A 2-D Model of Optical Satellite Communication System

Team 33

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1. Introduction

1.1 Problem and Solution Overview

With the rapid advancement of aerospace and communication technologies, there is an increasing demand for more stable, multifunctional, and efficient satellite communication systems. In particular, Low Earth Orbit (LEO) satellites have attracted substantial attention due to their advantages of low latency, reduced signal loss, and lower deployment costs compared to traditional geostationary satellites. As exemplified by commercial systems like Starlink, LEO satellites have demonstrated remarkable potential in various fields, including climate monitoring, geographical mapping, and global internet coverage. However, the inherent characteristics of LEO satellites also bring new challenges — their relatively low altitude and fast orbital speeds result in limited coverage per satellite, necessitating large-scale satellite constellations to ensure continuous global communication. This dynamic environment introduces complexities in maintaining reliable communication between satellites and ground stations, especially when leveraging optical communication methods that are highly directional and sensitive to alignment and synchronization.

To study and visualize these challenges, this project proposes the design and development of a 2D Model of Optical Satellite Communication Systems. This model aims to simulate the orbital motion of satellites and the rotational movement of Earth in a controlled environment, using rotating disks to represent the Earth and satellites in LEO. Optical communication will be emulated using a laser transmitter on the ground station (Earth disk) and photoreceptors on the satellite disk. Through adjustable motor-driven rotation, configurable laser transmission frequencies, and a software monitoring interface, this model will allow users to investigate the factors influencing optical signal transmission efficiency in LEO communication scenarios. Compared to previous conceptual models or purely software-based simulations, this solution provides an intuitive and interactive hardware-software hybrid platform that physically demonstrates real-world communication dynamics, signal loss due to misalignment, and system performance under various orbital conditions.

1.2 Visual Aid

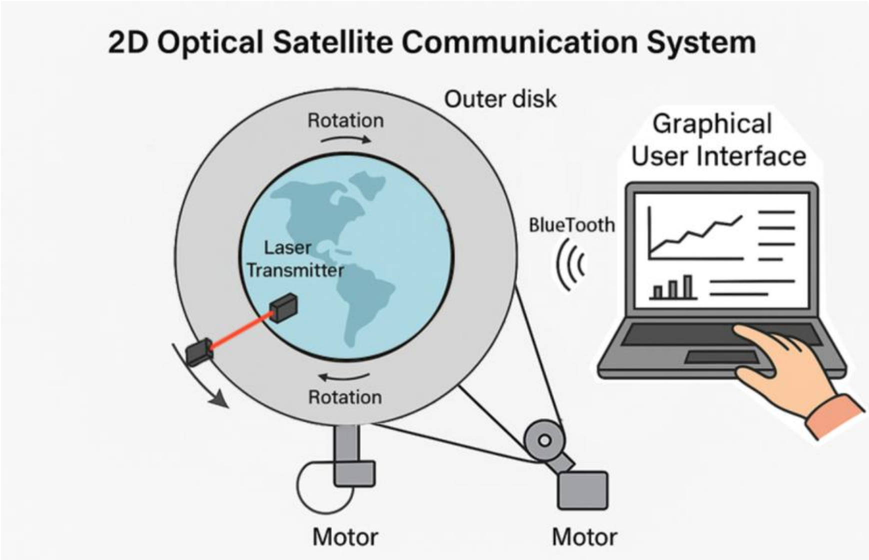

Figure 1 Schematic of the model

This visual aid illustrates the overall usage scenario of the proposed 2D optical satellite communication system. It includes:

- The inner rotating disk represents Earth's surface with a laser transmitter (ground station).
- The outer rotating disk represents LEO satellites, each equipped with an optical receiver.
- Motors beneath each disk to independently control their rotational speeds, simulating different orbital parameters.
- A computer interface connected wirelessly (via Bluetooth) to control disk rotation speeds and laser emission frequencies.
- The user interacts with the software interface to adjust system parameters and view performance metrics, such as received signal strength and transmission efficiency.

1.3 High-Level Requirements List

- The system must physically simulate the relative motion between LEO satellites and Earth by rotating two concentric disks with independently controllable speeds to mimic orbital dynamics.
- The optical communication subsystem must successfully transmit and receive binary-encoded signals using a laser transmitter and photoreceptor, with proper alignment constraints to reflect real-world scattering angle limitations.
- The software control and monitoring system must allow users to configure key simulation parameters, including disk rotation speeds and signal transmission

frequency, while visualizing the transmission efficiency and received data in real time.

- The system must decode the received optical signals into human-readable messages, demonstrating the feasibility of optical satellite communication and enabling the evaluation of transmission accuracy under different conditions.

2. Design

We plan to develop a 2-D model of a ground-to-satellite communication system using laser beams as an information medium. This optical communication-based simulation system integrates a graphical user interface (GUI) subsystem, a motion control system that we call the orbit simulation subsystem, a power subsystem, a data processing and control subsystem, and an optical communication subsystem. Our system allows a user to control and monitor the rotation speed of a two-disk system that simulates the movements of a satellite and a communication tower on the surface of the Earth and the data transmitted via an optical communication link. An Arduino-powered microcontroller is implemented to distribute motor control, signal processing, and efficiency analysis. Power is supplied via a 12 V Li-ion battery, and data transmission will be conducted through an optical communication system containing a laser transmitter and a laser receiver. Figure 1 shows the layout of our simulation system.

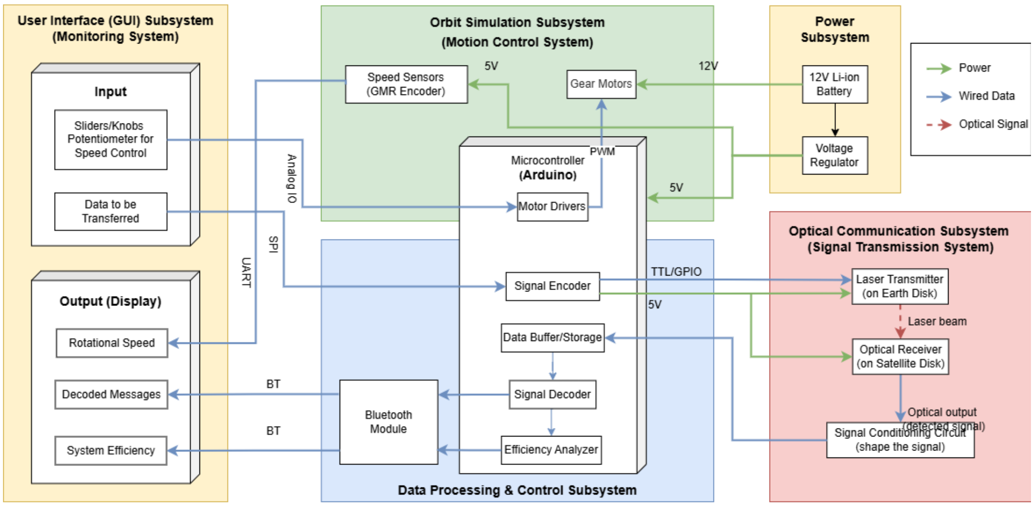

Figure 2 Block Diagram

The physical design involves a thick acrylic board as the foundation. The two motors are placed in parallel. A steel rod is fixed on the board as the rotational axis for the two disks, simulating the Earth and the orbit of a satellite. Each disk is attached to a gear. The gears are connected to the motors through two belts. The laser transmitter and laser receiver are mounted on the edge of the two disks.

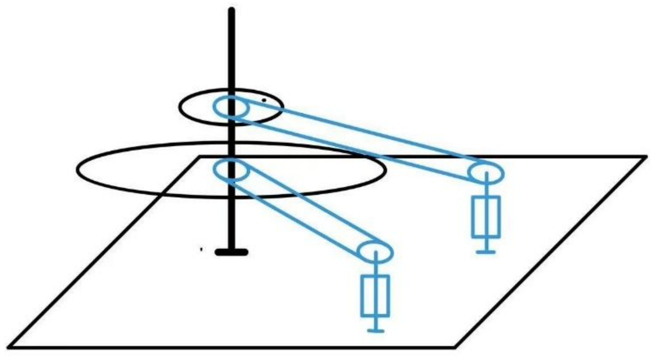

Figure 3 Physical Design Sketch

2.1 Orbit Simulation Subsystem

The Orbit Simulation Subsystem (Motion Control System) consists of speed sensors and gear motors. The speed sensors monitor the rotation speed of the motor and send the data to the user interface. The gear motors are controlled by the Microcontroller Subsystem. This system simulates the orbit system by controlling the speed of the rotation.

2.1.1 Speed Sensor

A MGR (Giant Magneto Resistive) encoder is used to measure the rotational speed of the gear motors in the Orbit Simulation Subsystem. It generates a digital pulse signal proportional to angular velocity, which is read by the microcontroller through a digital input pin. The encoder was selected for its high sensitivity, compact size, and durability compared to optical alternatives. It operates at 5V and provides 360 pulses per revolution, allowing precise speed monitoring. This information is used to simulate orbital motion and evaluate system efficiency in real time.

Requirements	Verifications
1. Must accurately detect rotational speeds from 10 to 1000 RPM with <1% error	A. Mount the GMR encoder on the motor shaft. B. Drive motor at known speeds using PWM control. C. Compare measured speed from encoder pulse count to actual speed from tachometer. D. Verify that the error remains <1% across the full speed range.

2. The encoder signal must update at a minimum 1 kHz sampling rate	A. Program microcontroller to sample rising edges of encoder output. B. Rotate motor at 1000 RPM and confirm microcontroller captures ≥6 pulses/ms (based on 360 PPR).

2.1.2 Gear motor

The gear motor drives the rotating disk in the Orbit Simulation Subsystem, simulating satellite motion. It operates at 12V and features a 1:30 gear ratio, providing a rated speed of 293 ± 21 rpm and a rated torque of 4.5 kg·cm. The motor is driven by a PWM signal from the microcontroller, enabling dynamic speed control. Its high torque and stable output are critical for maintaining consistent motion during optical signal transmission. The motor draws a rated current of 0.36 A and was selected for its balance of power (approx.. 4W), reliability, and compatibility with the system's voltage and torque requirements.

Figure 4 The Motor

Requirements	Verification
1. The motor must operate at 12V and draw no more than 0.4 A under-rated load.	A. Power the motor with 12V using a bench power supply B. Apply rated load (4.5 kg·cm) using a mechanical load C. Measure current draw with multimeter; confirm ≤ 0.4 A
2. The motor must rotate at 293 ± 21 rpm under rated load.	A. Connect the motor to the 12V supply and apply the rated load B. Use tachometer or encoder to measure rpm C. Confirm that the measured speed is between 272 and 314 rpm

3. The motor must generate torque ≥ 4.5 kg·cm at rated voltage.	A. Attach torque arm to motor shaft B. Suspend known weights to apply torque C. Confirm motor holds or rotates with ≥ 4.5 kg·cm torque at 12V

2.2 Power Subsystem

The Power Subsystem supplies and regulates electrical energy to all components in the system, including the microcontroller, motors, sensors, and communication modules.

2.2.1 Li-ion Battery

The system is powered by a 24V 12000mAh Li-ion phosphate battery. The battery outputs 22.4V nominal voltage, with a full charge voltage of 25.55V and a cut-off at 16.5V. It supports a continuous discharge current of 15A, ensuring stable and safe power delivery under all load conditions. A voltage regulator is used to step down the 24V to 12V and 5V for different subsystems. The battery features built-in protection against short-circuit, over-current, over-charge, and over-discharge, providing reliable operation across a wide temperature range (−20°C to 60°C).

Requirements	Verification
1. Must supply a nominal voltage of 22.4V and a full charge voltage of up to 25.55V.	A. Fully charge the battery using the specified charger B. Measure voltage using a multimeter C. Confirm reading is within 22.4V to 25.55V
2. Must provide at least 15A continuous discharge current.	A. Connect the battery to an electronic load B. Gradually increase current draw up to 15A C. Confirm that the voltage remains stable and no protection is triggered.

2.3 Optical Communication Subsystem

The Optical Communication Subsystem enables wireless data transmission between the rotating Earth and Satellite disks using visible laser beams. It consists of a laser transmitter mounted on the Earth disk and an optical receiver on the Satellite disk, along with a signal conditioning circuit to filter and shape the received signal. The system operates at 5V and uses TTL/GPIO control from the microcontroller to modulate data.

2.3.1 Laser Transmitter

The laser transmitter is a red dot-type module operating at a wavelength of 650 nm and is used to send optical signals from the Earth disk to the Satellite disk. It is powered by a regulated 5V supply and consumes less than 300 mA of current. It has a beam range of up to 100 m indoors at 10 mW, which provides reliable short-range free-space communication. The transmitter includes a focus adjustment ring and operates in temperatures ranging from −10°C to 50°C, ensuring robust performance in varied environments. It is also small enough (12×40 mm) to be integrated into the rotating platform.

Requirements	Verification
1. It must operate at 5V DC and draw no more than 300 mA.	A. Connect the transmitter to a 5V power supply B. Measure current draw using a multimeter C. Confirm current ≤ 300 mA
2. Must achieve indoor transmission distance of at least 5 meters at 10 mW.	A. Set transmitter to 10 mW output B. Place the receiver 5 meters away C. Confirm stable signal detection at receiver

2.3.2 Optical Receiver

The optical receiver uses a photosensitive diode sensor module to detect incoming laser signals from the Earth disk. It integrates a light-sensitive transistor with an onboard relay and comparator (LM393), enabling digital signal conversion based on light intensity. The module operates at 12V and triggers output when the received light exceeds a user-defined threshold. This receiver is critical for establishing line-of-sight optical communication and relaying signals to the decoding subsystem.

Requirements	Verification
1. Must operate at 12V DC.	A. Connect the module to a 12V DC power supply B. Use a multimeter to confirm stable voltage across VCC and GND pins
2. Must detect red laser light (650 nm) at ≥1 m indoors	A. Place the receiver module 1 m away from the laser transmitter B. Align laser beam directly at the sensor C. Confirm that the relay is triggered and the output LED activates

2.4 User Interface Subsystem

The software User Interface (GUI) Subsystem serves as a window for users to give commands to and read outputs from the microcontroller. The user should specify two input values: the rotational speed vector for the two motors and the binary stream to be transmitted by laser beams. The output displays the runtime motor speeds and the received signal from the laser receiver. It can also display a system efficiency analysis. Figure 3 shows a segment of the GUI source codes and a testing output read from the giant magneto resistive (GMR) integrated on a motor.

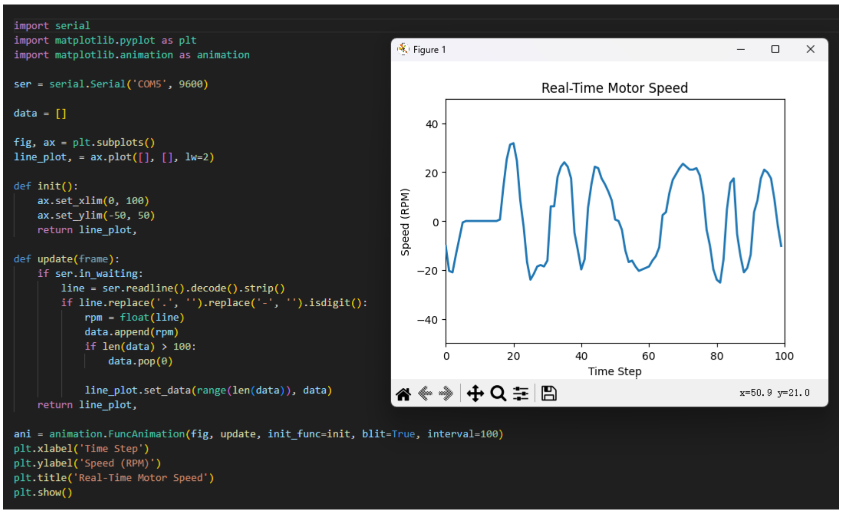

Figure 5 GUI Demo

2.4.1 GUI Software

The GUI software, implemented in Python, handles the user inputs and the outputs produced by our communication system. This software provides a channel for users to control the rotational speed of the disk and modify desired data for transmission. This software takes input from the user and sends speed control signals and transmission data to the Microcontroller in the Data Processing & Decoding Subsystem.

Requirements	Verification
Software should be user-friendly. The software should output run-time motor speeds and the received laser signals.	Software is easy to understand and use The software should include several windows to display graphs of the speeds and the recorded binary signal.

Table 1 R&V Table of the GUI Software

2.5 Data Processing and Control System

This subsystem acts as the processing hub, managing motion control and data transmission and ensuring smooth system operation. It processes motor control signals, encodes data for transmission, buffers and stores data, decodes received signals, and analyzes communication efficiency. As for connection, the motor drivers should receive speed control commands from the microcontroller and send power signals to the Gear Motors in the Orbit Simulation Subsystem. The signal encoder converts user data from the GUI software into an optical signal format for the Optical Communication Subsystem. The transmitted and received data should be held in the data buffers on the Arduino board. The signal decoder processes optical signals received from the Optical Communication Subsystem, converting them back into digital data. Finally, the efficiency analyzer evaluates signal integrity and system performance, sending results to the GUI for display. To avoid messy wiring, these outputs will be loaded into a Bluetooth module first and then sent to a computer wirelessly for our software to read.

2.5.1 Microcontroller (Arduino)

The microcontroller, an Arduino UNO R3 board [1], handles signal encoding/decoding and efficiency analysis and drives the motors. It receives motor speed commands through analog IO and digital data input through SPI. It sends data output to the Bluetooth module through the D0 and D1 pins. Figure 4 shows the schematic of our chosen board.

Requirements	Verification
1. Can receive over SPI and Analog I/O 2. Can transmit over D0/D1 ports 3. Can transmit over GPIO 4. Can control motors through PWM	1. For data I/O, test sending and receiving random data through these ports and see if they are correct 2. For PWM, see if motors can run at our desired frequency

Table 2 R&V Table of the Microcontroller

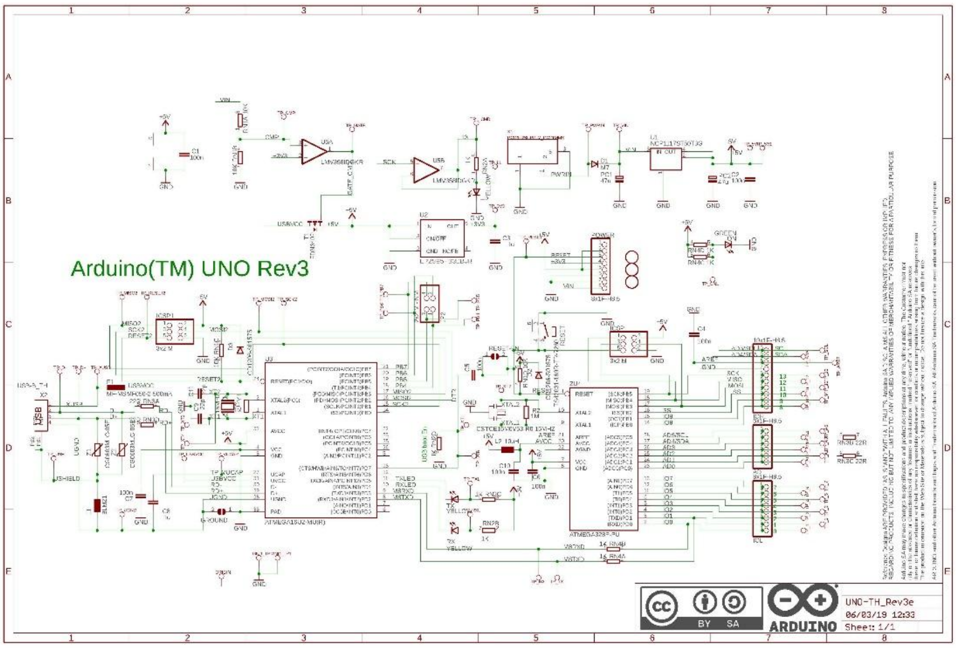

Figure 6 Arduino™ UNO R3 Schematic [2]

2.5.2 Bluetooth Module

The Bluetooth module serves as a bridge between the microcontroller and the user interface. Too many wirings affect the mobility of the physical disks system, so wireless data transmission seems like a solution. The Bluetooth module we use is HC-06 by HC Tech. We chose this Bluetooth chip for its compatibility with the Arduino board. Figure 5 shows the schematic of this Bluetooth device.

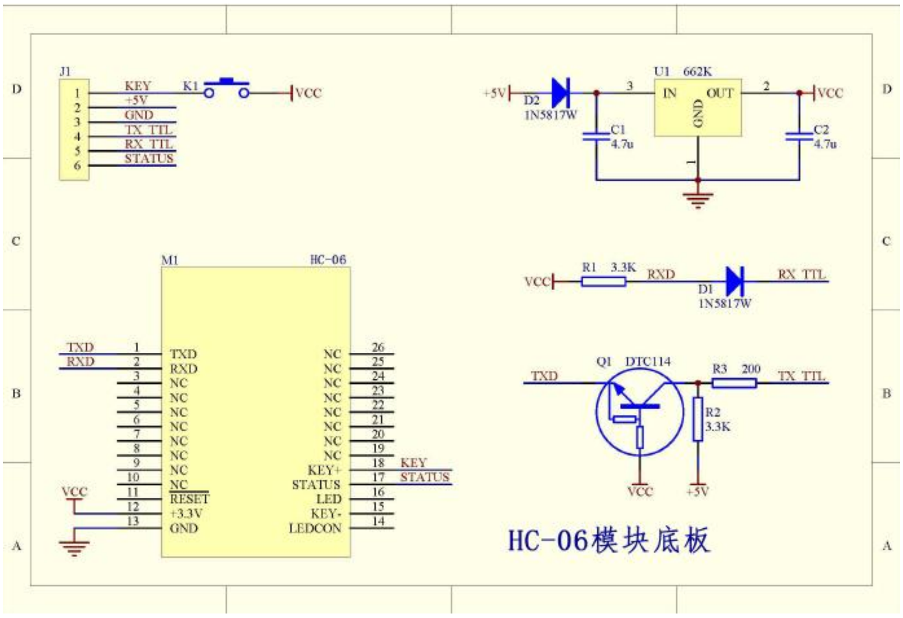

Figure 7 HC-06 Schematic [3]

Requirements	Verification
1. It can receive data over RXD. 2. It can transmit data over TXD.	1 & 2. Plug in the chip to the Arduino board. Send testing data to the device and see if the GUI can correctly read this test data.

Table 2 R&V Table of the Bluetooth Module

2.6 Tolerance Analysis

A key tolerance requirement in this system is the alignment between the laser transmitter and the optical receiver, which is critical for successful signal transmission across rotating platforms. Misalignment due to rotation speed fluctuation or mounting offset directly affects received signal power. The beam divergence half-angle for our laser is about 2.5°. We estimate the maximum angular misalignment tolerance is ±2°.

Motor speed variation introduces timing drift in beam scanning. Assuming the motor rotates at nominal speed ω_0, deviation $\Delta\omega$ introduces angular drift:

$$\Delta\theta = \Delta\omega \cdot t$$

To maintain beam alignment within ±2°, and assuming beam detection is updated every $t = 0.1s$,he speed tolerance must satisfy:

$$\Delta\omega < \frac{2°}{0.1s} = 20°/s$$

This corresponds to a ±5% speed tolerance for a nominal motor speed of ~293 rpm (≈30.6 rad/s).

3. Cost and Schedule

3.1 Cost and Analysis

Our fixed development cost for the whole group is estimated at \$30 per hour, 20 hours per week for the four-person team. We expect to achieve at least 85 % of the final design in this semester (14 weeks).

Including a 4 overhead factor representing 4 group members and a factor of 1.4 for extra costs (lab use, test equipment, documentation), the labor cost is calculated as

$$C_{dev} = 4 \times \frac{30\$}{hr} \times \frac{20hr}{wk} \times 14wk \div 85\% \times 1.4 \approx 55341\$$$

Part	**Cost (prototype)**	**Estimated Cost (bulk)**
12 V Li-ion battery pack (power subsystem)	21.25	12.00

Arduino-class micro-controller (data/GUI hub)	15.34	8.00
Dual H-bridge motor driver	8.10	3.00
DC gear motors × 2 (orbit simulation)	16.00	9.00
5 mW laser-diode transmitter (optical link)	10.25	1.50
Photodiode receiver	4.00	1.00
PP disks × 2 (orbit simulation)	4.30	1.50
Optical encoders × 2 (speed feedback)	4.00	2.50
Custom control PCB	7.20	5.00
3D printed spindles & enclosure	2.00	0.50
3D printed gear wheel × 2	1.30	0.50
Transmission track × 2	1.55	0.50
Base made of PVC board	8.30	5.50
Total	103.59$	50.50$

3.2 Schedule and Demonstration

The schedule maps directly onto the subsystems defined in our proposal: Orbit Simulation, Data Processing & Decoding, Optical Signal Transmission, and GUI.

Weeks 3/17–3/31: We focus on rapid prototyping—machining the rotating disks, bread-boarding motor control, and proving the laser link at low data rates.
Weeks 4/07–4/21: Transition to custom PCBs and mechanical mounts, bringing the system to near-final hardware. Concurrent GUI development enables real-time monitoring and control, satisfying the requirement that users can "adjust parameters to test our model under different scenarios".
Weeks 4/28–5/05: This period is reserved for optimization and environmental testing (speed, BER, vibration), addressing the risk analysis that highlights rotating parts and laser safety.
The final week is dedicated to documentation, rehearsal, and packaging firmware/hardware releases for evaluation in the ECE 445 demo.

Week (Mon-Sun)	Xuanyi Jin (Orbit Simulation)	Yuxuan Li (Firmware & Control)	Zhijun Zhao (Optical Link HW)	Jun Zheng (GUI & Analytics)
3/17/25	Finalise CAD for inner & outer PP disks; order gear-motors and couplers	Define MCU pin-map; create motor-driver breadboard	Select laser diode & photodiode pair; draft link budget	Sketch GUI wire-frame; set up Qt/PySerial project
3/24/25	Machine disks; mount motors; preliminary spin-test at 30 rpm	Write basic PWM & encoder ISR; log speed to serial	Build benchtop laser-driver; measure beam divergence	Implement live speed plot; serial parser
3/31/25	Integrate optical encoder wheels; safety-guard design	Close-loop speed control; 60 rpm target met	Prototype TIA on perf-board; verify 1 kbit s-1 eye-diagram	Add control sliders (speed, Tx pattern)
4/07/25	Prepare mechanical drawings for final 3-D-printed mounts	Capture v1 control-PCB schematic (MCU + drivers)	Capture v1 receiver-PCB schematic	Design GUI logging & CSV export
4/14/25	Assemble full mechanics with printed mounts; balance disks	Route & submit v1 PCB; write SPI-flash buffer code	Route & submit receiver PCB; order optics	Integrate efficiency-analysis module
4/21/25	System-level fit-check; enclosure for Li-ion pack	Solder & bring-up control PCB; motor autotune	Solder receiver PCB; BER measurements vs. angle	First end-to-end demo; GUI shows decoded text
4/28/25	Environmental vibration test; refine safety guard	Optimise ISR latency; add watchdog & fault LEDs	Shield optics; achieve BER $< 10^{-6}$ at 30 cm	Add real-time efficiency graph & status LEDs
5/05/25	Draft assembly guide & risk-mitigation docs	Firmware freeze; code review	Hardware freeze; documentation	Usability test; polish GUI layout
5/12/25	Rehearse final demo & poster	Prepare firmware release package	Prepare hardware BOM & gerbers	Compile performance report; final presentation slides

4. Discussion of Ethics and Safety

As with any engineering project, ethical considerations and safety precautions are essential for ensuring that the system is not only functional but also safe to use and aligned with professional standards. The following discussion outlines the key ethical and safety concerns associated with the development of the 2D Optical Satellite Communication System and the measures taken to address them.

4.1 Ethical Consideration

4.1.1 Data Privacy and Security:

While the 2D model simulates the physical aspects of satellite communication, future real-world applications of optical satellite communication must address the ethical concerns surrounding data privacy and security. Satellites in space will inevitably be involved in transmitting sensitive data, which can be subject to interception, hacking, or misuse. Although the model does not directly deal with data encryption or security, it serves as an introduction to the basic principles of optical communication, and it is critical to be mindful of these concerns for future developments.

4.1.2 Inclusivity in Technology Development:

The development of satellite communication technologies, especially with the potential to provide Internet access to remote areas, carries an ethical responsibility to ensure that the technology is accessible to underserved populations. Ensuring equitable access to advanced communication systems will be crucial as these technologies continue to develop and expand, aligning with broader societal goals of reducing the digital divide.

4.1.3 Transparency in Simulation:

As a research project, the system is expected to provide accurate and transparent simulations of optical satellite communication. This ethical responsibility to ensure the model's integrity requires rigorous testing and validation. Any discrepancies or errors in the model could lead to misinformation or misinterpretations of satellite communication performance, which would undermine the value of the research.

4.2 Safety Consideration

1. **Laser Safety**: The project employs low-power lasers as the signal transmission mechanism between the ground station (Earth disk) and the satellite (orbiting disk). While the lasers used are low-power and fall within safety limits for eye exposure, it is important to implement safety protocols to avoid accidental exposure. Specifically:

    - The laser beams will be used in a controlled and confined environment to minimize exposure risks to the eyes of users or bystanders.
    - Laser warning signs will be displayed in the vicinity of the project setup.
    - Users will be instructed not to look directly into the laser beam, even if it is low power, and proper personal protective equipment (PPE), such as safety glasses, will be provided to users during the demonstration.

2. **Rotating Disks and Mechanical Safety**: The rotating disks, driven by motors, simulate the motion of Earth and satellites. These disks will rotate at varying speeds to replicate orbital dynamics, posing a potential mechanical risk if mishandled. To mitigate the risk:
    - The motors will be encased in protective housing to prevent accidental contact with moving parts.
    - Emergency stop buttons will be easily accessible to halt the system in case of unexpected issues.
    - Properly designed mechanical supports and guards will ensure that the rotating disks remain stable and safe throughout the demonstration.
    - Regular maintenance checks will be conducted to ensure that all moving components are properly secured and functioning as expected.

3. **Electrical Safety**: The system requires electrical power for the motors and laser subsystem. While low voltage is used, proper electrical safety precautions are necessary:

- All electrical components will be grounded properly to prevent electrical hazards.
- Wiring will be insulated and secured to avoid short circuits or accidental contact with exposed wires.
- Users will be instructed on safe handling of electrical components to avoid potential electric shock hazards.

4.3 Procedures to Mitigate Safety Concerns

To ensure that safety concerns are addressed and mitigated throughout the project, the following procedures will be followed:

- **Safety Training**: All individuals working with the project will undergo safety training that includes laser safety, mechanical safety, and electrical safety protocols.
- **Protective Gear**: Safety goggles and gloves will be provided to all personnel working directly with the system. In addition, appropriate warning signage will be displayed in the work area.
- **Inspection and Maintenance**: Regular inspections of both hardware and software components will be carried out to identify and fix any potential hazards. This will include checking the laser alignment, motor components, and wiring.
- **Clear Documentation**: A Safety Manual will be developed, detailing safety protocols and emergency procedures.

While the 2D Optical Satellite Communication System does not inherently involve high-risk factors such as high-voltage systems or aerial vehicles, it still requires careful consideration of safety and ethics. The implementation of low-power lasers and rotating machinery necessitates strict safety measures to protect users and ensure a safe working environment. Furthermore, ethical considerations related to environmental impact, data security, and inclusivity must guide the project, especially as it lays the groundwork for future communication technologies. By adhering to these safety protocols and ethical guidelines, the project will contribute to advancing satellite communication technologies while prioritizing user safety and social responsibility.

5 Reference

[1] Arduino, “UNO R3,” Arduino Docs. https://docs.arduino.cc/hardware/uno-rev3/ (accessed Apr. 14, 2025).
[2] Arduino, “Arduino (TM) UNO Rev3,” A000066-schematics. https://docs.arduino.cc/resources/schematics/A000066-schematics.pdf (accessed Apr. 14, 2025).
[3] HC Tech, “HC-06 Bluetooth 2.0 Module User’s Guide,” HC-06.