telescope was determined to be $20^\circ/min$
- motor moves 360º per 10,000 pulses
- gear ratio of antenna is 158:1

$$158 * 1000 * x/36 \; Pulses = x°$$

$$1° = 158000/36 \; pulses$$

- for 1º/min we will need, 73.148148 ppm
- for peak velocity we will need, 1462.962962Hz

Using this information the limits of velocity that the telescope can take were bound. Below is the graph showing the velocity profile of the motor:

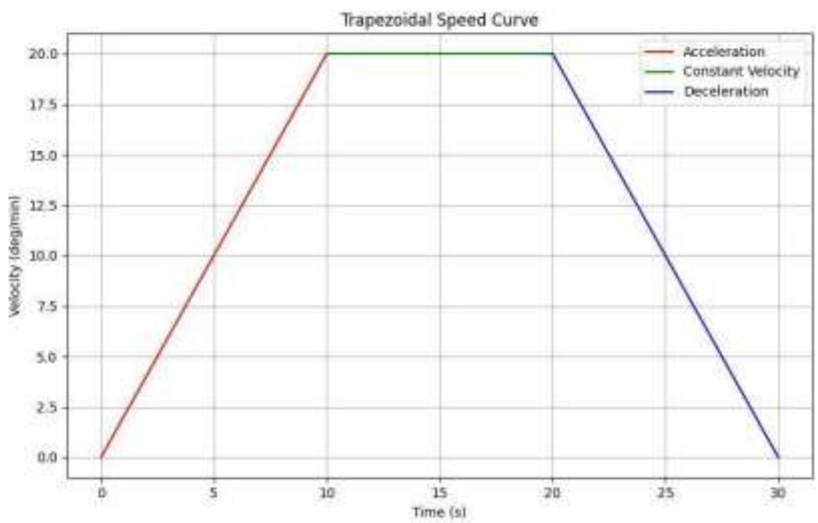


Figure 3.2 Trapezoidal Velocity Profile designed for Motor

3.1.4 Tracking

Once the pointing of the celestial object has been achieved by the system, then we need to start tracking the object for the rest of the observation time very smoothly. This can be done in two ways:

1. Position Tracking
2. Velocity Tracking

Both of the above stated methods have their pros and cons, which we will discuss briefly as their implementation and use will greatly affect the quality of observation.

Position Tracking

This is achieved in a similar fashion as the method used for pointing, that is by sending position of the celestial object at precise intervals and following the path accurately with time. This method is simple and easy to implement. Hence it was observed that the error during this method was to bare-minimum while testing this method in the lab. This result is as expected because the error remained during the pointing was also observed to be 0.1° which is the least count of the encoder currently in use.

Velocity Tracking

The application of this method is a bit challenging as we do not have direct control over the position of the telescope, rather we are using the velocity to control the position of telescope during the observation. It is also evident that while position tracking is good method, we do not move our telescope smoothly during the observation rather we move it in small steps, which can vary from 1sec to 0.1 sec or so depending on the required precision of the telescope. Whereas in velocity tracking since we are just varying the velocity of the telescope to match that of the object throughout the observation, we are left with a much smoother movement of the telescope. In this method similar to position tracking, we send velocity values to the telescope, point to be noted here is that since the velocity of the object does not change drastically over the course of observation, it becomes feasible to implement this method without generating any mechanical stresses in the system.

The challenge in this method is the requirement of even sharper time control over the communication time, required to send these parameters to the Raspberry Pi Pico W as the delay of more than the time intervals made will result in an incremental increase in the error which will add up throughout the observation and we will loose tracking.

3.2 Hardware Configuration and Justification

3.2.1 On site Computer

Raspberry Pi 4B is used as an onsite computer that will be placed near the antenna itself to do most of the calculations and computing that is required by our system. It is used instead of a proper computer or a PC setup to reduce the overall cost of the system as well as reduce the computational load at the observation. By doing so we will essentially be reducing the time consumed to send the command to the antenna every single time throughout the observation, essentially making it a much more efficient setup.

3.2.2 Motor Control

The motor driver used for the control of the motor is ASDA-B series, by delta electronics. This motor and driver were chosen as this is similar to one that is currently being used in the at present system, in its dimensions and use, but has a higher precision count than the one in the current system. Now since in our case, our choice of motor was evident from the start, the driver selection became evident as both motor and driver are made in pairs, and are sold that way only. The control input signal of this driver is a PWM signal of amplitude range 12V to 24V. The configuration of the driver is set such that for every 10000 PWM Pulse input the motor moves precisely 1 revolution. Given that this is the configuration it can also be deduced that speed of the motor is dependent on the frequency of the PWM pulses provided to the driver, the higher the frequency the higher the revolution speed of the motor. I can actually be shown mathematically the relation between the speed of the motor and the frequency of PWM waves provided. The formula is written below:

$$\mathbf{x\ deg/s = 27.77 * x\ PPS}$$

3.2.3 PWM Pulse Generation

Pulse generation for the motor control is handled by a Raspberry Pi Pico W, which is a microcontroller manufactured by Raspberry LTD. This microcontroller provides a stable frequency and pulse shape which is required by our system. The code for the pulse generation is written in MicroPython, which is a programming language that is similar to Python in structure but is specifically designed to work with microcontrollers.

The Raspberry Pi Pico W has 8 independent PWM generators called slices. Each slice has two channels, channel A and channel B, which makes a total of 16 PWM channels. Important thing to note here is that we can only produce 1 frequency on one slice i.e. 0A and 0B cannot have different frequencies, but they can be operated at different duty cycles.

GPIO	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PWM Channel	0A	0B	1A	1B	2A	2B	3A	3B	4A	4B	5A	5B	6A	6B	7A	7B
GPIO	16	17	18	19	20	21	22	23	24	25	26	27	28	29		
PWM Channel	0A	0B	1A	1B	2A	2B	3A	3B	4A	4B	5A	5B	6A	6B		

Figure 3.3 Raspberry Pi Pico W PWM Slices[9]

The range of PWM frequencies that can be generated by this device is of range 8Hz to a few MHz where it can create PWM waves with good form and reliable accuracy, which is very good for us as we are well within the range of its use. The thing to keep in mind is that the amplitude of output frequency is at max 3V which is not in the desired range and needs to be amplified while retaining its structure and frequency in real time. The plot of PWM frequency generated by Raspberry Pi Pico W is shown below:

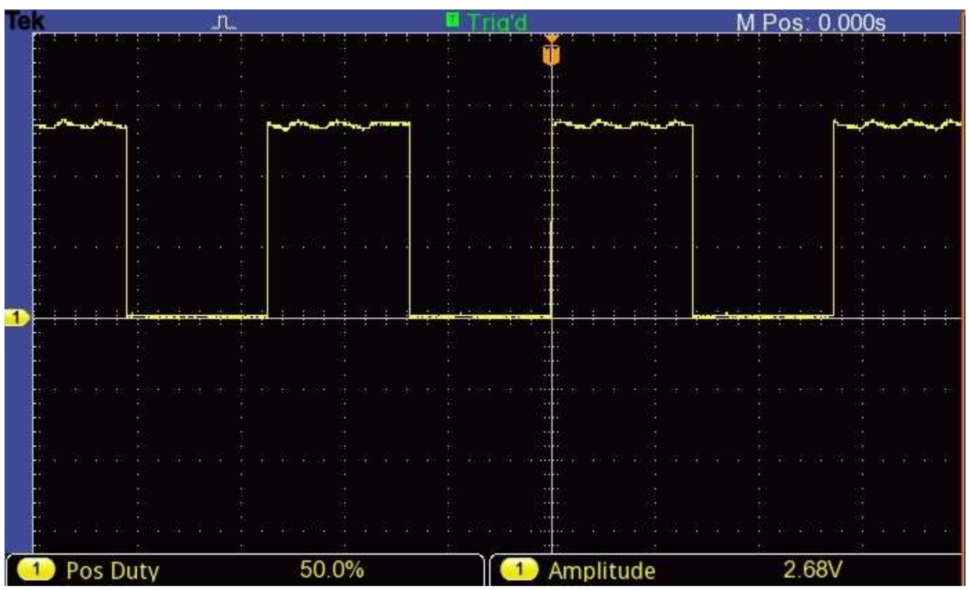


Figure 3.4 PWM output of Raspberry Pi Pico W

3.2.4 PWM Pulse Amplification

The key point to this setup is that the pulse that is generated by the microcontroller is stable and steady, but its voltage is 3V which is out of the acceptable range of servo drive, which means it needs to be amplified to the desired levels, without losing its integrity and fed to the servo motor driver. This task is done by utilizing the motor driver for smaller motors, L298N which is a versatile motor driver used in many small robotics projects, to control the servo motors and DC motors. The task was done by feeding the PWM output of Raspberry Pi Pico W to the input of the driver, and working the driver in the following:

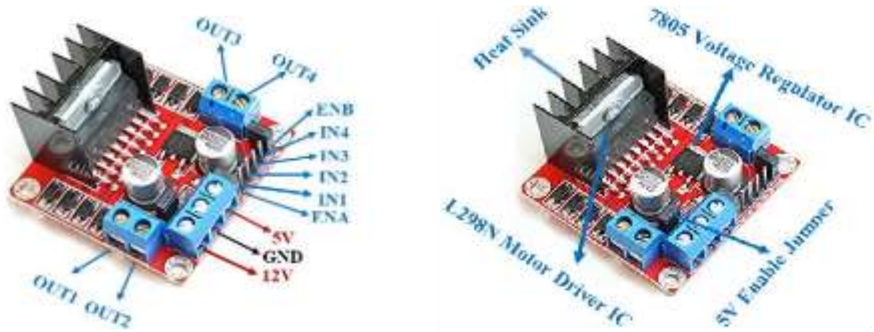


Figure 3.5 Pinout of L298N Motor Driver[12]

- removing the 5V enable Jumper
- providing logic input to IN1
- 5V input to 5V pin
- 15.6V input to the 12V pin
- GND to GND pin
- output from Out1 and Out2

Using the described connection, we are able to amplify the PWM signal without any trouble and loss of structure, as can be seen below:

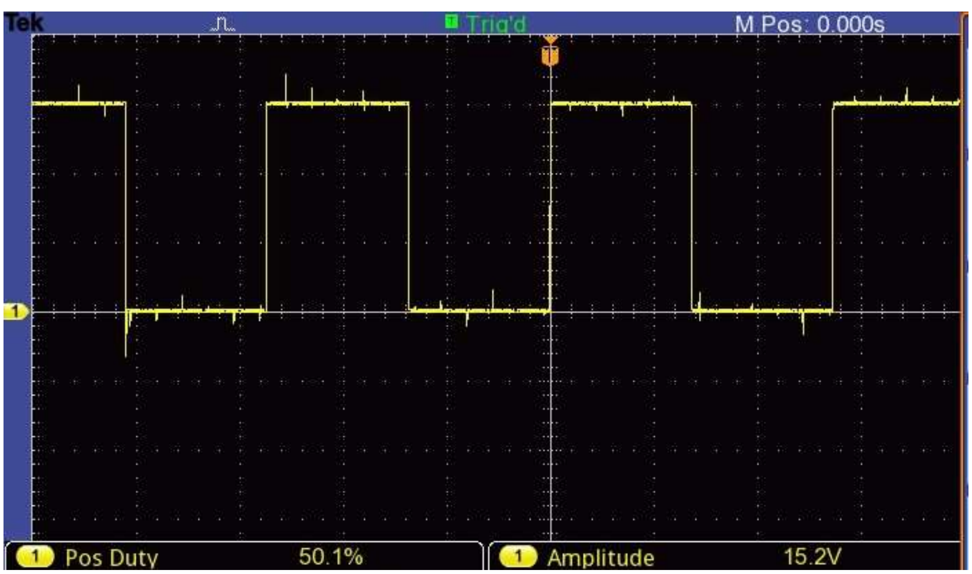


Figure 3.6 Amplified PWM wave using L298N Motor Driver

3.2.5 Feedback

Once this is done the motor is moved and we need to check whether the motor has moved according to our input signal or not. This is achieved by the use of an external encoder which is put at the output of the motor to note the rotation and give back PWM pulses in accordance to the rotational value of the motor. The encoder used in this project is an incremental encoder named E50S8-3600-3-T-1. Below is the encoder naming convention as stated by the manufacturing company.

E50S	8	8000	3	N	24	
Series	Shaft diameter	Pulse/1Revolution	Output phase	Output	Power supply	Cable
Diameter ø50mm, shaft type	ø8mm	Refer to resolution	2: A, B 3: A, B, Z 4: A, $\bar{A}$, B, $\bar{B}$ 6: A, $\bar{A}$, B, $\bar{B}$, Z, $\bar{Z}$	T: Totem pole output N: NPN open collector output V: Voltage output L: Line driver output	5: 5VDC ±5% 24: 12-24VDC ±5%	No mark: Cable type C: Connector cable type(※) CR: Axial connector type CS: Radial connector type

※Standard : E50S8-[PULSE]-3-N-24 ※Cable length: 250mm

The reason for selecting this encoder was to keep the hardware as similar to the existing hardware used in the system currently in use, as we have done with many of our other parts. The resolution of the encoder is 3600 PPR. Given this information we can easily deduce the current position of the encoder by counting the number of pulses sent by the encoder. And the formula for deducing the current position of encoder is written below:

$$\boldsymbol{current\ position(deg) = 0.1 * Pulses\ Received}$$

This will only tell us the relative position of the encoder from its current position, as it's an incremental encoder it doesn't keep track of its current position. This also means that we will not be able to tell the direction of motion from just reading the PWM pulses. To achieve control over directionality, the incremental encoders provide 3 outputs.

- Phase A
- Phase B
- Phase Z

The phase A and phase B of the encoder are made such that their pulsed output is out of phase with one another by 90 degrees. For clockwise rotation phase A leads phase B by 90 degrees, and for counter-clockwise rotation phase B leads phase A by 90 degrees. This implies that by measuring the phase difference between the two outputs we can accurately tell the direction the antenna dish is moving in. Where the number of pulses counted at only of the phase will tell us the amount of change in degrees to its current position. This is shown below in the image below:

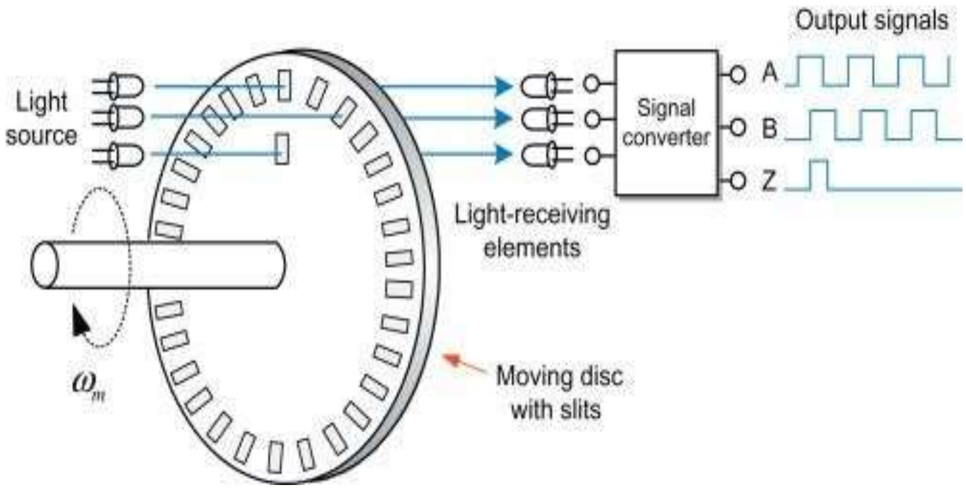


Figure 3.7 Incremental Encoder Output signal generation and relation

It is to be noted that though phase Z is not of any use to us in this case, it will just give 1 pulse per revolution, which may or may not be relevant to some cases.

The accuracy of pulse counting is of paramount importance as if it's not accurate then that means that the feedback system will be of no use and will provide wrong results and eventually the deviation in the system will increase so much as to make it of no practical use. Hence extensive testing was done to check the reliability of pulse counting, which will be explored in next.

3.2.6 Pulse Counting

The feedback signal from the encoder at the output is also in the form of PWM Pulses, which we need to count and the number of pulses according to the least count of the encoder which in our case would be 3600 pulses per revolution. The counting of these pulses needs to be highly accurate as even a single pulse missed will lead to the system having wrong feedback which will cause the system to effectively point to some other undesirable coordinates. This task is also performed on the Raspberry Pi Pico W, as its system clock is sufficiently fast (125 MHZ) to count the number of pulses with high accuracy. The reliability of pulse counting by Raspberry Pi Pico W was found to be very high as was seen after testing it for a range of PWM frequencies, the graph of which can be seen below:

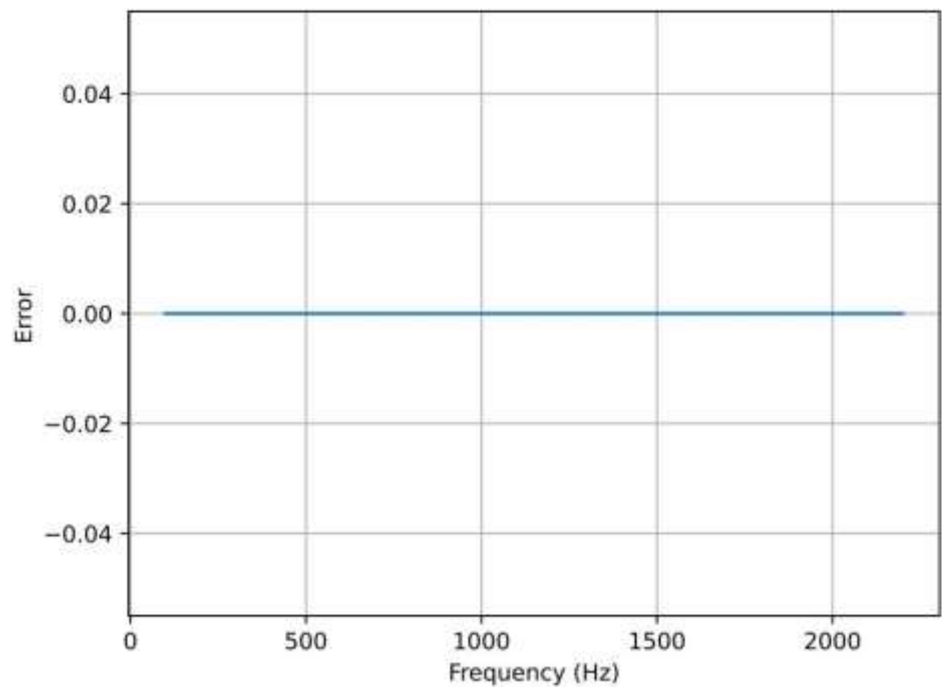
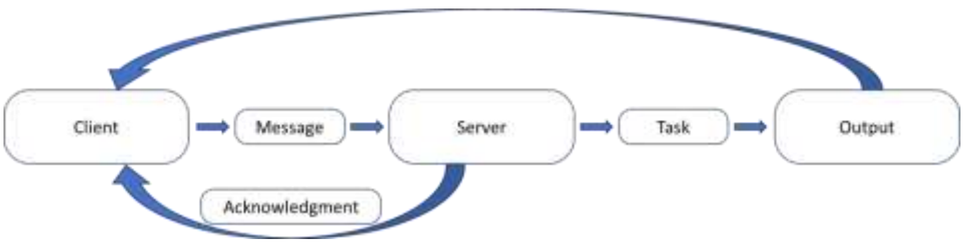


Figure 3.8 The error in counting number of pulses received in 1 sec for frequency range varying from 100Hz to 2.2KHz by Raspberry Pi Pico W

It is to be noted that the above graph was plotted by using Raspberry Pi Pico W to count the number of pulses for 1 second only over a range of frequencies, implying that we should ideally get a straight line, which we got in this case. The function generator was used to generate the PWM pulses for the range of frequencies, to get reliable input pulse frequency.

Chapter 4 : Implementation

The observation will start by the observer giving in necessary information regarding the observation, at the observation hut. This information will then be transferred to each antenna (Raspberry Pi 4B) to be used in the observation using wired communication via Optical fiber cables/ethernet cables. Below is the flow chart for the communication.



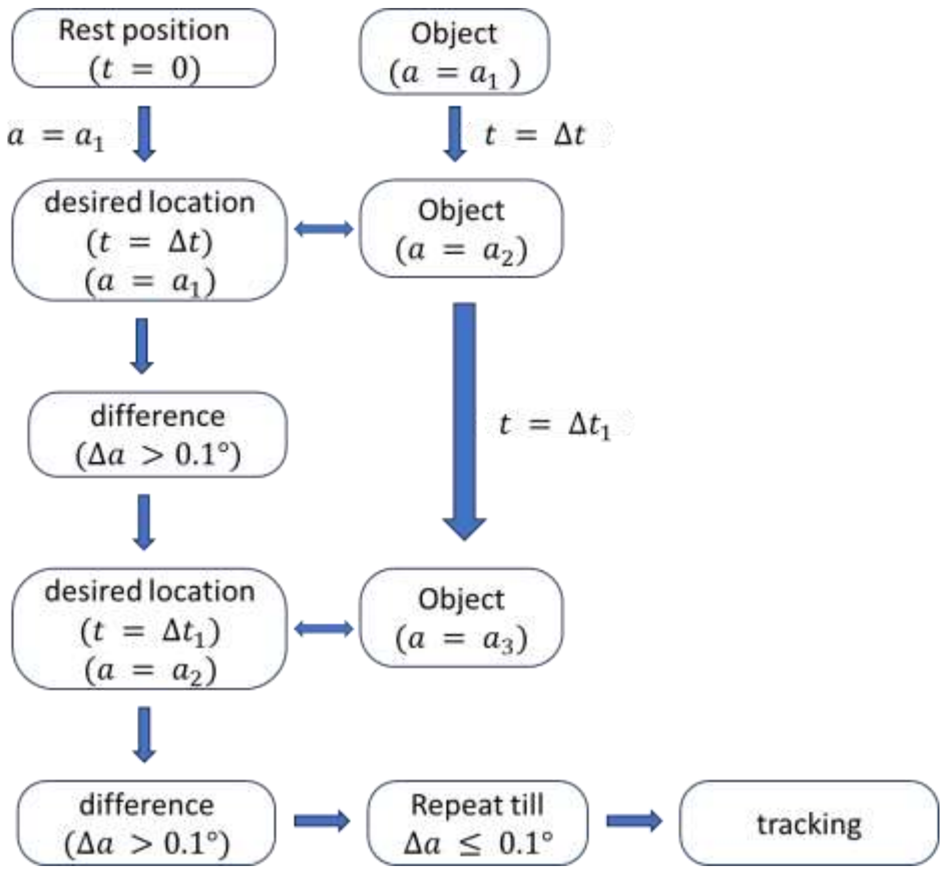
This information is then utilized to calculate the trajectory of observation throughout the duration of observation. Once we have our observable values, these are then communicated to the Raspberry Pi Pico W, to generate necessary control output.

Since the signal strength of Raspberry Pi Pico is not enough and falls outside the functional range of the servo motor drive, the signal had to be amplified and then fed to the servo drive for it to function properly. For this purpose, motor driver named L298N which is used to drive smaller motors is used. The power to the motor driver is provided by an external DC power source, which is set at 24V DC. Once the signal was fed to the servo motor drive, the drive uses that signal and moves the AC servo motor to the desired position. Currently, the drive is set to move the servo motor in the following way:

- For every 10,000 pulses provided the servo motor will move one full rotation.
- The speed of rotation of the servo motor depends on the frequency by which we provide the PWM pulses, the higher the frequency the faster will be the rotational speed of the servo motor.

Once the servo motor reaches the desired position it will hold that position using the brakes, which are also powered using a 24V DC power supply. The information regarding the current position and direction of motion of the motor is noted by an incremental encoder, which is in the form of PWM pulses. These pulses are then sent to the Raspberry Pi Pico W for pulse counting. Then this information is used to discerned the current position of the motor and the error in the pointing is calculated. Then this information is converted to correction command and sent back to motor for correcting. The flow chart of the feedback shown below:

Once the accurate pointing of the object is achieved at the desired time, then the tracking of the object is started, and the observation is carried on.



It is to be noted that the ground of each component in the system is to be at same level, for the system to work, otherwise system will either not work or will not work according to its design.

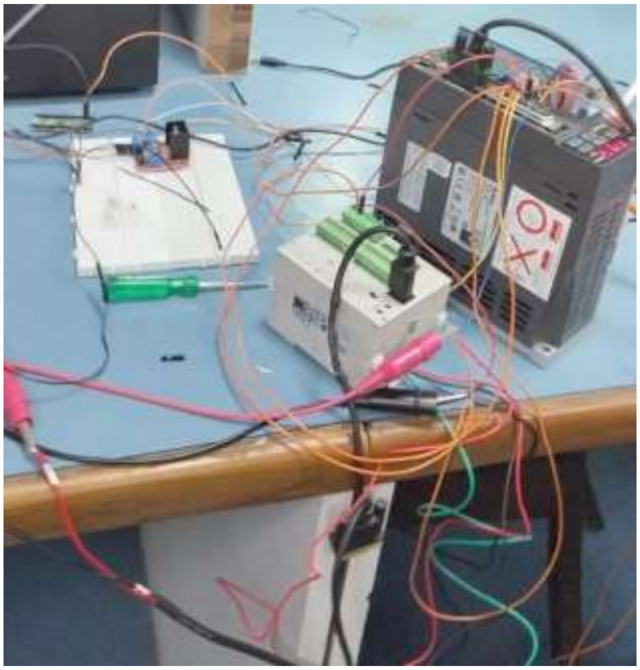


Figure 4.1 The Lab setup of Servo motor test run

Figure 4.2 Lab Setup of System for 1 Motor

4.1 Wiring Details

4.1.1 Raspberry Pi Pico W

- Output Pins: 18, 19
- Input Pins: 13, 11
- GND Pin connected to common ground rail

4.1.2 L298N Motor Driver

Input

- 5V Pin - 5V
- GND Pin connected to common ground rail
- 12V Pin - 15.6V
- IN1, IN4 - Logic input from Pico W

Output

- Out2, Out4 - GND
- Out1, Out3 - Logic input to motor

4.1.3 Encoder

- Blue and F.G. - common ground rail
- Brown wire - 5V input
- Black, White - logic output to Pico W

4.1.4 Brake - 24V D.C. input

4.1.5 Drive

- 220V D.C. input
- Pin43 - 24V logic input from L298n
- Pin39 - 24V direction control input from L298n
- Pin35 - 0V D.C.
- Pin 11 - 24V D.C.
- Pin14 - 0V D.C.

Chapter 5 : Results

1. The code to generate the trajectory of object to be followed by using the known parameters of the observation is complete and tested for objects in our solar system and outside as well.
2. The test of successful data transmission between computer devices using UDP was also tested successfully with no data loss and low latency.
3. The use of L298N motor driver for the use as a amplifier in the system without compromising the structure or frequency of the wave was also tested successfully for a wide range of frequencies.
4. The precision of servo motor to reach the desired potion upon receiving the command was also tested with great success using encoder output as a tool to measure the angle reached by the servo motor.
5. The feedback loop to reach the desired position using encoder was also tested successfully with the precision of 0.1 degree as the precision of encoder is 0.1 degrees.
6. The velocity profile for motor was successfully implemented with feedback loop to reach the desired angle.
7. The operation of the AC servo motor was tested using the proposed setup.

Chapter 6 : Conclusion

The design of the control system for the IIRI is going as expected and the results thus far also in the favor of the proposed design. The use of Raspberry Pi and Raspberry Pi Pico W, have so far proven to be quite useful and trustworthy and have validated the point of reducing the cost of the system to be completed. Currently the system is in the final stages of lab trials and will soon be tested on site for testing its accuracy and reliability during an actual observation.

While this will also help in fine tuning this setup to become a reliable control system for the interferometry site at IIT Indore.

REFERENCES

[1] NCRA, “Introducing GMRT — National Centre for Radio Astrophysics.” http://www.ncra.tifr.res.in/ncra/gmrt/about-gmrt/introducing-gmrt-1/introducing-gmrt (accessed May 10, 2024).

[2] V. Hotkar, “The GMRT Servo System”.

[3] J. Kodilkar and R. Balasubramanian, “A Control and Monitoring system for the GMRT : Description and Requirements Prepared by : A Control and Monitoring system for the GMRT Description and Requirements,” 2011.

[4] R. Balasubramanian, “A Control and Monitor System for the GMRT”.

[5] “Servo System for GMRT Antennas — National Centre for Radio Astrophysics.” http://www.ncra.tifr.res.in/ncra/gmrt/sub-systems/servo-system-for-gmrt-antennas (accessed May 10, 2024).

[6] Rs-Components, “Datasheet Raspberry Pi Model B,” *Raspberrypi.Org*, no. June, p. 1, 2019, [Online]. Available: https://datasheets.raspberrypi.org

[7] Raspberry PI Ltd, “Buy a Raspberry Pi 4 Model B – Raspberry Pi.” https://www.raspberrypi.com/products/raspberry-pi-4-model-b/ (accessed Nov. 20, 2023).

[8] Rasperry Pi, “Pico-W-Datasheet (1),” 2020.

[9] “Raspberry Pi Pico and Pico W Pinout Guide: GPIOs Explained | Random Nerd Tutorials.” https://randomnerdtutorials.com/raspberry-pi-pico-w-pinout-gpios/ (accessed Mar. 02, 2024).

[10] Raspberry, “Raspberry Pi Pico y Pico W,” no. November, 2021.

[11] Raspberry PI Ltd, “RP2040 Datasheet - A microcontroller by Raspberry Pi,” 2023, [Online]. Available: https://datasheets.raspberrypi.com/rp2040/rp2040-datasheet.pdf

[12] “L298N Motor Driver Module Pinout, Datasheet, Features & Specs.” https://components101.com/modules/l293n-motor-driver-module (accessed May 10, 2024).