

System Design Document

emStart: A Satellite Transceiver and Small Radio Telescope Emulator

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Author	Date	Version
All	9/28/21	1.0
All	10/26/21	1.1
All	11/30/21	1.2
All	2/4/22	1.3
All	3/6/22	1.4

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1. INTRODUCTION

1.1. Purpose and Scope

This document aims to lay out an overview of what the emStart project will consist of, and clearly define what a finished product looks like. By the end, an understanding of what hardware is required, what objectives the software will have, and human interfaces shall be established.

1.2. Project Executive Summary

The goal of this project is to first create a model of a real-world SRT antenna for data verification and then to move that implementation to an already existing full-scale antenna, operating at 1.42ghz. The existing implementation of the antenna is on a fixed arm that does not move with the Earth's rotation. The purpose of the Antenna is to capture astronomy data from an object in space that will be moving with respect to the antenna. We plan on using a pan-tilt configuration for micro servos that can best match the rotation of the earth, and therefore extend the capture time frame of data from the satellite, helping with the debugging of the received signal.

This emulator will include the construction of a mockup satellite that will transmit and attenuate data (by making the object in space signal weaker when the SRT isn't pointed at it), and a model ground station that will receive that data, and attempt to move with the expected movement of the satellite.

1.2.1. System Overview

The system will have three main subsystems. Firstly, the "Earth" platform will be a two-degree of freedom pan-tilt configuration in order to simulate the Earth's movement. On top of this will sit the second platform which is the ground station which also is a two degree of freedom pan-tilt configuration using micro servos. Its objective is to control the position of the antenna which will be mounted on top of the last extending servo. Finally, the last system is a stationary transmitting "satellite" which will have an attenuator in order to mimic the effects of an off-positioned ground station.

1.2.2. Design Constraints

The project has a few constraints. The first relates to the pan-tilt configuration for the arm. The size of the arm is another constraint, with the model needing to be able to fit on a tabletop. Hardware is a minor constraint, with only three options for cheap, mid-range, and

more expensive Software Defined Radios being presented to us. Another constraint is the minimum PC requirements needed to run the software, which is recommended as having at least Windows 7, a 64-bit processor on either Intel or AMD's architecture, 4 GB of RAM, and about 5 GB of open storage. The final constraint is the budget, which has been set at \$3400.

1.2.3. Future Contingencies

Within the available hardware and software given to us we have Contingencies for them. For hardware, we plan on using easily programmable devices such as Arduino Nano, raspberry pi, and Hack RF boards. This should make any changes to the mission easy as the hardware should be flexible in the event one of these hardware breaks we plan on ordering another. For software, we are using open source so when our code isn't working we plan on reviewing it to find the error.

1.3. Document Organization

This document is organized in the following fashion:

1. Introduction and project overview
2. System Architecture Overview
3. Human Machine Interfaces
4. Detailed Design
5. External Interfaces
6. System Integrity Controls

1.4. Project References

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1.5. Glossary

DOF - Degrees of freedom
GPSDO - GPS disciplined oscillator
PWM- Pulse width modulation
RF - Radiofrequency
SDR - Software-defined radio
SMA - SubMiniature version A
SRS - System Requirements Specification
SRT - Small radio telescope

2. SYSTEM ARCHITECTURE

2.1. System Hardware Architecture

There are three main subsystems in the design. These subsystems are the Earth emulator, the Ground Station, and the Space System which is emulating a satellite that is transmitting some signal. Each subsystem serves a unique purpose in the emulation, allowing rapid prototyping and testing different angles between the ground station and the system in space.

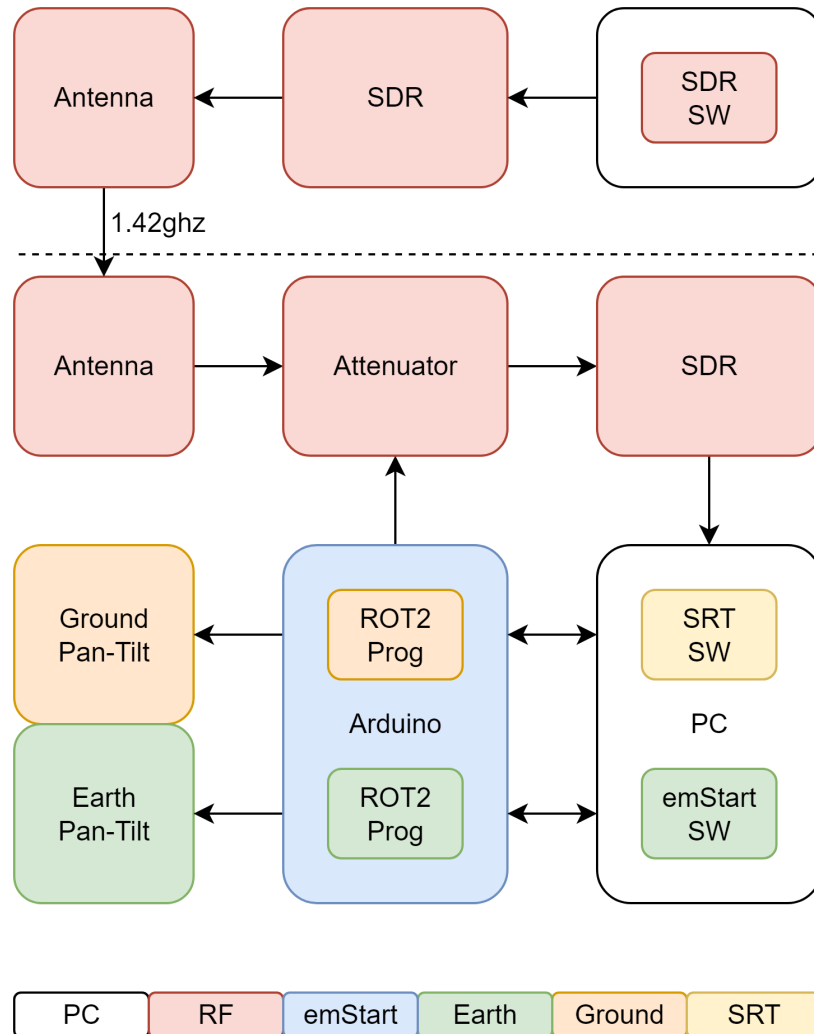


Figure 1: emStart Hardware Architecture

The Earth Emulator is conceptually independent of the other two subsystems and makes minimal communication with them. The only shared information is the current date and time of the emulation in order to

synchronize the ground station, as well as some handshaking to set up the emulation from the start. The Earth subsystem will serve as a platform for the ground station, so the two subsystems will move in unison. The Earth subsystem is intended to emulate the rotation of the Earth relative to the system in space. It consists of a robotic arm with three degrees of freedom, which is directly controlled by a computer. This will allow the arm to reposition a platform to which the ground station is fastened.

The centerpiece of the ground station is the communications system. Using a software-defined radio (SDR) and an antenna that can rotate with two degrees of freedom, the communications system can receive transmissions from the system in space. The computer in the design serves two purposes. The first purpose is to interpret the received transmissions from the software-defined radio. The second purpose is to send commands to a microcontroller to alter the rotation of the antenna. These two operations are performed independent of each other on two separate serial ports (individual RX & TX) of the computer using the ROT2 Prog protocol.

The system in space generates the transmissions which the ground station receives. This subsystem is driven by a computer that sends commands to the software-defined radio, which then sends its signal out through the fixed antenna. This subsystem is entirely stationary with no moving parts.

2.2. System Software Architecture

For the Earth subsystem, the software must control the position of the emulated Earth. In the ground station, the software must perform two independent operations: receive radio signals from space on software-defined radio and control the position of the antenna. Finally, the system in space must transmit radio signals using a software-defined radio.

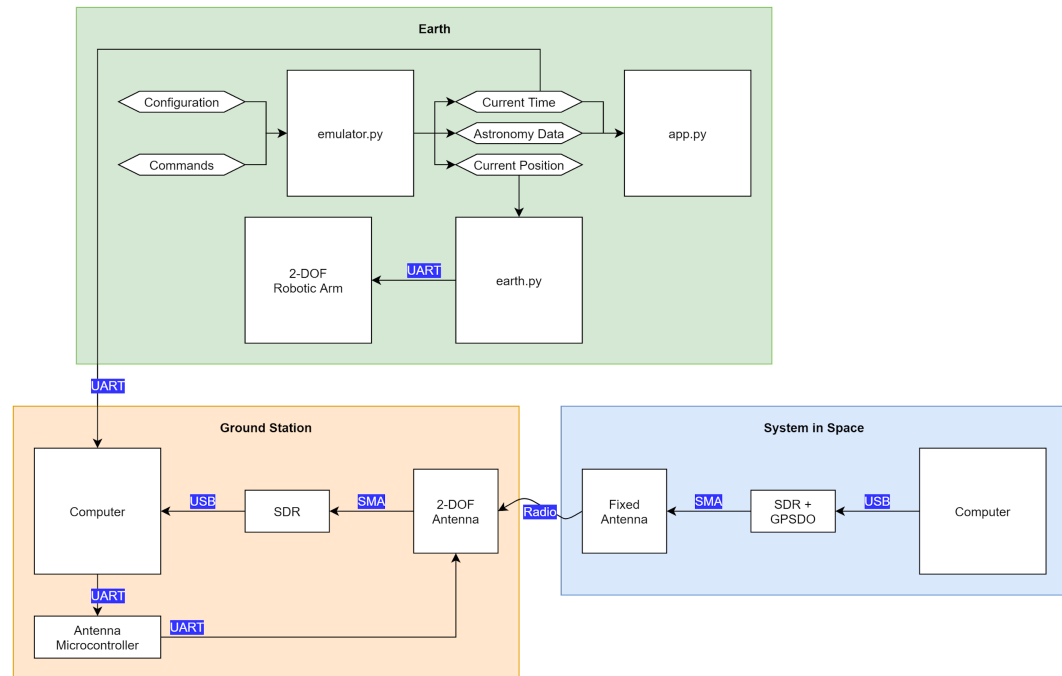


Figure 2: emStart Software Architecture

The Earth subsystem has a computer that will be running all of the software we require. The purpose of this software is to translate a stream of astronomy data into commands for the earth rotator system, allowing it to emulate the relative rotation of the Earth so that the system in space can remain stationary. Our software must accept the astronomy data as an input to understand the relative position of the Earth, then translate that relative position to the earth rotator system to properly emulate the Earth's rotation and orbit. Both ends of this process will have their own respective APIs which we must adapt to properly pass information through our design. The Earth will also need to transmit the current time (using Python DateTime library) in order to synchronize the other subsystems.

The ground station computer will use a python script to send commands to the antennas Arduino mega microcontroller, which will then interpret those commands and rotate the servos accordingly. The computer must also send commands to the software-defined radio. This will be accomplished using GNU Radio which has a GUI interface where blocks can be placed to create certain functionalities in the SDR.

The system in space strictly controls the transmission from the SDR (Hack RF). This will send commands to the software-defined radio through the use of GNU companion radio software.

The code produced will be in Python to act as a universal language between the individual platforms of this project. Some of the Python code

will be interpreted by a laptop or similar device, and some of it will be interpreted by a Raspberry Pi 4 and communicated with a host computer over a serial port. This will reduce the amount of software required for each machine in the system, making it easier to change them out as needed should the customer wish to test different equipment.

2.3. Internal Communications Architecture

Most communication in the design is constrained within each individual subsystem. The only instance of the subsystem boundary being crossed is the radio signals being transmitted from the system in space to the ground station. Other than that, standard communications such as USB and PWM are used for sending commands and controlling servos respectively.

The Earth subsystem will be fully controlled by a computer. This computer will communicate with a 2-DOF rotator system over USB to adjust the tilt and rotation of the Earth platform.

The ground station will have an antenna with 2-DOF rotation. The antenna will receive radio signals transmitted by the system in space. This antenna will then connect to a software-defined radio with analog signals using an SMA connector. The software-defined radio then communicates with the computer over USB. The antenna mount will be controlled by a microcontroller using PWM signals. This microcontroller will be connected to the computer over a separate USB port and communicate using a message queue to send commands from the computer to the microcontroller.

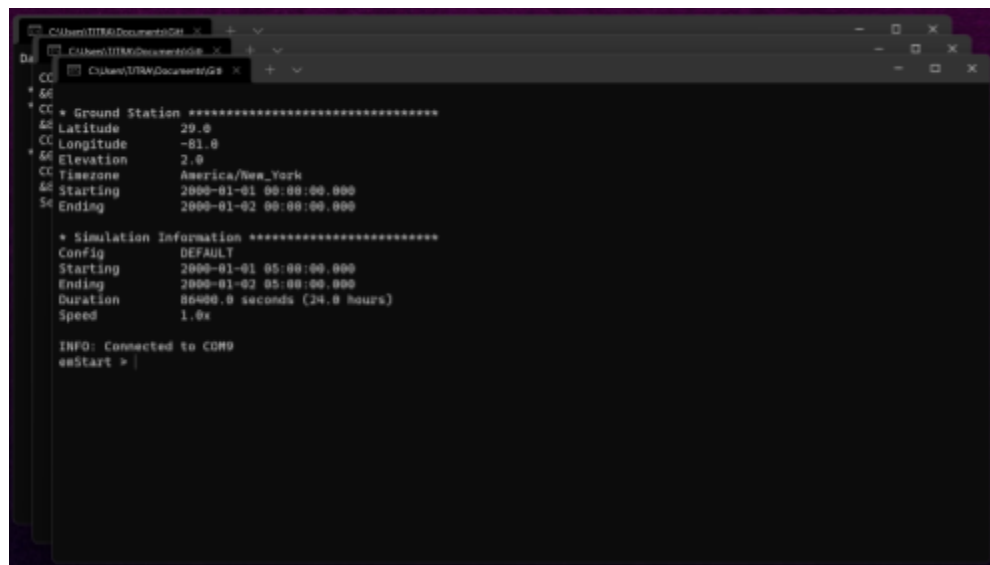
The system in space will have a stationary antenna that communicates with another software-defined radio using analog signals. This software-defined radio will then interpret this input and make the information available to the computer over USB.

3. HUMAN-MACHINE INTERFACE

EmStart has 3 main parts: the system in space, the simulated satellite, the system on the ground, the simulated receiver antenna station, and the 2-DOF rotator system which is simulating Earth. The system in space is meant to transmit signals similar to that of objects in space, the system on the ground that controls the antenna which moves toward the signal in space generated by the simulated satellite, and the emulation station which moves the system on the ground to mimic earth.

3.1. Inputs

Once initial setup procedures have been completed and the system is at its default main screen. The User creates a standard python virtual environment that handles all project files in use (Background Tasks). With the virtual environment created it opens a command prompt allowing the user to input the location data which consists of latitude, longitude, and date.

A screenshot of a Windows command prompt window titled 'Emstart.bat'. The window shows a series of commands and their outputs. The first command is 'cd C:\Users\ITM\Documents\G8', followed by 'cc', 'cc * Ground Station *****', 'cc Latitude 29.0', 'cc Longitude -81.0', 'cc Elevation 2.0', 'cc Timezone America/New_York', 'cc Starting 2000-01-01 00:00:00.000', 'cc Ending 2000-01-02 00:00:00.000', 'cc * Simulation Information *****', 'cc Config DEFAULT', 'cc Starting 2000-01-01 00:00:00.000', 'cc Ending 2000-01-02 00:00:00.000', 'cc Duration 86400.0 seconds (24.0 hours)', 'cc Speed 1.0x', 'INFO: Connected to COM9', and finally 'emStart >'. The background is black and the text is white.

```
cd C:\Users\ITM\Documents\G8
cc
cc * Ground Station *****
cc Latitude 29.0
cc Longitude -81.0
cc Elevation 2.0
cc Timezone America/New_York
cc Starting 2000-01-01 00:00:00.000
cc Ending 2000-01-02 00:00:00.000
cc * Simulation Information *****
cc Config DEFAULT
cc Starting 2000-01-01 00:00:00.000
cc Ending 2000-01-02 00:00:00.000
cc Duration 86400.0 seconds (24.0 hours)
cc Speed 1.0x
INFO: Connected to COM9
emStart >
```

Figure 4: Emstart.bat Command prompt.

3.2. Outputs

When the system is initialized with the proper positional values of the tracking target i.e. the position you are on earth and the location of your target. The robotic arm “Earth” will orient itself in its starting position to mimic that of the initial conditions found in a real environmental setting. Once the system is set to begin “Earth” will move according to the imputed time-frame for both objects in question. The same can be said of the “Rotator” mounted on top of the “Earth.” At the same time, the azimuth and altitude are shown on a Plotly GUI on an HTML website.

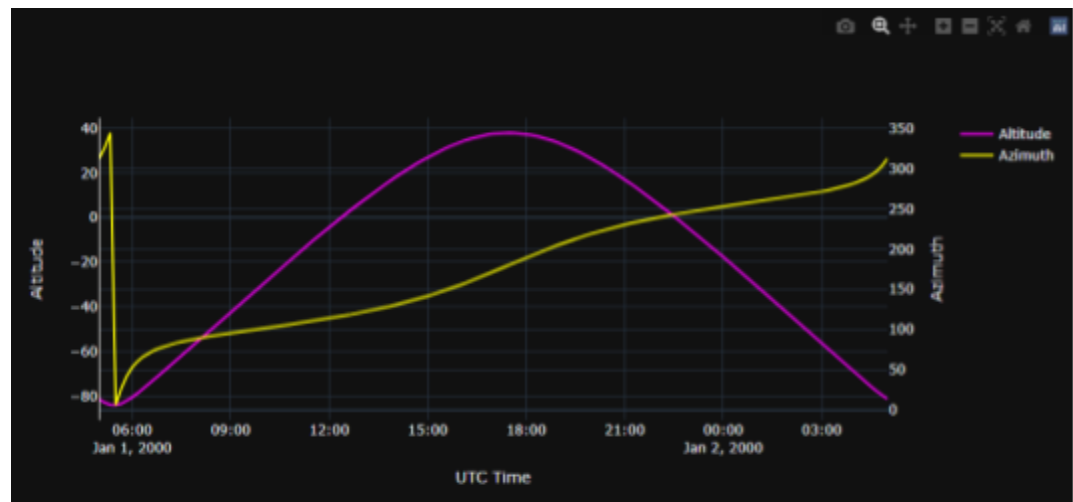


Figure 5: Plotly Graph.

4. DETAILED DESIGN

This section contains detailed information about the hardware and software design of the system.

4.1. Hardware Detailed Design

The design of the hardware system can be viewed through the lens of two distinct systems. The first is the “Earth” emulation system and the second is the rotator antenna system.

The hardware components are connected as follows to perform the overarching goals of the system. First is the Earth Emulation system whose main control is stemmed from a laptop or PC connected to the robotic arm via a USB-A to USB-C connector. The laptop/PC is also connected to a Raspberry Pi 4 via a USB-C to USB-A connector which controls our second system, the rotator antenna system. This raspberry pi 4 is connected also to an Arduino nano via a USB mini-A to USB-C connector. Which is then connected to the electromechanical controlling points of two individual servos controlling azimuth and elevation for the patch antenna. Furthermore, the Raspberry Pi 4 is also connected to a HackRF via a USB connector which handles all communications received by a said patch antenna.

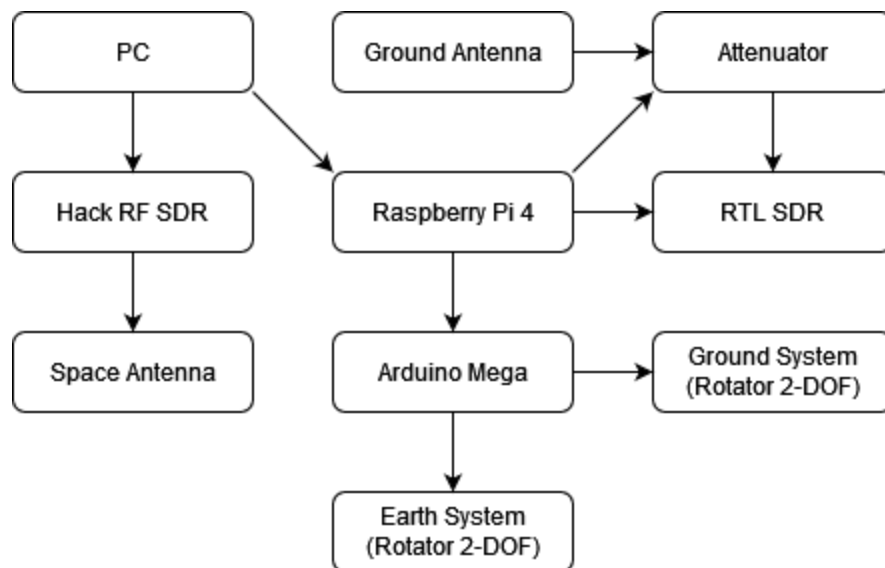


Figure 6: Hardware Detailed Design

The Raspberry Pi 4 is the processor used to control the radio communications and the rotator emulator commands. It boots its operating system off an SD card which is inserted into the Pi 4, on this card is also stored all program data for its operation in the system. It will be used in such a way to receive communications

from the Hack RF and perform operations relating to the data received. It will also be used in order to control the Rotator emulator via inputted astronomy data positions relative to its position on the emulated “Earth”. These commands it sends will be received by an Arduino Nano.

The Arduino Nano is the microcontroller used to control the rotator emulator. It does this by first receiving commands from the Raspberry Pi 4, which it then sends signals to two different servos: a 180-degree servo used for moving up and down and a 360 for moving around the base of the rotator. This allows them to adjust the patch antenna fixed to the end of the rotator to the correct orientation to receive incoming signals.

The Hack RF is a software-defined radio (SDR) that handles receiving of communication signals. It is connected to a patch antenna via an SMA connector on the Hack RF, it is also attached to the Raspberry Pi 4 via a USB connection to communicate its data. The antenna used for this system consists of a metal plane connected to the SMA connector wire.

The robotic arm platform is used to emulate earth. It has 6 available axes of movement providing superior movement control to the system. It is connected to a laptop or personal computer (PC) via a USB connection which can then be controlled by the code programmed on the computer.

4.2. Software Detailed Design

The emStart software systems can be divided into four distinct subsystems; Ground Communications, Space Communications, Earth Emulator, and Ground Emulator. Both communications are responsible for handling the emulation of two communicating bodies, ground communications being the receiver and space communications being the transceiver. The Earth Emulator has the responsibility of taking in requested astronomy data and breaking it down to its core directional units to then be sent to the simulation subsystem, then send the data to the Earth Emulator and the Rotator Emulator respectively. For both emulators, they will then take the data they receive and translate it into their respective movements on the physical hardware system.

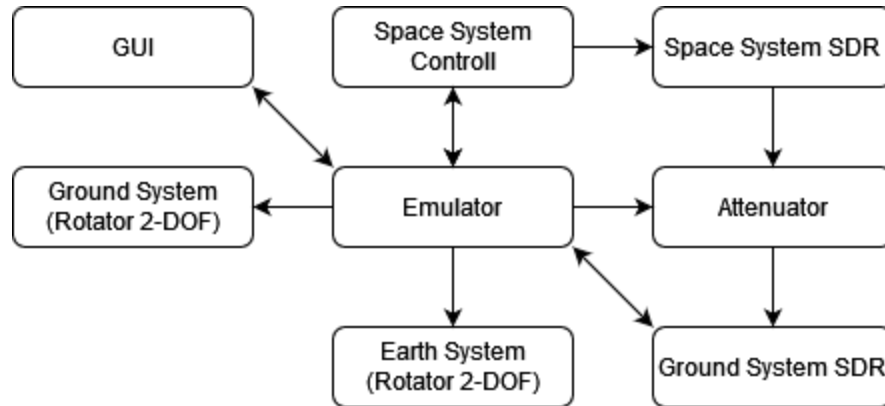


Figure 7: Detailed Software Design

4.2.1. Ground Communications Subsystem

The Ground Communications subsystem is responsible for receiving incoming data from the Space Communications subsystem. The data is then stored within a file for test engineers to inspect for accuracy during the emulation. This data can also be used to perform some other verification task if deemed necessary. This information can be accessed through the specified file which was written during emulation.

4.2.2. Space Communications Subsystem

The Space Communications subsystem is responsible for transmitting data from an emulated source, to the Ground Communications subsystem. The data is transmitted is inputted via a file transfer for a given test to then be received on the other end by the ground communications and decoded.

Hack RF SDR (GNU Radio Companion Transmitter): Through the use of software blocks on the GNU companion software the specified frequency is able to be selected and transmitted from the SDR (Hack RF) when connected to the system. It automatically detects the SDR's presence as long as its libraries are installed and are able to be activated with the click of the start button the companion.

RTL RF SDR (GNU Radio Companion Receiver): Through the use of software blocks on the GNU companion software the specific frequency is able to be selected and received from the SDR(RTL 232). It also provides the ability for an output block to visually show Signal inputs from the antenna. It automatically detects the SDR's presence as long as its libraries are installed and are able to be activated with the click of the start button the companion.

4.2.3. Earth Emulator Subsystem

This subsystem is responsible for collecting astronomy data and converting it into altitude and azimuth angles, then send commands to the hardware. First, the test engineer configures the simulation or inputs a file including all necessary

astronomy data; it is then inspected by the parser for positional data relating to the position of the Earth Emulator relative to the astronomical body; this can be either a satellite or a far-off entity. Once this data is collected, it is displayed on the user interface and begins sending instructions to the hardware. Once the data is received it is converted into a set of commands that tell the 2-DOF servo system which angles to position the joints to properly emulate the current state of the simulation.

Parameters: The parameters module reads the configuration data from a file and retrieves the corresponding astronomy data. The retrieved data contains an altitude and azimuth angle, describing where the system in space is located relative to an observer on Earth.

Simulator: The simulator module manages the progress of the emulation, keeping track of the current time. This is how the Earth Emulator and ground subsystems know how to position themselves. Each subsystem is configured based on the same parameters, and once the data is obtained the only requirement to remain synchronous is that each subsystem knows what time it is.

Emulator: The emulator module is the main controller for the 2-DOF servo system. This subsystem takes the current time and determines the position of the servos. Then it sends commands which will move the servos to the appropriate position.

App: The app is the user interface, which displays the altitude and azimuth relative to the time. It also shows the current time so the operator can easily understand the state of the emulation.

Sockets: The sockets module coordinates the communications between the simulator, emulator, and app. Each of these interfaces uses ZeroMQ to communicate, where the simulator acts as the server and the emulator and app act as clients, making requests to the server to get new data.

4.2.4. Rotator Emulator Subsystem

The rotator emulator subsystem receives commands from the simulation system and converts them into a series of signals to the rotator's electromechanical components.

4.3. Internal Communications Detailed Design

There are several protocols for communication used for the emStart system providing various levels of complexity for each. For communication between the 2 DOF servo rotator and the PC, a USB protocol is used; this is also used for communication between the Raspberry Pi4 and Hack RF. Furthermore, the communication between the Raspberry Pi4 and the PC uses ethernet for its

communication. Lastly, the Arduino Nano and the Raspberry Pi4 use UART for their communication.

5. EXTERNAL INTERFACES

This section examines the external systems, which is any system that communicates data between the different systems found in the product.

5.1. Interface Architecture

The primary communication between our systems will be the analog signals sent from the System in Space, which will be used to convert astrological data into movements for the antenna attached to the Ground Station.

The Earth Emulator shall work independently, with no communication from either the Ground Station or System in Space other than time which is used to emulate the Earth's rotation.

5.2. Interface Detailed Design

The following class diagrams show which classes use which interfaces. The earth rotators, ground station, and fixed antenna are all off-the-shelf hardware that the emStart system requires in order to operate.

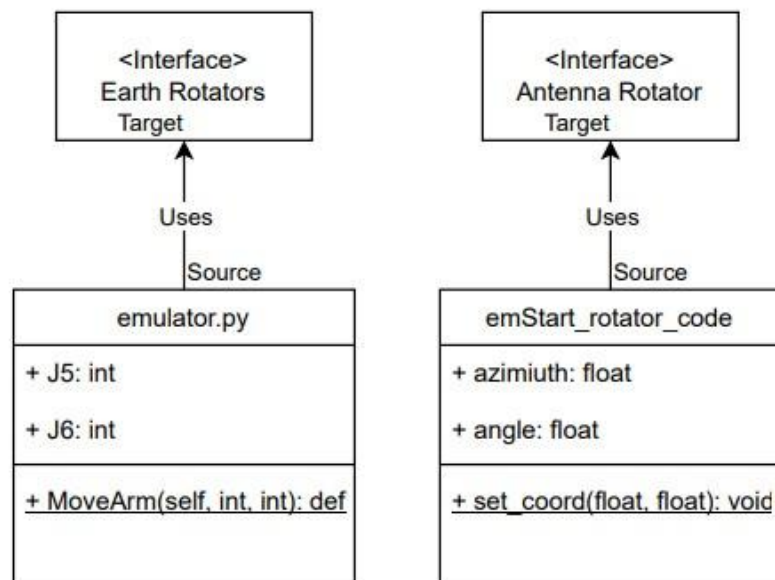


Figure 8: Class Diagram for Earth Rotators and Antenna Rotator.

Besides these interfaces, the rotator antenna can receive signals sent through the satellite system through wireless transmission. This diagram shows the use of variables in adjusting the azimuth and angle of the antenna and servos rotating the Earth.

6. SYSTEM INTEGRITY CONTROLS

The system shall store all of its code onto a shared repository using the internet hoster Github, which maintains its own built-in safety features to maintain its security. Moving on to the system's internal controls; the system shall obtain community-provided Astropy data from public servers which will then be stored into the internal memory of the Raspberry Pi 4 and personal computer. Once this information is stored it will be used for all emulations of the system. Next, each individual 2-DOF system must be calibrated to ensure proper 0 positioning before emulation. This most of the time is not an issue due to previous calibrations through PWM dead reckoning and visual verification, due to the scope of our system this is not a serious issue. Continuing on when the virtual environment is in an active state it verifies that its dependencies are properly installed and up to date. It does this by referencing the server cache version to its own version.