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Control System Design for a Small-Scale Radio Telescope: A Senior Design Project

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Control System Design for a Small-Scale Radio Telescope; a Senior Design Project

Abstract- This paper presents the management of a student-led initiative to launch an Institute of Electrical and Electronics Engineers (IEEE) award-winning small-scale radio telescope as a senior design project. This challenge provided the students with the opportunity to develop their skills in project management as well as demonstrate and hone their technical abilities in their field. The project involved in-depth research, short-term and long-term goal development with stakeholders, component specification, project funding requests, multidisciplinary team coordination for concurrent and future aspects of the project, and the transfer of the project and documentation to new student teams.

While many are familiar with looking at the stars with an optical telescope, they provide a limited perspective of the universe. Radio telescopes expand our access to aspects of the universe beyond the visible spectrum, including pulsars and imaging black holes. To establish the foundation for this new project, this team took on the design of the control of the pointing system of a radio telescope. This control system employs a microcontroller-based electronic system to orient a 3-meter dish antenna for taking measurements. The system's primary objective is to create a layer of abstraction to allow simple directional control from the main computer using the altitude and azimuth coordinate system.

This project gave the students invaluable experience in managing a complex project over several months. Through the implementation of the project, students learned skills such as scheduling design and testing time based on vendor timelines and other commitments, acquiring and allocating funding, and regularly updating key stakeholders in the student astronomy and electrical engineering clubs, as well as the involved faculty. The resulting radio telescope project provides university undergraduate students with the ability to learn the basics of radio astronomy through the easily accessible small-scale radio telescope system.

Introduction

This project was developed as an extension of a collaborative project between student engineering and astronomy clubs. The members of the capstone team took on the design of the control system and coordination of the overall project. During the initial development of the project, a system block diagram was established as shown in Figure 1. This block diagram gives an overview of the major components of a radio telescope system. It was divided into three major sections, which were then assigned to task teams. In this block diagram, the receiver (in yellow) obtains radio frequency intensity measurements from the antenna. This data is then relayed to the computer through a Universal Serial Bus (USB) interface. The control system (in red) handles the orientation of the dish antenna and communicates with the computer. The computer software system (in green) combines the position data and receiver data to create raster images of the received signals. The primary objective of the capstone project described in this paper was to create a robust control system platform for pointing a 10-foot dish antenna for use in radio astronomy projects. In addition to designing a custom control system, the capstone team directed the overall project and coordinated with the other task groups to create a design that is simple to interface with using a USB port on a computer. To ensure continuity with the project management and development, the development of the project was in coordination with the student IEEE chapter.

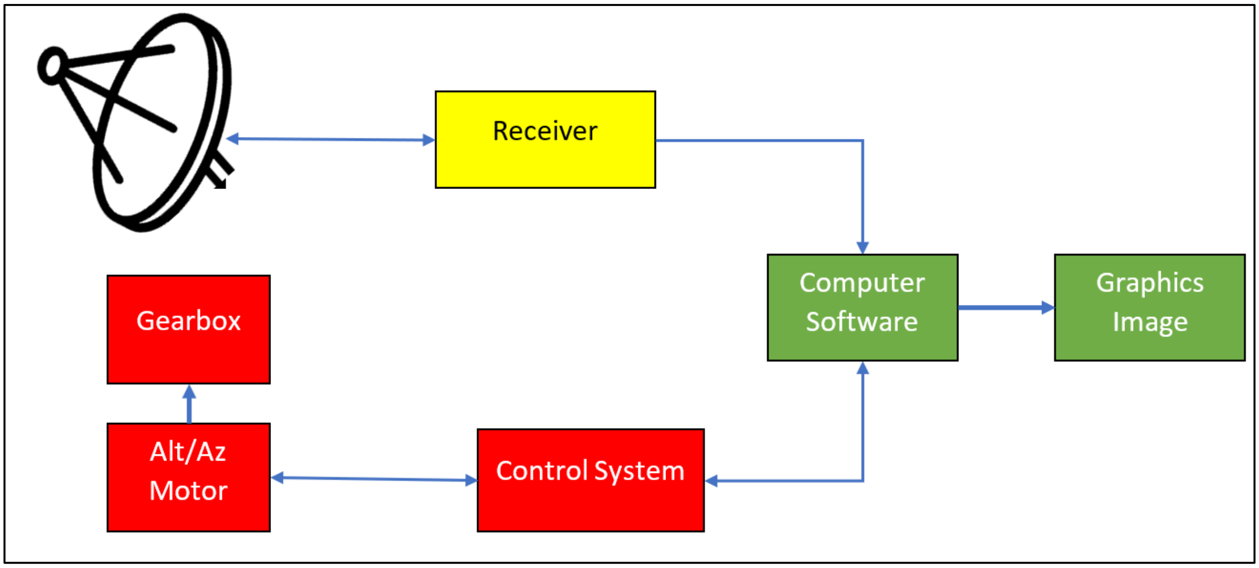

Figure 1: Block Diagram of a Radio Telescope System.

History and Literature Review

Humans have been trying to understand space and the relation of Earth to it for centuries. Between 1928 and 1930, Bell Labs scientist Karl Jansky discovered during an electromagnetic interference experiment that electromagnetic waves from objects in space can be received by antennas on Earth [1]. Jansky built a system of rotating directional antennas that rotated every twenty minutes to obtain measurements from sources from the north, south, east, and west [2]. Engineer and radio amateur Grote Reber studied Jansky's work and replicated it at different wavelengths by using a 31.5 foot paraboloidal reflector, the first of its kind, and made it fully controllable and measure submillimeter wavelengths [3]. Since then, numerous paraboloidal dish antenna systems have been developed across the world, notable among them the Arecibo observatory in Puerto Rico, Five hundred meter Aperture Spherical Telescope (FAST) observatory in China, Giant metrewave radio telescope in India, and the Very Large Array (VLA) in New Mexico.

Figure 2: Very Large Array Radio Telescope [4].

There have been a handful of attempts at small-scale radio telescopes in recent times, such as the 1998 MIT Haystack observatory Small Radio Telescope (SRT), and its updated version in 2012 [5]. The system diagram of the 2012 version is shown in Figure 3 below. The smaller telescopes present problems in that the capture resolution is restricted to the size of the telescope. One of the newer approaches to combat this is Very Long Baseline Interferometry (VLBI) that utilizes a PC and many radio telescopes to increase the effective angular resolution by algorithmically combining measurements from all telescopes in the array. This technique was utilized in the Atacama Large Millimeter Array (ALMA) on fifty telescopes, and separately in the Event Horizon Telescope (EHT) that captured an image of a black hole [6, 7].

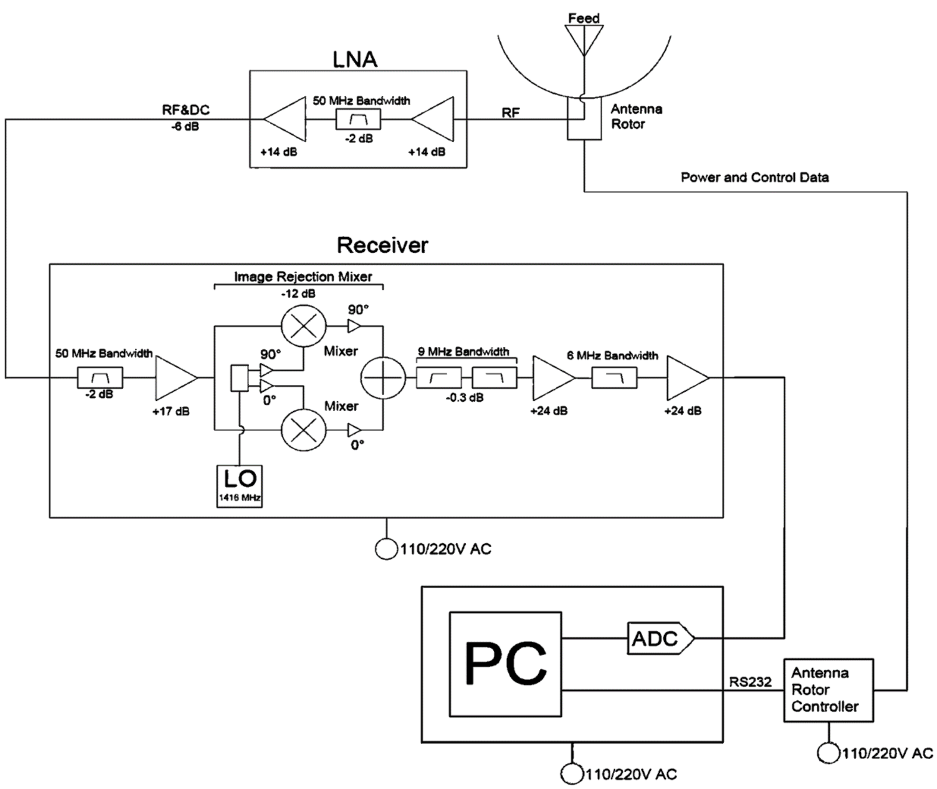

Figure 3: 2012 SRT Radio Telescope System Block Diagram from MIT [5].

One of the more difficult aspects of designing a radio telescope is the control system, as the accuracy of the measurement obtained by the antenna is only as good as the underlying confidence on the orientation of the antenna system. Single-dish antennas are positioned by virtue of two controls: altitude and azimuth [8]. These azimuth and altitude (also called elevation) positions are dictated by a main computer running a program which calculates the equatorial coordinates of the desired celestial body. This computer directs the operation of the controller system for the angular position.

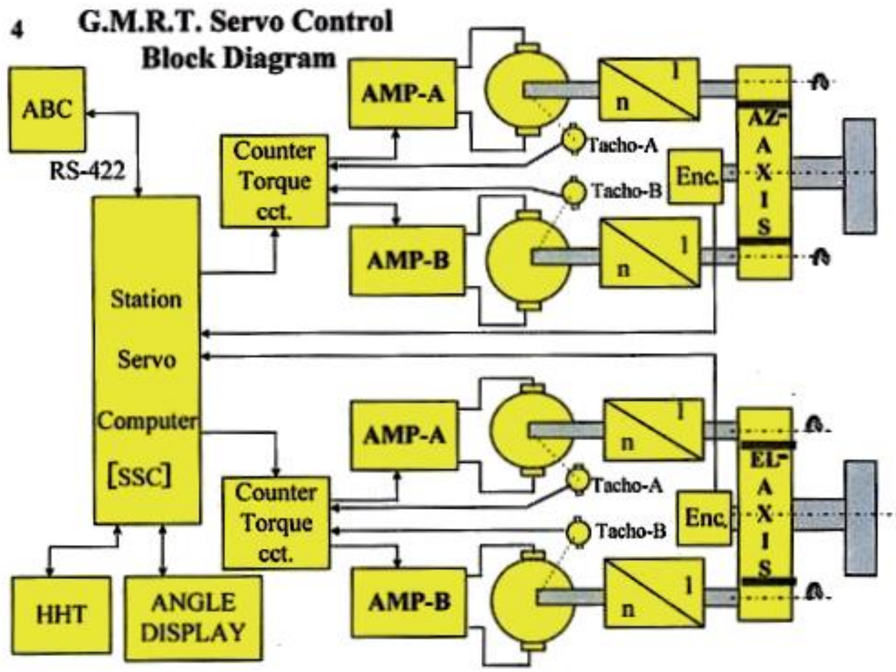

Figure 4: Block diagram of the GMRT Control System [7].

An example of a computer-controller relationship is given in the Giant Metrewave Radio Telescope (GMRT). This telescope system is an array of thirty large dish antennas of 45-meter diameter each [8]. The control system (shown in Figure 4), driven by an embedded computer denoted as the Station Servo Computer (SSC) communicates the position data over a wired link to the antenna base computer (ABC). This SSC system has since been upgraded to a real-time embedded system [9]. In a similar manner, the system that was designed for this capstone project is an embedded microcontroller-based system that was designed to maneuver a 10-foot parabolic dish antenna toward celestial electromagnetic sources in an altitude-azimuth configuration and communicate with a station computer for desired direction commands.

Customer and Engineering Requirements

Meeting the requirements of the customer is crucial for the success of the product. To meet this need for the product, a customer survey was created and completed by potential customers to obtain an idea of the requirements the product must meet for a satisfied end user. We obtained more insight on the necessary specifications of the project by consulting with other experts in this field from within our college, personal network, and reached out to experts in radio astronomy projects at other universities. In addition to the customer surveys, constraints were developed from the environment, cost, and capstone design course requirements. These requirements, along with applicable electronics standards, were organized in a document of engineering requirements, which is summarized below in Table 1. Relevant marketing requirements are referenced in the first column of the table, with the associated engineering requirement and justification.

Table 1: Engineering Requirements.

Marketing Requirements	**Engineering Requirements**	**Justification**
1	Accurate to 0.5 degrees or better.	Maintain precise positioning better than the antenna's angular resolution.
2	Minimum 1RPM Motor Speed	Obtain a measurement within 10 minutes
6	Microcontroller for <$15	Keep cost low
4	Dish antenna resonant at 1.42 GHz	Narrow beamwidth, higher accuracy
11	USB Communication with 115.2kbps baud rate	Communicate with main program computer.
10, 12	At least 32 Character Liquid Crystal Display (LCD)	Ability to monitor local control.
13	Limit Motor Current to 15A	Automatically shut down in case of damaged motor or wiring, or in the case of human interference in the mechanical system for safety.
14	Bidirectional current for motor movement in either direction	Control motor speed & direction
10	Three or more buttons for local input	Control the device locally via human input
15, 6	Subsystem PCB size < 200x200mm	Manufacturability & low price

Customer Requirements:	**Standards and Constraints:**
Measurement 1. Accuracy to less than 0.5 degrees (R) 2. Get result in less than 10 minutes (R) 3. Automatically scan a section of the sky (R) 4. Be able to measure hydrogen radiation (1.42 GHz) (R) 5. Be able to measure other frequencies (D) Access 6. Price is less than $5000 (R) 7. Easy to access for student research, amateur astronomers, and researchers (D) Product Usability 8. 120 V AC Power (R) 9. Remote control of device using USB standard (R) 10. Option for local control at device location (D)	11. USB standard communication. 12. I2C or SPI standards for communication to an LCD display. 13. Protect against motor failure. 14. Bidirectional Motor Movement 15. Prototype PCB 16. Must be completed by May 2023 17. Integrate with IEEE club project.

Block Diagram

The system block diagram is shown in Figure 5. The connections between the sub-modules and the system's overall inputs and outputs are shown in this diagram. The microcontroller coordinates all the functions of the control system. It executes any recognized commands that it receives from the main PC through the USB-UART interface (in blue). This primarily involves the control of two H-bridge circuits which correspondingly control the polarity of 24 Volts DC (VDC) across the motors (in green). This in turn determines the direction of rotation in the azimuth and elevation directions of the motors. The rotary encoders included in the obtained motor module send feedback to the microcontroller to calculate real time position of the motor for accurate pointing of the antenna system. This positional data is then sent back to the PC over the UART-USB interface. The motors operate at 24 VDC, which is obtained from a power supply which can be connected to standard 120 VAC (in orange). The remainder of the circuitry operates at 5 VDC that was converted from the 24 VDC using a 5 V regulator circuit previously designed by a member on this project. Lastly, as per customer request, a local control interface was implemented using a 16x2 liquid crystal display (LCD), three push buttons, and an LED indicator (in yellow) to provide the user at the radio telescope with some basic control actions.

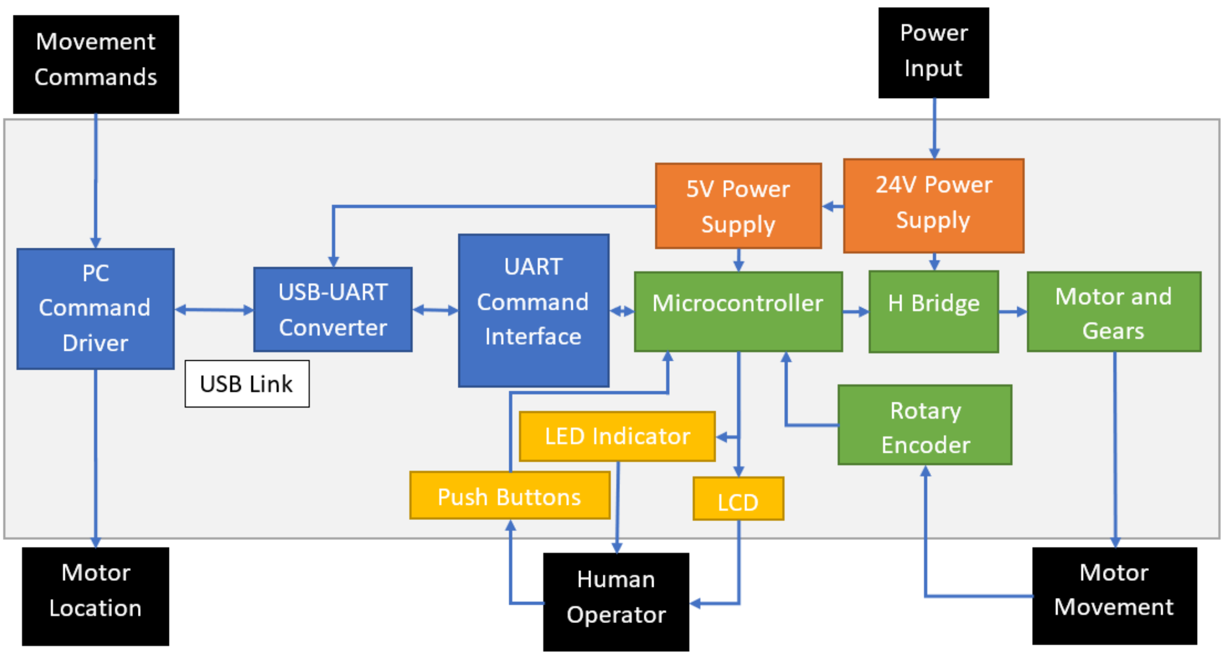

Figure 5: System Block Diagram.

Subsystem Design

This project contains a DC motor driver subsystem which was designed using discrete components to meet the needs of the overall system function. Specifically, it uses a metal-oxide-semiconductor field-effect transistor (MOSFET) H-bridge topology due to its simplicity and its ability to easily reverse the DC motors by passing current in either direction through the H-bridge. The final circuit in Figure 6 was used on the PCB, which included the H-bridge, supporting logic circuitry and overcurrent detection circuitry. Circuit simulation using OrCAD PSPICE was used to validate the circuit design and obtain reference parameters to compare with the results obtained during the integration and testing phase of the project. The goal of these simulations was to measure the time-domain response of the H-bridge switching circuit, particularly when transitions between on and off states occur. Of particular concern with a circuit of this type that switches a heavily inductive motor load is counter electromotive force (EMF) (flyback voltage effect), gate coupling, and transistors fully turning on and off.

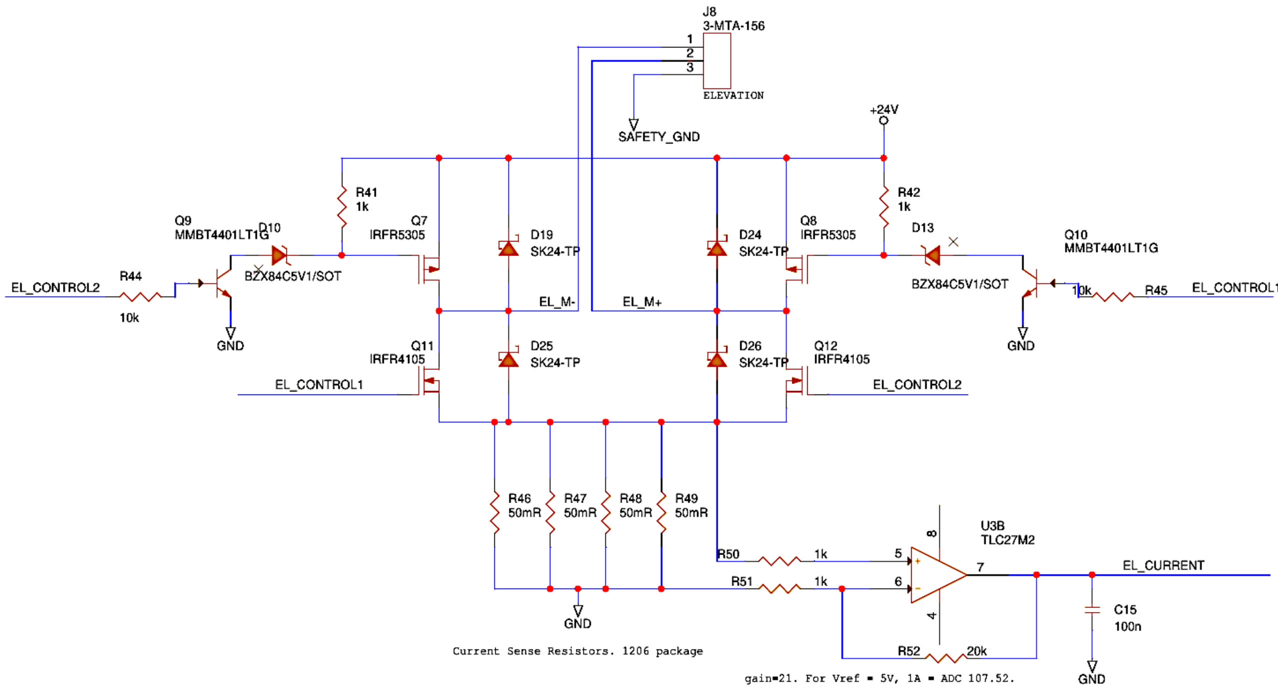

Figure 6: The Schematic of One of the Two H-Bridge Circuits.

This simulation passes the engineering requirements criteria when the transistors do not turn on accidentally (their gate voltages are quiet), the counter EMF does not affect desired circuit operation, circuit oscillations do not affect operation, the transistors quickly reach saturation and cutoff with minimal time in the Ohmic region, and the transistors are not subjected to extreme currents or drain to source voltage greater than the datasheet recommends.

The simulation was first run with a simplified 2-Ohm resistive load to validate the switching logic of the circuit under approximately 12-amp load current. However, the motor system that was purchased requires only up to 2 A, so later simulations reflected this reduction in load current. This oversizing of the components allows for flexible installations should a larger motor become necessary in future iterations of the design.

With no issues seen in this simulation, the next step was to introduce the DC motor model as the load as seen in (b) of Figure 7. This model included the armature resistance, the armature inductance, and a voltage that represents the loading. While the motor inductance was unknown at the time, an arbitrary value was chosen for the purpose of the simulation. However, the antenna that would be used for prototyping was known to be a small weight in comparison to the output torque of the 24 VDC motors that were being researched. So, it was known that the loading voltage in this model could be up to 17 VDC (essentially unloaded). The resistance was also chosen in accordance with the expected current requirement of the motor.

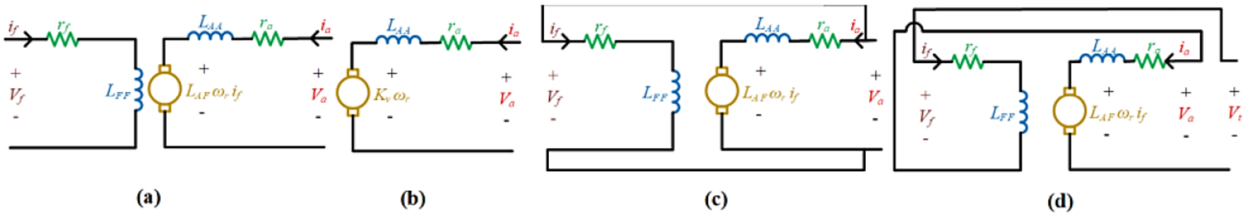

Figure 7: DC Motor Models: "Equivalent Circuit of (a) Separately Excited, (b) Permanent Magnet, (c) Shunt-Connected and (d) Series-Connected DC Motors" [10].

The result of this simulation can be seen in Figure 8. Overall, the system does reach a steady state of 17 V, which means off in this simulation due to the DC voltage included for the loading. This indicates that the motor can only be switched on and off up to a certain rate. The oscillations in this period could be potential problems if exhibited by the real motor, but an RC dampening circuit can be connected in parallel to mitigate the high frequency oscillations and reduce the rise time and overshoot. However, the oscillations do not share a large current passing through the motor model, so it will likely not be an issue.

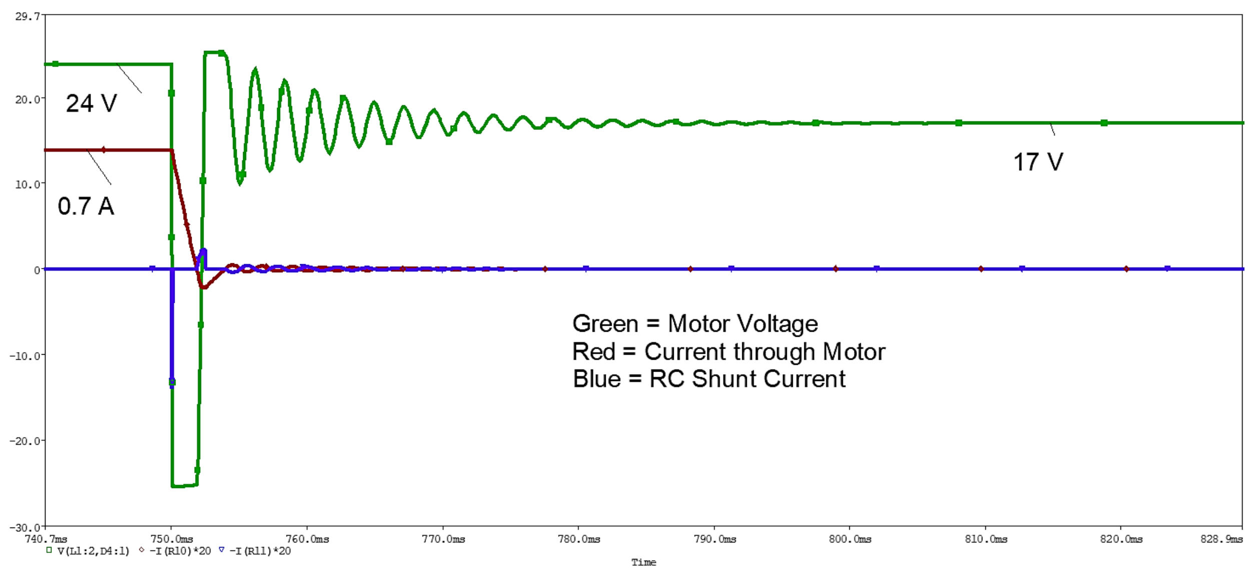

Figure 8: Motor Voltage, Current, and RC Shunt Current with Oscillating Values.

To demonstrate the ability to run the motor in both directions, the motor model was flipped, and the other two transistors were turned on to cause current in the opposite direction. The response for this reverse direction is the same as in the forward direction. This simulation indicates that the power electronics for the motor rotation can cause the motor to rotate in counterclockwise and clockwise directions.

Final System Integration

One custom PCB was developed as an integration of the motor control, local control, and computer (remote) control interface. The power supply section was provided by external off-the-shelf modules. The circuit was designed for a DC motor with Hall-effect quadrature encoder feedback, which is detected and controlled via a firmware control loop in a 16-bit PIC microcontroller. The microcontroller was designed to be the heart of the system, which decides how to move the motor and records the position of the motor, as well as communicates with the main computer as to the position and status of the controller system. The H-bridge section of the circuit was chosen as the subsystem to be designed using discrete components. The H-bridge activates two of the four transistors to control the direction of current in the motor. One H-bridge circuit was used for the motor that controls the elevation angle and the other H-bridge controls the azimuth angle. The microcontroller that controls the whole board including the H-bridges has a program that ensures the transistors are never on such that there is a short from 24 V to ground.

Figure 9 shows the finalized system encapsulating the system enclosure, temporary stand, temporary antenna, and the dual-axis motor. The enclosure protects the PCB, LCD, the power supply with a connector in the shell of the enclosure to connect a power cable to 120 VAC power outlet, two more connectors to connect to the motor controls and encoder cables, and three buttons for local user input. It also includes a micro-USB connector to connect with the main PC.

Figure 9: Final Configuration of Prototype, Using 1-Meter Grid Dish Antenna for Testing.

System Testing and Validation

Individual tests were completed on each subsystem to ensure they functioned on their own, then a complete test of the whole system followed. Test plans were developed to target specific system functionality. Four place holders for resistors were left disconnected to electrically separate the microcontroller connections to the motor driver system for all individual tests that did not involve the motors. These were connected later with solder for full system integration.

All subsystems were tested individually for their performance against engineering requirements and specifications. These involved validating voltage levels, current outputs, communication and programming channels' functionality, polarity control across motor nodes, general purpose input output (GPIO) pin performances, peripheral connections, analog to digital conversion readings, component outputs, etc. A diagnostic program was written to complete these tests and the test setup in Figure 10 was used. All functionality was within expected parameters for each subsystem.

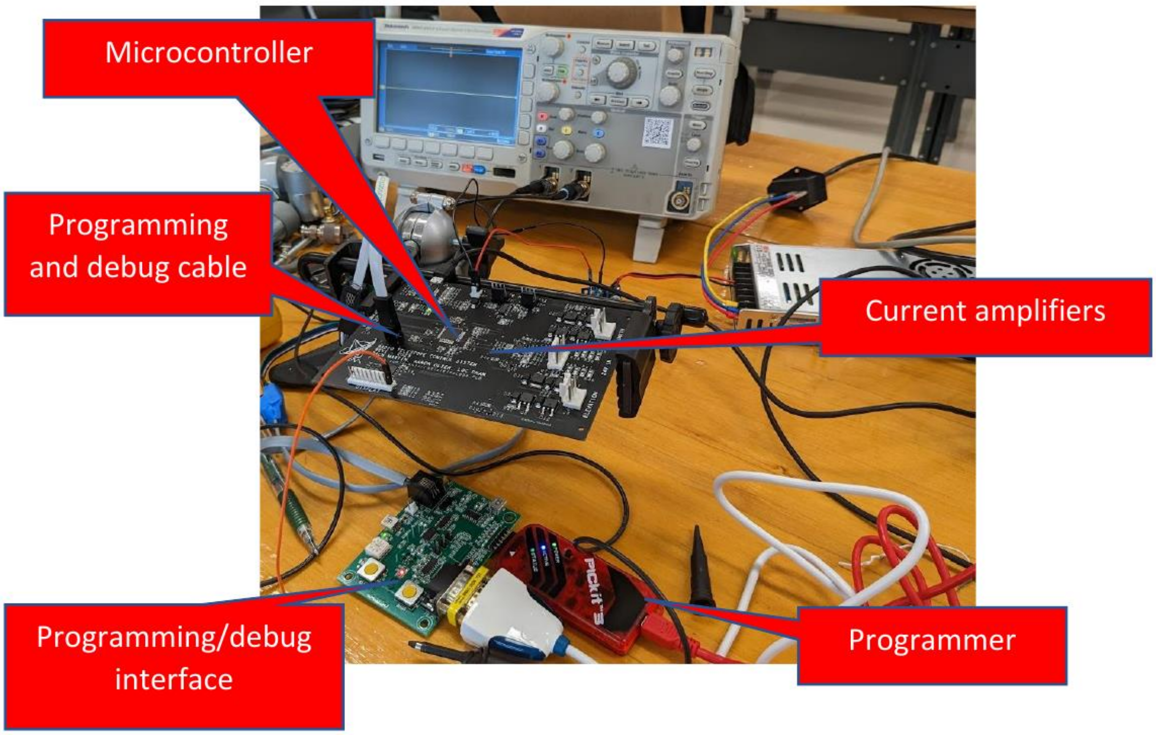

Figure 10: Test Setup.

The fully integrated system incorporated all subsystems and was tested according to desired performance. A program was written to receive commands from the main PC, diagnostic port, and local control interface to operate the motors and display the source of the command, the current antenna altitude and azimuth angles, and motor rotational directions to the PC terminal and LCD. It also analyzed data received from the current protection circuitry and encoder feedback. The LCD allows the user at the device location to know what the motor is doing and the display on the computer indicates the device operation to a remote operator.

Several commands were developed to be sent from the remote computer for coordinate movement and status commands to the control system. These were tested over the USB interface to validate the operation of the whole unit over a remote link. At the conclusion of this test and subsequent debugging, the USB remote control interface was determined to pass the engineering requirements.

The buttons and LCD that comprise the local control interface were also tested to determine that the system was controllable from the installation location, responded quickly, and that the local control interface would take precedence in case of a situation that required urgent control. In the case that the local control interface is not being used and the system is operating under remote control, the LCD and status LEDs on the control PCB will indicate the system operations and current antenna pointing angle in altitude/azimuth coordinates to the user. A video URL link is provided below to show the motor and small test antenna rotating in a time lapse during a movement test: https://www.youtube.com/watch?v=-fnis7qi-ZQ.

During the design and testing phases of the project, there were several technical challenges that were identified. One of the challenges was driving the MOSFETS in the H-bridge so that their on-state resistance was sufficiently low during the high current output test, as it was identified that some of the MOSFETS may overheat under certain conditions. Future iterations of this project should also include hardware interlocks that protect the circuit from certain conditions in case of microcontroller failure such as enabling both sides of the H-bridge simultaneously which would short out the 24V power supply. Finally, there was a small pinout error in a programming connector that was missed during the PCB design phase.

Project Management

The major tasks of the project were broken down into a work breakdown structure that can be seen in Figure 11. This diagram provides a graphical view of the deliverables in this project with the lead of each task. The first letter of the task leader's last name is used to conserve space in the diagram: (M), and (O). The research and proposal stage provides the necessary background information, requirements, and standards for the project moving forward as well as the target plan for the rest of the project. Using this research, the design stage moves to creating the schematic, simulating each section of the project design, and selecting the necessary parts based on the design. This stage also provides the PCB layout for the prototype and the basis of the firmware and computer interface used in the system.

The next step was integrating the system by ordering the parts, soldering the components onto the PCB, and connecting all external modules. Upon completion of the integration, the system was moved to the testing stage where each subsystem was tested separately for desired performance. Then, the fully integrated system was tested and any problems in overall operation were debugged with reflected changes made in the code. Lastly, the final report and presentation provides an overview of the finalized product.

The work breakdown diagram shown in Figure 11 was laid out onto a detailed Gantt chart where the team members could easily observe the deadlines and current progress of each task. Figure 12 is an overview of the design and implementation timeline based on this Gantt chart. This displays the tasks and subtasks that were completed throughout the project and who was responsible for ensuring these were completed by the target date, but any team member may support each task. One of the constraints of the project given in the engineering requirements table was that the project results and presentation were given by the end of the semester, May of 2023.

The five main tasks in the work breakdown structure include Research and Proposal, Design, Integration, Testing, and Final Report and Presentation. In the timeline below, the research and proposal stage were completed by the end of the Fall 2022 semester to provide the supporting information for the rest of the project. Beginning in the fall semester and extending into the spring was the design and integration of the project, which began with the PCB layout and completed with final changes in system configuration and program code. During the integration stage, each system was tested thoroughly to ensure the device complied with expectations. The final report and presentation were updated throughout the spring semester up until the final presentation.

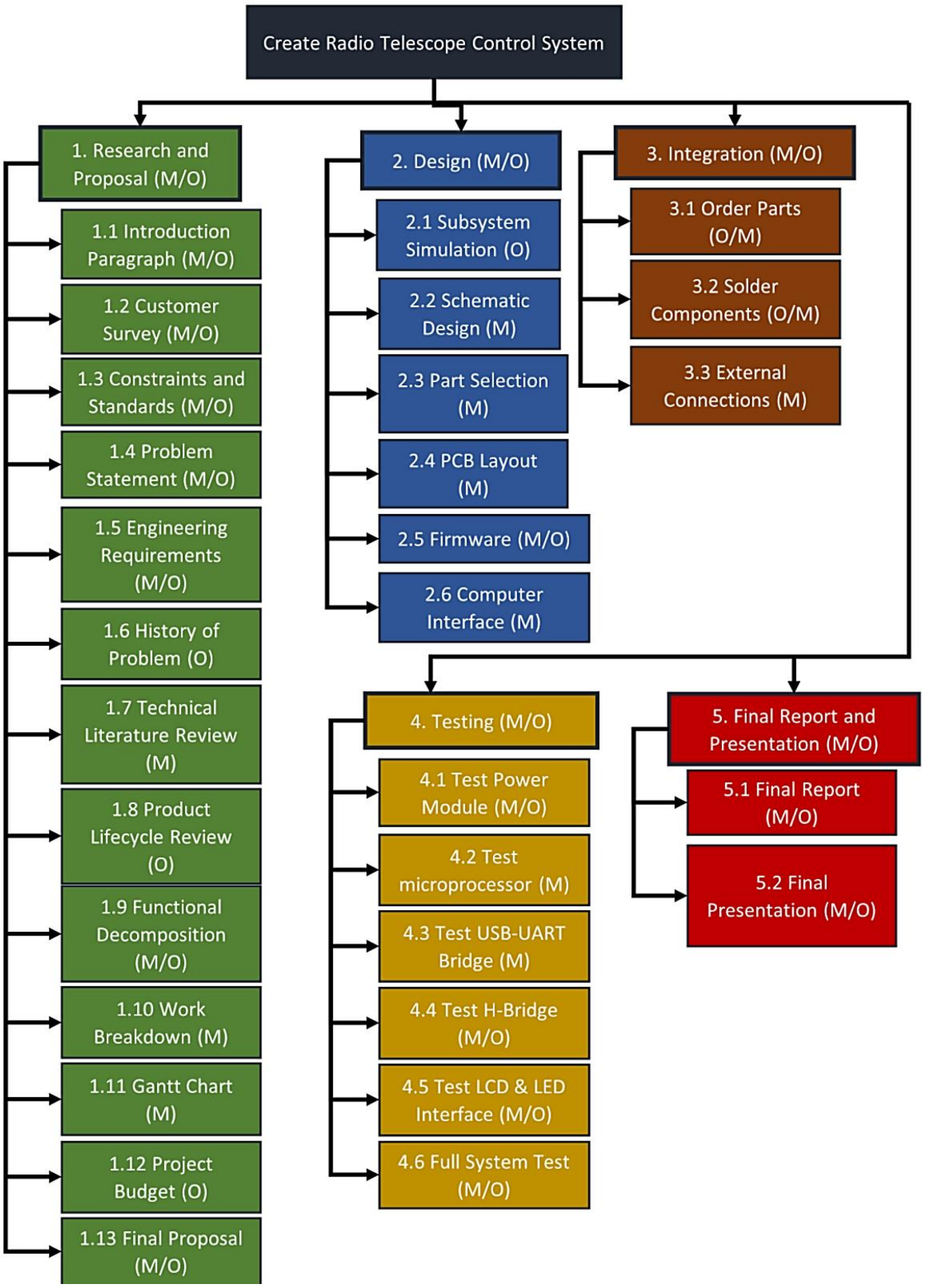

Figure 11: Work Breakdown Structure Diagram.

Development Stage	Research & Proposal	Circuit Design	Firmware Design	System Integration	Testing
Start Date	September 1	November 1	February 15	February 6	February 15
End Date	December 8	February 20	April 20	April 20	April 14

Figure 12: Project Schedule (Summary of Gantt Chart).

Project Budget

This document contains the project budget breakdown in Table 2. Some assumptions were made for the cost estimate using publicly available salary data. A rough estimate of $30/hr was assumed, somewhere between an intern's pay and a new engineer's pay. The hours of engineering labor were estimated to be 10 hours per week averaged across the two-semester timeline. It was assumed that the time would be distributed according to the Design, Integration, and Testing Gantt chart categories.

For the parts category of the cost analysis, there are a few things to note. First, some of the components that were placed on the custom PCB were sourced from personal, school, and employer contributions, so the out-of-pocket cost turned out to be lower than budgeted. As the project was intended to be donated to the school and managed by the Astronomy and IEEE student clubs on campus, the precision dual-axis motor and gear system was funded by the school. Overall, the out-of-pocket cost was estimated to be several hundred dollars for components and development tools, which was split between the members of the capstone design team.

Table 2: Project Budget.

Item Description			Cost
Components, Power Supply, Etc.			$ 413.37
Dual Axis Motor			$ 931.00
Griddy Antenna			$ 179.00
Subtotal			$ 1,523.37
Labor Cost	Cost ($/hr)	Hours	
Design	30	400	$ 12,000.00
Integration	30	150	$ 4,500.00
Testing	30	100	$ 3,000.00
Total Cost			$ 21,023.37

Conclusion

The system described in this paper delivered a robust and expandable control system for accurate pointing of a small dish antenna for use in university radio astronomy projects. The device documented herein is at a scale and price that is much more accessible to students, researchers, and amateur astronomers. Interfacing with this device is simple for a multitude of users from many backgrounds, and can be done with simple pushbutton control, a terminal interface, or via a custom radio astronomy software program.

This system, combined with the installation of the 3-meter dish antenna and low-noise receiver, provides a method of mapping intensity of radio sources such as Hydrogen-line radiation across the sky. Its operation over a wired USB link simplifies the connectivity requirements and makes the computing requirement generic to any computer capable of running the application software. The system has ample speed to provide desired results in an extended time. The final cost of the system was reduced in comparison to commercial products.

One of the most important lessons learned in this project was how to coordinate within the team and with the other teams of the radio telescope project. As the leading team of the overall radio telescope project, this team had to perform project management duties for the duration of the project such as leading team meetings to keep each team updated on tasks, assigning tasks to each group, and staying updated on team progress. This included breaking down major components into individual tasks and assigning due dates and personnel for each task. This is an important skill for the team members to have in the future when working on multidisciplinary engineering projects. Additionally, the team built skills in developing power electronic hardware for motor control. Part of this lesson applies to future projects, including adding hardware interlocks to preserve circuit function and safety in case of fault conditions.

At the conclusion of the capstone project, the capstone team completed a self-assessment "after-action report." The purpose of this report was for the students to reflect on the effectiveness of their work and the value of their experience. This report assesses the students' ability to address the customer's requirements and deliver a well-engineered system based on those requirements. It also evaluates their ability to use skills from their engineering coursework and research, to network and consult with experts in the field, and to function effectively as an engineering team. Overall, this project scored well in self-assessments, as the students felt that they delivered beyond their expectations and were able to effectively network with potential customers and consult with others throughout the entire design process.

Acknowledgements

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