

# **Design of the Autonomous, Tracking & Pointing System (ATP): A generalized satellite test bench demonstrator for free-space optical communication systems**

## **Internship Report**

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## Abstract

The need for efficient and reliable communication systems in satellite applications has been on the rise, particularly in the context of distributed satellite systems. Optical communication, with its potential for high data rates and secure communication, has emerged as a promising solution for satellite communication. However, achieving optimal performance of optical communication systems requires careful consideration of factors such as directivity, which determines the accuracy and efficiency of communication links. The report expects to aid the understanding of optical communication and directivity concepts in the context of satellite communication systems, and to gain hands-on experience in mechanical design, fabrication, and testing for optical communication applications.

While designing any satellite architecture those implements the method of free space optical communication, it is imperative to validate and test the performance of optical communication systems on the ground before deploying them in space. In this context, the development of a satellite test bench demonstrator is of paramount importance. This work gives the groundwork on the concept and implementation of the Autonomous Tracking & Pointing (ATP) system, which is planned to be a generalized Test Bench demonstrator that focuses on investigating directivity. This also addresses implementation techniques for mechanical parts, such as optical transceivers, beam steering mechanisms, and mounting structures. The performance of the developed mechanical parts is evaluated and challenges are discussed to assess the accuracy and signal strength required to improve the system.

**Keywords:** Satellite, Optical Communication, Test Bench, Directivity



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## Abbreviations

<b>ADCS</b>	Attitude Determination & Control System
<b>AHRS</b>	Attitude Heading Reference System
<b>ATP</b>	Autonomous Tracking & Pointing System
<b>DSS</b>	Distributed Satellite Systems
<b>DOF</b>	Degree of Freedom
<b>CF</b>	Complementary Filter
<b>ECI</b>	Earth Centered Inertial
<b>ECEF</b>	Earth-Centered Earth-Fixed
<b>EDRS</b>	European Data Relay System
<b>EMI</b>	Electro Magnetic Interference
<b>FSO</b>	Free Space Optical
<b>FSS</b>	Federated Satellite Systems
<b>FSM</b>	Fast Steering Mirrors
<b>IMU</b>	Inertial Measurement Unit
<b>I2C</b>	I <sup>2</sup> C Serial Communication
<b>ISL</b>	Inter Satellite Link
<b>KF</b>	Kalman Filter
<b>LOS</b>	Line of Sight
<b>LLCD</b>	Lunar Laser Communication Demonstration
<b>LASER</b>	Light Amplification by Stimulated Emission of Radiation
<b>NASA</b>	National Administration for Space Agency
<b>PID</b>	Proportional Integral Derivative
<b>RF</b>	Radio Frequency
<b>Rx</b>	Receiver
<b>STK</b>	Systems Tool Kit
<b>Tx</b>	Transmitter



# 1 Chapter 1: Internship Report

## 1.1 Introduction

### 1.1.1 Space Communication Background

Space communication, also known as satellite communication, plays a critical role in modern society, enabling a wide range of applications such as global telecommunications, weather forecasting, remote sensing, navigation, and scientific research. With the increasing demand for reliable, high-speed, and secure communication, space communication has become an essential part of our daily lives, connecting people and devices across the world and facilitating the exchange of information on a global scale.

The Federal Communications Commission states that as of March 2023, there are over 4,500 active satellites in orbit around the Earth which are worked by numerous governmental, commercial, and scientific entities [1]. These satellites employ a variety of communication technologies, including radio frequency, microwave, and optical, to establish communication links between ground-based stations, airborne platforms, and other satellites in space.

Optical communication, in particular, has gained significant attention in recent years due to its potential for high data rates, low latency, and secure communication. Optical communication systems use lasers to transmit and receive information in the form of light, allowing for faster and more efficient communication compared to traditional RF-based systems [2]. Optical communication has been successfully deployed in space-based applications such as the EDRS and the LLCDC project by NASA [3], demonstrating the viability and advantages of optical communication in space [4].

One of the critical factors influencing the performance of space communication systems is directivity, which refers to the ability of a communication link to accurately establish and maintain a connection over a specific direction or angle. Directivity is a critical parameter in satellite communication, as it determines the coverage area, signal quality, and link efficiency of a communication link [5]. Optimizing directivity is crucial for achieving reliable and efficient space communication, especially in the context of federated satellite systems, where multiple satellites need to establish communication links with each other to enable seamless communication and coordination [6], [7]. In this internship project, the focus is on designing a satellite test bench demonstrator for a free-space optical communication system, with a specific emphasis on exploring directivity in the context of satellite communication. The aim is to gain insights into the performance of mechanical parts and optimize directivity to enhance the efficiency and reliability of optical communication links in distributed satellite systems.

Distributed satellite systems have gained increasing attention in recent years due to their potential for improved coverage, flexibility, and resilience compared to traditional monolithic satellite systems [8]. In DSS, multiple satellites, or "nodes", are deployed in orbit to work together as a coordinated network to achieve a common objective. These nodes can be geographically dispersed, forming a constellation or a formation in space, and communicate with each other to exchange information, perform collaborative tasks, or provide services.

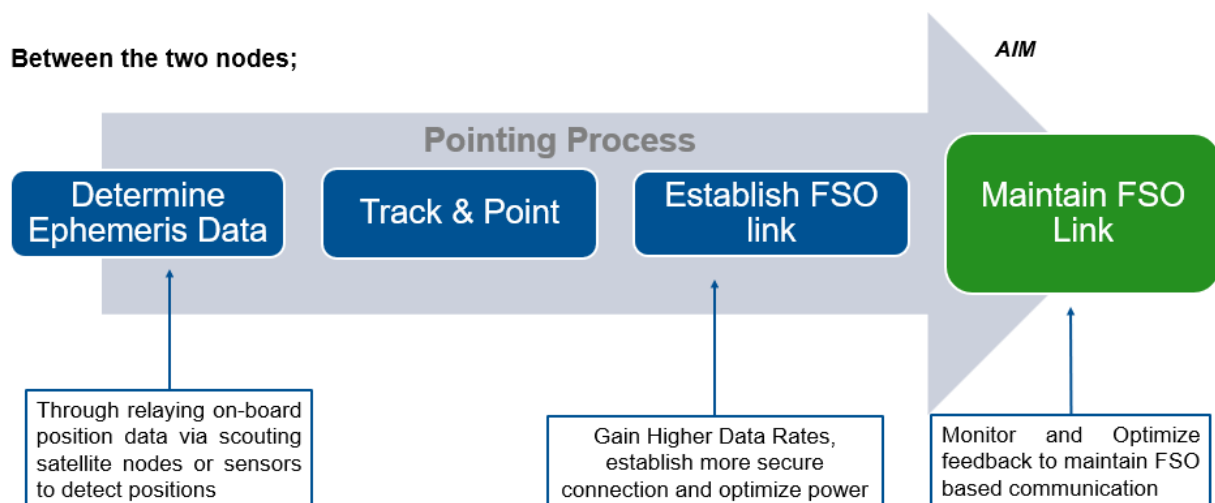


Efficient and reliable communication among the distributed satellite nodes is critical for the success of these systems. Optical communication, which uses light waves to transmit information, has emerged as a promising solution for satellite communication due to its potential for high data rates, low latency, and secure communication [9]. However, achieving optimal performance of optical communication links in distributed satellite systems requires careful consideration of various factors, including directivity.

Directivity refers to the ability of a communication system to focus its transmitted or received signals in a specific direction, typically using a beam steering mechanism. It determines the accuracy and efficiency of communication links by minimizing signal loss and interference, and maximizing signal strength and quality. Directivity plays a crucial role in optimizing the performance of optical communication links in distributed satellite systems, as it enables precise pointing and tracking of optical beams between satellites, minimizing the impact of atmospheric attenuation, scattering, and other environmental factors. Understanding the concept of directivity and its implications in the context of satellite communication is essential for designing and optimizing optical communication systems in distributed satellite systems. The design of mechanical parts, including optical transceivers, beam steering mechanisms, and mounting structures, plays a critical role in achieving the desired directivity performance. Therefore, the mechanical design of a test bench demonstrator for optical communication systems, with a focus on investigating directivity, is a crucial aspect of this internship project.

### 1.1.2 Objectives, Scopes and Top-level Requirements

A review of relevant literature on optical communication in space, including the principles of optical communication, advantages, and challenges was done. The literature review briefly covers the importance of directivity in satellite communication and its impact on link performance and efficiency. The design of this satellite test bench was focused to involve handling and testing of multiple satellites subsystems and nodes. Subsequently, a generalized design for mechanical integration was conceptualized and implemented.



**Figure 1.1.1:** Process Flowchart Diagram

Next, the project involved hardware setup for a simpler, generalized test bench demonstrator for the optical communication system constituting three satellite nodes. This included the selection and integration of mechanical components such as actuators, laser modules, communication components such as transceivers and antenna for a selected RX-TX group, and other supporting structures such as microcontrollers and inertial measurement units. The setup of appropriate measurement and evaluation methods depended on both, analytical models as well as contribution from experimental data. Finally, optimizing directivity was discussed to enhance the efficiency and reliability of optical communication links in distributed satellite systems. Figure 1.1 describes the simplified flow cart for the pointing process that is required to achieve and maintain a FSO communication in space.

After the test bench demonstrator was set up, experimental tests were conducted to evaluate the performance of the mechanical parts and their impact on directivity. Data analysis and interpretation was carried out to identify any limitations or areas of improvement in the mechanical parts. Subsequently, appropriate modifications or optimizations are proposed. The project also ventured into viable methods to be incorporated post completion of the work and explored related aspects of the optical communication system, such as increasing the kinematics complexity, modulation techniques and signal processing, to ensure a holistic approach towards achieving the overall project objective. To summarize, an brief definitions of objectives and scopes of the work are given below.

#### **Primary Objective:**

*“To design a generalized satellite test bench demonstrator for optical space communication”.*

#### **Secondary Objectives:**

1. To investigate the importance of directivity in optical communication links.
2. To understand and implement multi node space communication essential for DSS.
3. To investigate methods for autonomous pointing for DSS Architectures.
4. To gain hands-on experience in mechanical design, fabrication, and testing for optical communication applications.

#### **Scope:**

1. Review of relevant literature and research on optical communication systems, distributed satellite systems, and directivity concepts.
2. Definition of the space environment to operate nodes in a simulated 3D space in the lab.
3. Design of a multi-node mechanical system with optical transceivers, beam steering mechanisms, and mounting structures, for the optical communication system where positions of the nodes are unknown.
4. Implementation of a multi-node mechanical system with optical transceivers, beam steering mechanisms, and mounting structures, for the optical communication system where positions of the nodes are known.
5. Evaluating the performance of the developed system in a test bench demonstrator setup.
6. Analyzing and interpreting the results to assess directivity of optical communication links.
7. Documenting the methodology, results, and conclusions in a comprehensive report, including recommendations for future work.

**Top-level Requirements:**

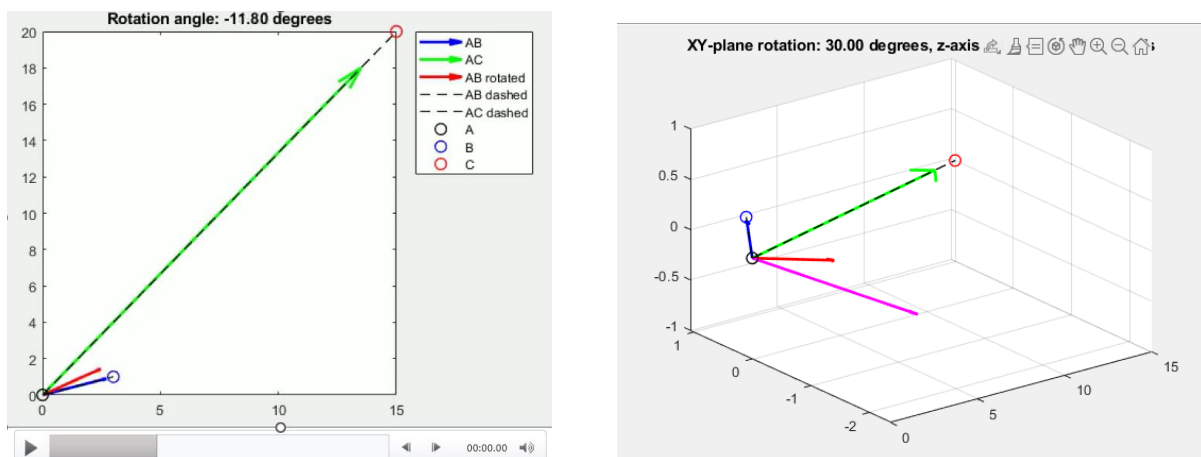
#	ID	Name	Text	Satisfied by
1	DOSP-TB-001	Pointing of Multiple Nodes	The Test Bench shall perform the pointing of multiple satellite nodes.	ATP – Test Bench
2	DOSP-TB-002	Obtaining Orientation Data without Communicating with ground station	The test bench shall be capable of obtaining positional data from the satellite nodes.	MPU-6050 IMU Chip
3	DOSP-TB-003	FSO Link visualization & Pointing Verification	The test bench shall be capable of visualizing the FSO link.	KY-008 Laser Module and Optical Receiver
4	DOSP-TB-004	Telemetry for multi-node communication	The test bench shall be capable of relaying positional data to a central node.	NRF24L01+ RF Transceiver
6	DOSP-TB-005	Control for actuators	The test bench shall be capable of rotation in 3D Space	SG 90
7	DOSP-TB-006	Data Processing for Pointing Maneuver	The test bench shall implement control algorithms onboard the satellite node for pointing and enabling FSO link	Node 1 & 2 Microcontrollers

## 1.2 Methodology

### 1.2.1 Mathematical Modelling and Control Algorithms

In order to point two satellites towards each other for FSO communication, there needs to be a mathematical understanding of how two systems can point each other. The approach involves using vectors and dot products to determine the relative positions of the two satellites in space. Vectors are mathematical objects that have both magnitude and direction. In the context of satellite pointing, we can use vectors to represent the position of each satellite in space.

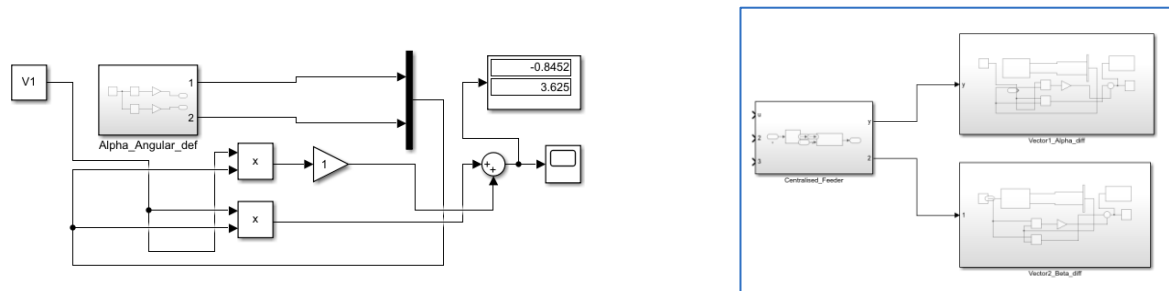
To point one satellite towards another, we need to determine the vector pointing from the first satellite to the second. This is known as the line-of-sight vector, which represents the direction in which the first satellite needs to point its communication antenna to communicate with the second satellite. We can calculate the LOS vector by subtracting the position vector of the second satellite from the position vector of the first satellite. Once we have the line-of-sight vector, we can use the dot product to determine the angle between the line-of-sight vector and the pointing vector of the first satellite's communication antenna. The pointing vector is a unit vector that points in the direction of the communication antenna. By taking the dot product of the LOS vector and the pointing vector, we can determine the cosine of the angle between them.



**Figure 1.2.1:** MATLAB 2D (Left) and 3D (Right) animation plots for visualizing pointing

To simulate pointing, a control algorithm was designed to adjust the orientation of the first satellite's communication antenna to point towards the second satellite. Figure 1.2.1 depicts 2D and 3D simulation plots in MATLAB to help visualize the gradual pointing (alignment vector given in red) in 2D space (Left window) and 3D space (Right window) with equations of motion defined.

The equations of motion defines a fixed angular velocity that is considered as the satellite's re-orientation capability, i.e., the capability of the ADCS on board to point the optical transceiver towards the incoming optical beam. This is done by adjusting the position of the satellite's attitude control system, which could involve thruster firings or reaction wheel rotations.



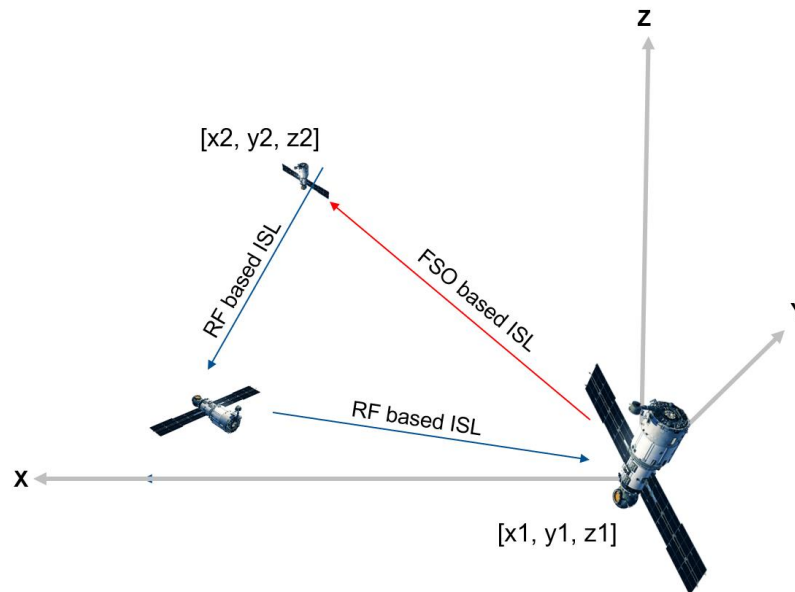
**Figure 1.2.2:** MATLAB Simulink model representing gradual pointing of two satellite nodes.

The control algorithm use rotation matrices and the dot product value to determine the necessary adjustments to make to the satellite's orientation. For 2D space, pointing requires one angle, i.e., azimuth. For 3D space, pointing requires two angles, i.e., azimuth for rotation in XY plane and elevation for rotation required for compensating the Z-Axis difference. Figure 1.2.2 depicts a Simulink model also implemented in MATLAB to simulate the pointing of the satellite with equations of motion defined but the angles determined and fed by a central feeder. The nodes were again assumed to be vectors defined in cartesian coordinate system. A central computer calculates and feeds back angles with PID Control.

## 1.2.2 Environment, Hardware and Schematics

In order to construct the necessary mechanical components for the test bench, it is crucial to establish the hardware layout beforehand. The system layout is illustrated in Figure 1.2.5, which shows the integration points for the hardware, effectively representing three nodes.

To develop control laws for laboratory components, it is essential to define the 3D environment of the test bench that can handle multiple satellite nodes. For this internship, a table is chosen as the 3D environment, where the length and width represent the XY plane and the distance upwards from the table is considered as the positive Z direction. The origin is fixed in the right bottom corner. This approach enables a consistent and precise measurement of the movements and positions of the components, thereby facilitating the development of accurate control algorithms. The idea of the project was to have RF based ISL communication for relaying positional data via a relaying satellite node. The FSO based ISL is enabled when the relayed positional data is received on the satellite node that is performing the maneuver for pointing.

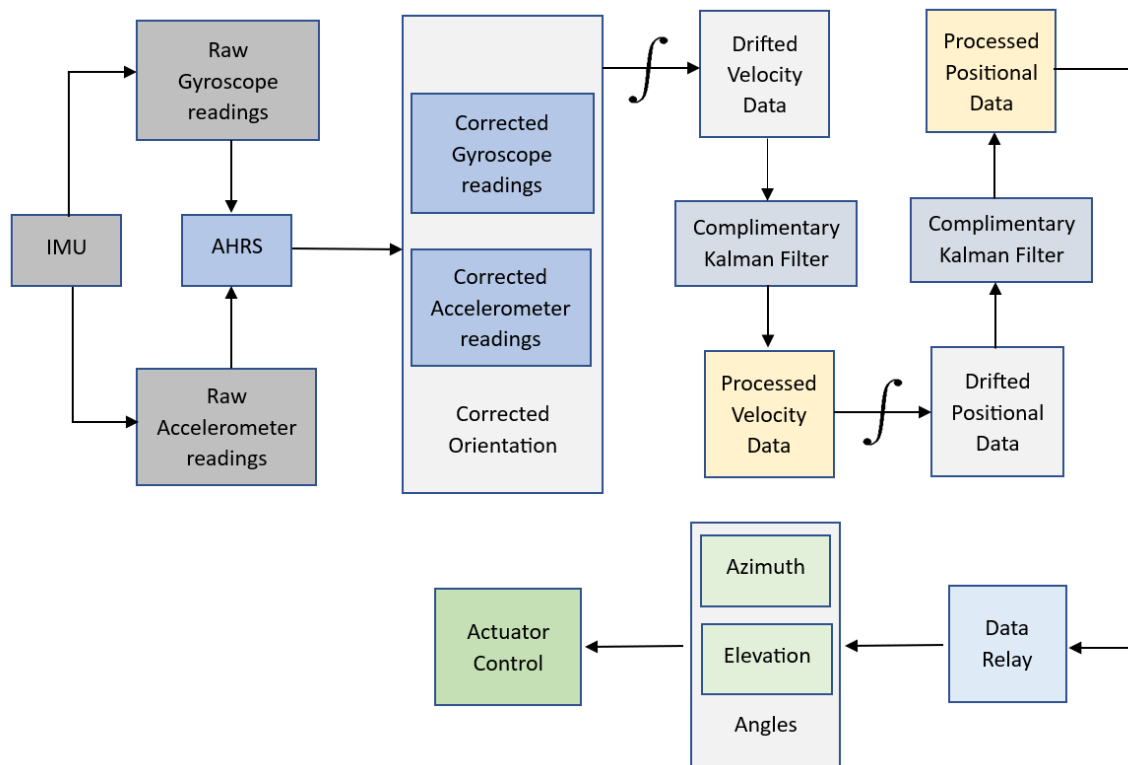


**Figure 1.2.3:** Representation of the 3D Environment with the positions of the nodes.

The reference inertial frame for this Test Bench is fixed to a physical 3D space defined in cartesian coordinates in the laboratory. To accurately point one satellite towards another in space, it is crucial to obtain processed and corrected positional readings. However, it is assumed in this work that the satellite nodes do not possess their own positions in space. Each satellite in space is more or less aware of its own position in orbit through its own positional tracking algorithms or through updated NORAD Database on satellite ephemeris data through ground stations. This work however does not establish link with ground stations on Earth.

Almost every satellite in space incorporates some form of an inertial measurement unit. The IMU gives the orientation of the satellite in orbit, which is crucial for ADCS. The orientation data however can also be used to obtain positional data. Integrating the accelerations twice gets us the positions. But the raw orientation readings are not in reference to the Nadir, or the gravity field of the Earth nor it encompasses sensor fusion techniques, since we have multiple DOF-category readings. To get the corrected orientation we need to process it through a system that provides orientation information based on sensor measurements. This is achieved through the use of AHRS, KF, and CF. Figure 1.2.4 depicts the functional chart of the Test Bench.

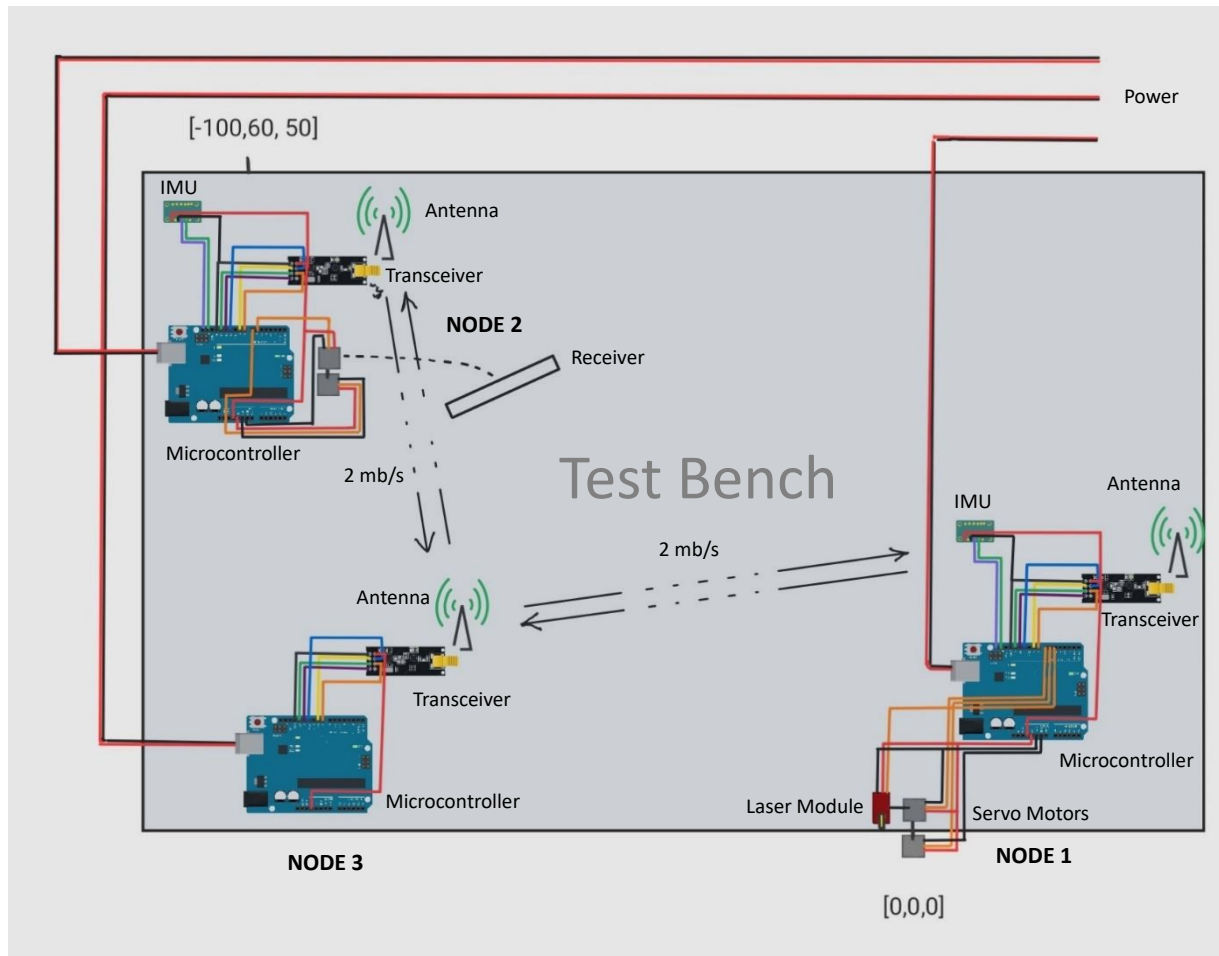
The AHRS provides orientation information, while the Kalman filter estimates the true value of the position and helps remove noise and errors in the data. Complimentary filters are used as high pass filters to remove drift, which is essential for accurate and stable readings. These filters help to ensure that the positional data obtained is precise and reliable. Once positional data is obtained, it is relayed via a third satellite, which then calculates the required azimuth and elevation angles necessary for pointing the first satellite towards the second. The use of AHRS, KF, and CF is therefore critical in achieving accurate and stable satellite pointing, which is essential for efficient and effective communication in space.



**Figure 1.2.4:** Functional Diagram for the ATP

Figure 1.2.5 depicts the electrical wiring for the Test Bench, where three nodes are present: two satellites (Node 1 and Node 2) and a Central computer that acts as either another orbiting satellite or the Ground Station back on Earth. To develop the test bench layout, three Arduino Uno R3 boards are set up - one for each node. Each Node 1 and Node 2 is connected to an MPU-6050 module to gather acceleration and gyro readings, while the laser module (KY-008) is used for pointing in free space optical communications. The laser modules can be controlled using digital pins of the Arduino to emit a laser beam in the desired direction. To relay sample data, a transmitter module (NRF24L01) is assigned to each of the satellite nodes. The NRF24L01 wireless transceiver module operates in the 2.4 GHz radio frequency band and can communicate each other using a simple and efficient RF protocol implemented using the Arduino library.

The central node receives the sampled data through a receiver module (NRF24L01) from each of the satellite nodes. Additionally, two motors are assigned to each of the satellite nodes to rotate them based on the calculated angles from the central node. These motors, which are commonly used in precision positioning applications, can be controlled using appropriate motor drivers and Arduino's digital pins.



**Figure 1.2.5:** Hardware and Electrical Schematic for the Test Bench

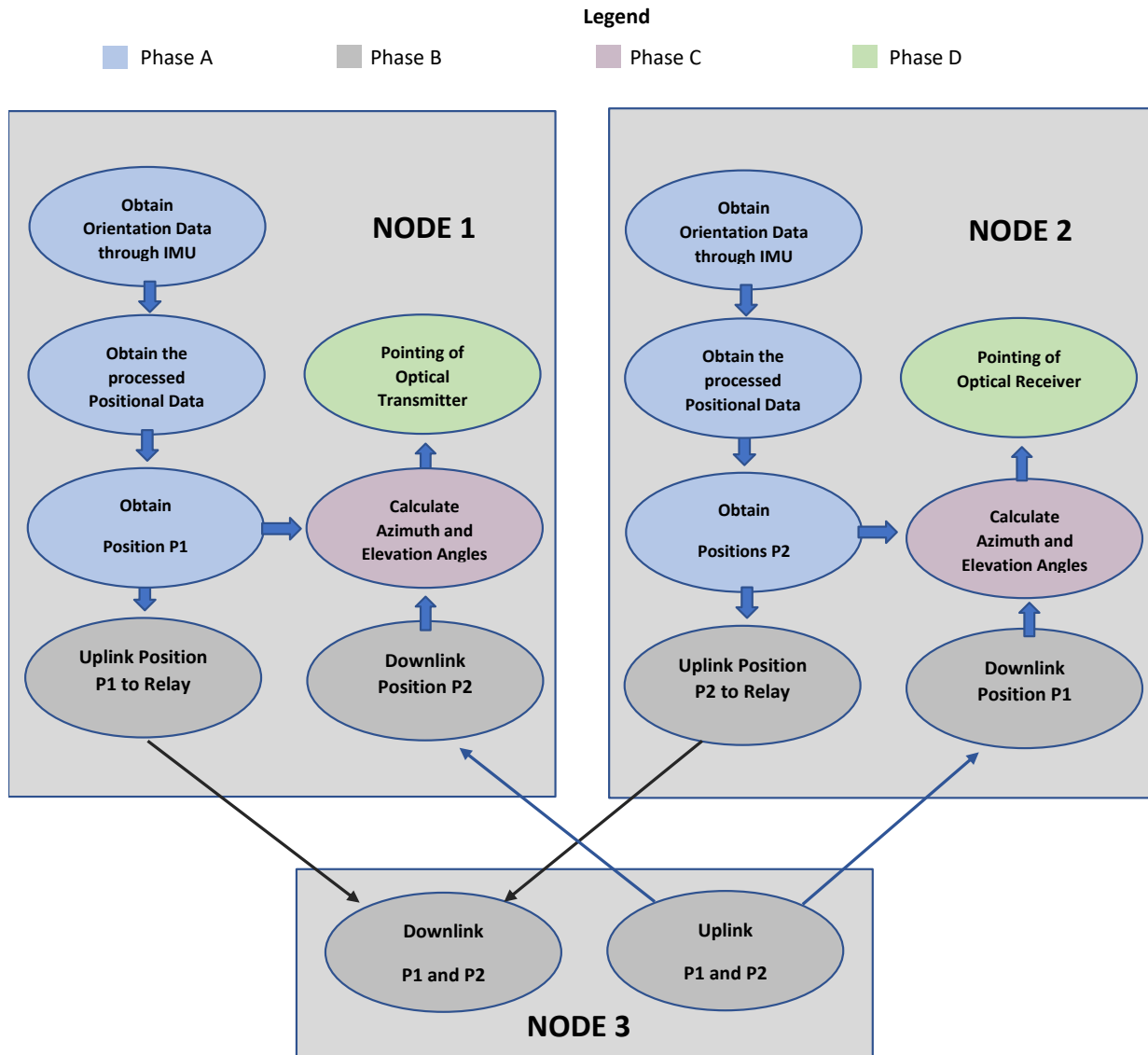
### 1.2.3 Data Handling and Telemetry Challenges

The Data handling processes are divided into four phases for the sake of simplicity as shown in Figure 1.2.6. Phase A involves in obtaining the positional data. Phase B deals with data relay through RF channels. Phase C deals with the determination of the required rotation matrices and angles for pointing. Phase D finally delivers the control codes for actuators required for pointing.

In phase A, the satellite nodes reads the acceleration and gyro data from MPU-6050 module using I2C communication protocol using the RF24 Arduino library to communicate with the MPU-6050 module and obtain the raw acceleration and gyro data. The data is then processed as needed, such as filtering or calibration. Then, the corrected orientation bias is processed through AHRS as an fusion sensor fusing agent and to obtain reliable readings onboard the chip. Now, with the orientation data onboard, the data packet undergoes a double integration to calculate the position of the satellite nodes in the project's 3D test space. However, accelerometer data can be noisy and prone to drift, so it required filtering and calibration to obtain accurate position data.



Putting a KF in combination with a CF algorithm reduces noise in the position data. KF is a widely used filtering technique that combines sensor measurements and system dynamics to estimate the state of a system. Whereas CF is a relatively simpler filtering approach that combines low-pass filtered and high-pass filtered data to obtain a filtered output. The processed Positional data P1 is then transmitted to node 3.



**Figure 1.2.6:** Data Handling Phases of the Test Bench

In Phase B, node 3 receives the positional data from both satellite Nodes 1 and 2 and using the Arduino library the data is decoded at the central. Subsequently, the updated data packets are transmitted back to Node 1 and Node 2 since the objective of the central is to be a relay satellite for this setup.

In Phase C, after receiving the processed positional data, the required angular differences were calculated, i.e., the azimuth and the elevation. An appropriate algorithm using trigonometry and vector-based calculations was implemented to calculate the angle based on the position data and obtain the required rotation matrices.

The two angles, one for the rotation in XY-plane and the other for rotation in Z-plane can cumulatively represent the pointing direction of the first node and second node towards each other in space. The choice of the algorithm was specific to the requirement and availability of specific hardware based capabilities.

In phase D the calculated angles were fed to the motor control commands to rotate the stepper motors for pointing. Suitable control algorithms, such as PID and custom control algorithms was used to accurately control the stepper motors based on the received angle data. The motor rotation speed, direction, and steps according to the calculated angle were calibrated and documented to achieve precise pointing of both nodes towards each other.

There were unexpected issues in the relay of the positional data. The challenge was that the data packets uploaded and downloaded had different data rate for the initialization of the positional data P2 and thus the system calculated two different sets of  $\theta_{xy}$  and  $\theta_z$ . This phenomenon caused the ATP on-board Node 1 controlling the laser module to oscillate from both values. This was resolved by matching the frequency of the data packets received with the initialization of P2. Below the serial com data received on Node 3 is displayed;

```

Calculated  $\theta_z$ : 28.22
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_z$ : 28.22
Calculated  $\theta_{xy}$ : 26.57
Received P2: x: 100.00, y: 60.00, z: 50.00
Received P2z: x: 0.00, y: 0.00, z: 0.00
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_z$ : 0.00
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_z$ : 0.00
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_z$ : 0.00
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_z$ : 0.00
Calculated  $\theta_{xy}$ : 26.57
Calculated  $\theta_z$ : 0.00
Calculated  $\theta_{xy}$ : 26.57
Received P2: x: 100.00, y: 60.00, z: 0.00
Received P2z: x: 100.00, y: 60.00, z: 0.00
Calculated  $\theta_{xy}$ : 30.96
Calculated  $\theta_z$ : 0.00

```

#### 1.2.4 Generalized Equations and Rotation Matrix

This section elaborates on the Phase D's on-board calculations that takes places on the satellite nodes. Node 1 is the satellite performing the pointing and Node 2 is the target satellite, the cosine of the angle between the two vectors can be calculated using the dot product as described in equation 1.2.1.



For the simplified test bench,  $P1 = [X_{1\_xy}, Y_{1\_xy}, Z_{1\_xy}] = [0,0,0]$  and  $P2 = [X_{2\_xy}, Y_{2\_xy}, Z_{2\_xy}] = [100,60,50]$ . This makes the LOS,  $V = P2 - P1 = [100,60,50]$ . Equations 1.2.1 and 1.2.2 shows two methods for obtaining the required control angles. The  $\theta_{xy}$  is the angle made with positive x-axis to the line of sight and taking the projection of P2 on XY-Plane, we get;

$$\begin{aligned}\theta_{xydot} &= \cos^{-1} \left( \frac{(X_1 \times X_2) + (Y_1 \times Y_2) + (Z_1 \times Z_2)}{\sqrt{X_1^2 + Y_1^2 + Z_1^2} \times \sqrt{X_2^2 + Y_2^2 + Z_2^2}} \right) \\ &= \cos^{-1} \left( \frac{(100 \times 1) + (60 \times 0)}{\sqrt{100^2 + 60^2} \times \sqrt{1^2 + 0}} \right) \\ &= 31.7 \text{ deg}\end{aligned}\tag{1.2.1}$$

With the atan method, the result for azimuth is;

$$\theta_{xyatanz} = \text{atan} \left( \frac{60}{100} \right) = 30.5 \text{ deg}\tag{1.2.2}$$

Note that values obtained on theoretical calculations are also slightly different from the experiment, i.e., the serial com data shown earlier where  $\theta_{xy}$  is 30.96 deg.

To find a generalized equation that can compute the necessary angles, we can define rotated vectors  $P1_{xy\_otated} = [X_{xy\_r}, Y_{xy\_r}, Z_{xy\_r}]$  and  $P1_{z\_otated} = [X_{z\_r}, Y_{z\_r}, Z_{z\_r}]$ .

$$\theta_{xy3D} = \cos^{-1} \left( \frac{(X_{xy} \times X_{xy_r}) + (Y_{xy} \times Y_{xy_r})}{\sqrt{X_{xy}^2 + Y_{xy}^2} \times \sqrt{X_{xy_r}^2 + Y_{xy_r}^2}} \right)\tag{1.2.3}$$

$$\theta_{z3D} = \cos^{-1} \left( \frac{(Z_z \times Z_{z_r})}{\sqrt{X_z^2 + Y_z^2} \times \sqrt{X_{z_r}^2 + Y_{z_r}^2}} \right)\tag{1.2.4}$$

Using equation 1.1, we can find the rotation matrix for rotating Node 1 towards Node 2 can be calculated as;

$$(1.2.5)$$

$$R = \begin{pmatrix} \cos\theta + (1 - \cos\theta).x_1^2 & (1 - \cos\theta).x_1.y_1 - \sin\theta.z_1 & (1 - \cos\theta).x_1.z_1 + \sin\theta.y_1 \\ (1 - \cos\theta).y_1.x_1 + \sin\theta.z_1 & \cos\theta + (1 - \cos\theta).y_1^2 & (1 - \cos\theta).y.z_1 + \sin\theta.x_1 \\ (1 - \cos\theta).z_1.x_1 + \sin\theta.y_1 & (1 - \cos\theta).z_1.y_1 - \sin\theta.x_1 & \cos\theta + (1 - \cos\theta).z_1^2 \end{pmatrix}$$

## 1.2.5 Test-Bench ATP Program-Code and Algorithms

This section shows the pseudo code flowchart of the entire test-bench that incorporates the essence of all data handling phases iterated before. Since there are multiple code segments in the test-bench system written in Python and C++, it is not reasonable to include all the program lines in this report. The next section describes some essential algorithms needed to make the Test Bench work. The pseudo code for the algorithms and satellite nodes are described as;

### 1.2.5.1 ATP Algorithms

#### Algorithm 1.2.1: ATP AHRS using MPU-6050 Chip

1. Initialize variables: Gyroscope bias, Quaternion, estimated gravity vector
2. Read raw sensor data from gyroscope, accelerometer, and magnetometer
3. Apply calibration to raw sensor data if necessary
4. Convert accelerometer and magnetometer data to unit vectors in the earth frame
5. Calculate reference direction of the gravity in ECEF using accelerometer data
6. Calculate reference direction of the magnetic field in ECEF using magnetometer data
7. Convert the gravity vector to the body frame using the estimated orientation
8. Compute difference between the measured gravity vector and reference gravity vector
9. Update the gyroscope bias estimate using the difference calculated in step 8
10. Integrate the gyroscope data to obtain an estimate of the change in orientation
11. Correct the estimate using the difference calculated in step 8
12. Normalize the Quaternion
13. Repeat steps 2-12 at a fixed rate (150 Hz)

#### Algorithm 1.2.2: ATP Kalman Filter:

1. Initialize the state estimate and the error covariance matrix.
2. Measure the system state and the measurement noise covariance matrix.
3. Calculate the Kalman gain using the error covariance matrix and the measurement noise covariance matrix.
4. Update the state estimate using the Kalman gain and the measured system state.
5. Update the error covariance matrix using the updated state estimate and Kalman gain.
6. Repeat steps 2-5 for each measurement.

#### Algorithm 1.2.3: ATP Complimentary Filter:

1. Measure the system state.
2. Filter the system state using a low-pass filter.
3. Filter the derivative of the system state using a high-pass filter, here KF and CF.
4. Combine the filtered system state and filtered derivative of the system state using a weighted sum.
5. Repeat steps 1-4 for each measurement.

**Algorithm 1.2.4:** ATP Angles:

1. Calculate the relative position vector  $P_{rel}$
2. Calculate the norm of  $P_{rel}$ :  $\|P_{rel}\|$
3. Calculate the azimuth angle  $theta_{xy}$ .
4. Project the relative position vector onto the xy-plane by setting  $P_{rel.z} = 0$
5. Calculate the norm of the projected vector:  $P_{rel_{xy}}$
6. Calculate the elevation angle  $theta_z$ .
7. Correct the elevation angle for the Earth's curvature by adding the term:
8. Return  $theta_{xy}$  and  $theta_z$  as the results.

**1.2.5.2 Pseudo Program Codes****START****C++ Pseudo Program Code 1.2.1: Node 1:**

- 1:** Initialize *IMU-1* and run in through *AHRS*
- 2:** Initialize position data *P1*
- 3:** Initialize radio communication
- 4:** Initialize servo motor for x-y plane
- 5:** Initialize servo motor for z-axis
- 6:** Initialize laser module
- 7:** Set address for communication with other nodes
- 8:** Set pin modes for motor control and LASER output
- 9:** Set initial motor speed and direction

**For Loop:**

- 10:** Check if data is available in radio buffer
- 11:** If available, read position data *P2* and *P2z*
- 12:** Update *P1* with last received *P2* data
- 13:** Turn on *isDataReceived* flag and set *lastDataReceivedTime* to current time
- 14:** If no data is received for the defined interval, set *isDataReceived* flag to false
- 15:** If data is received, parse and store position information
- 16:** Calculate  $theta_{xy}$  and  $theta_z$  from *P1* and *P2z* data
- 17:** Calculate motor speed and direction based on position information
- 18:** Control motor using calculated speed and direction
- 19:** Control LASER output based on motor direction
- 20:** Set servo positions with  $theta_{xy}$  and  $theta_z$  values
- 21:** Turn on the laser module for 10 seconds
- 22:** Turn off the laser module

**C++ Pseudo Program Code 1.2.1: Node 2**

- 1: Initialize *IMU-2* and run in through *AHRS*
- 2: Initialize position data *P2*
- 3: Initialize position data *P2z*
- 4: Initialize radio communication

**For Loop:**

- 5: Update position data *P2* and *P2z* with current node position
- 6: Send *P2* and *P2z* data through radio

**C++ Pseudo Program Code 1.2.1: Node 3**

- 1: Initialize Serial communication
- 2: Initialize RF24 radio communication

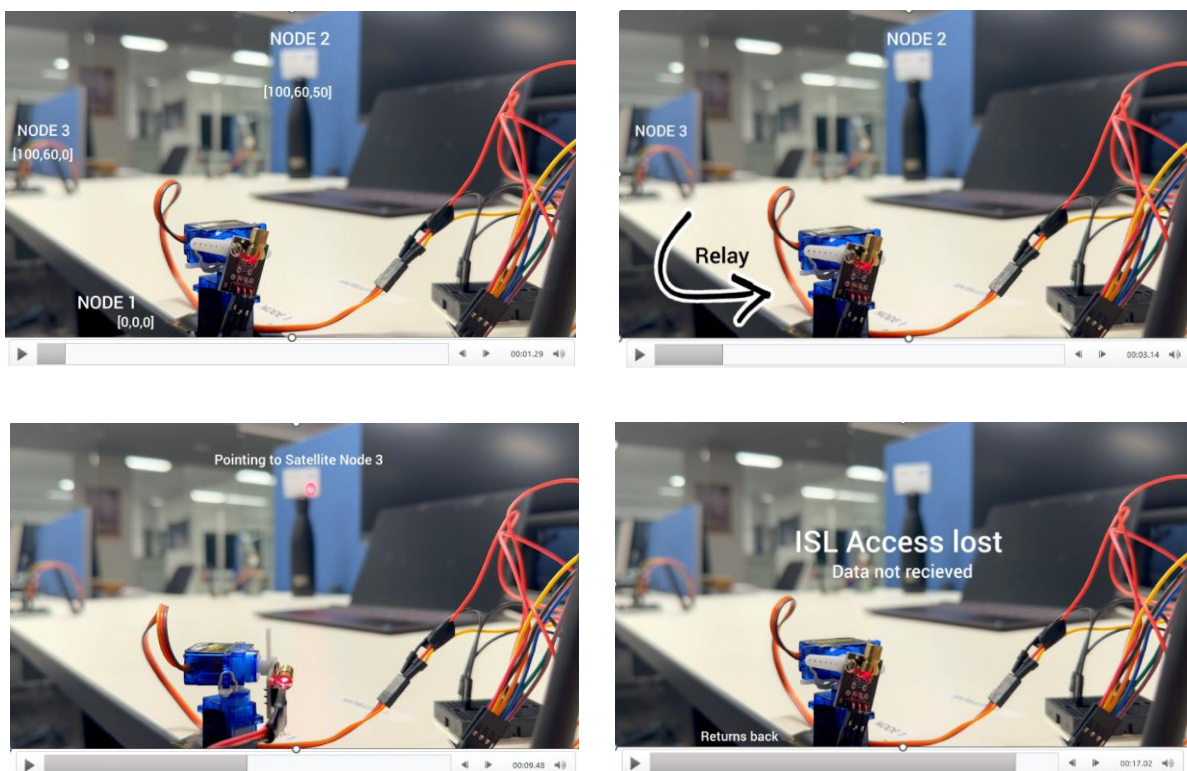
**For Loop:**

- 3: Check if data is available in radio buffer
- 4: Read data from other nodes using RF24 radio communication
- 5: Send data to other nodes using RF24 radio communication

**END**

### 1.3 Results and Discussion

In the simplified ATP simulation test, position of satellite 1 and 2 are fixed and known as shown in Figure 1.3.1. A close-by satellite 3 Node relays positional data. Satellite 1 processes and determines the required azimuth and elevation for pointing. Satellite 1 activates laser and points to satellite 2. This test was simulated for an access window selected according to real case access windows of existing satellite architectures, from the NORAD database. In this experiment, a simulated time for the RF relay is set for 10 seconds and it was observed that ATP maintained the FSO link for 7 seconds before returning to its orthogonal stowed position.



**Figure 1.3.1:** Simplified Test Bench Experiment

Figure 1.3.1 (Top left) shows the initialization of the ATP on Node 1 where the RF link, i.e., Simulated RF based ISL is enabled. The same Figure 1.3.1 (Top Right) depicts the relay from Node 2 to Node 3 and then from Node 3 to Node 1. The ATP on-board node 1 upon processing required angles moves into a default station keeping set at orthogonal angles, here called orthogonal positioning. Then after, in the same Figure 1.3.1 (Bottom Left) depicts the successful pointing of the KY-008 Laser module on the node 2 optical transceiver placed afar. Lastly, the Figure 1.3.1 (Bottom Right) shows the loss of FSO based ISL on which the ATP on Node 1 returns back to orthogonal positioning.

In the experiment it was estimated that the latency in the hardware relay using the transceivers over a distance of one meter was to be 68 milliseconds. The prime suspect for delay would be the un-optimized control codes and the limitations of the selected off-the-shelf servo motors used for this work. Table 1.3.1 shows the total power consumed by the Generalized Test Bench Setup.

**Table 1.3.1:** Generalized Test Bench Power Budget

Power Required	Current Required	Power Required
Node 1	589.8 mA	2.949 W
Node 2	574.8 mA	2.874 W
Node 3 (Central)	70 mA	0.35 W
<b>Total (Test Bench)</b>	<b>1.235 A</b>	<b>6.173 W</b>

The accuracy of the system is limited to the capabilities of the existing positional servo motors used for this project. Also, the experiment does not account for a method to control the angular velocities for the rotation of the motors, and the sudden halts in the pointing process produces miniscule jerks in the system. This causes it to be a few milli-degrees off the true target on the optical receiver. Table 1.3.2 shows the pointing errors of the simplified ATP in terms conducted in 20 trials. The result was more or less consistent with a standard deviation of 0.208 units and a median error of 1.41 units.

**Table 1.3.2:** Pointing Errors in Simplified Test Bench

Theoretical P <sub>theo</sub>	Experimental P <sub>exp</sub>	Error in units (cm)
[100, 60, 50]	[99.1, 61.0, 49.0]	1.50
[100, 60, 50]	[99.3, 61.5, 50.7]	1.38
[100, 60, 50]	[101.4, 60.2, 50.9]	1.44
[100, 60, 50]	[98.9, 59.6, 49.6]	1.52
[100, 60, 50]	[100.2, 59.8, 49.1]	1.13
[100, 60, 50]	[99.8, 60.4, 51.4]	1.03
[100, 60, 50]	[100.7, 58.9, 49.9]	1.32
[100, 60, 50]	[100.5, 60.1, 48.6]	1.16



[100, 60, 50]	[99.2, 61.2, 50.1]	1.22
[100, 60, 50]	[100.8, 60.3, 50.6]	1.22
[100, 60, 50]	[98.6, 61.5, 50.9]	1.58
[100, 60, 50]	[100.4, 61.2, 51.9]	1.33
[100, 60, 50]	[99.6, 59.1, 49.7]	1.57
[100, 60, 50]	[101.3, 61.5, 49.7]	1.27
[100, 60, 50]	[98.4, 59.8, 51.2]	1.52
[100, 60, 50]	[100.3, 59.3, 48.7]	1.33
[100, 60, 50]	[99.9, 61.8, 51.4]	1.41
[100, 60, 50]	[101.2, 59.2, 49.5]	1.40
[100, 60, 50]	[98.5, 59.1, 50.3]	1.60
[100, 60, 50]	[100.4, 60.1, 48.6]	1.17

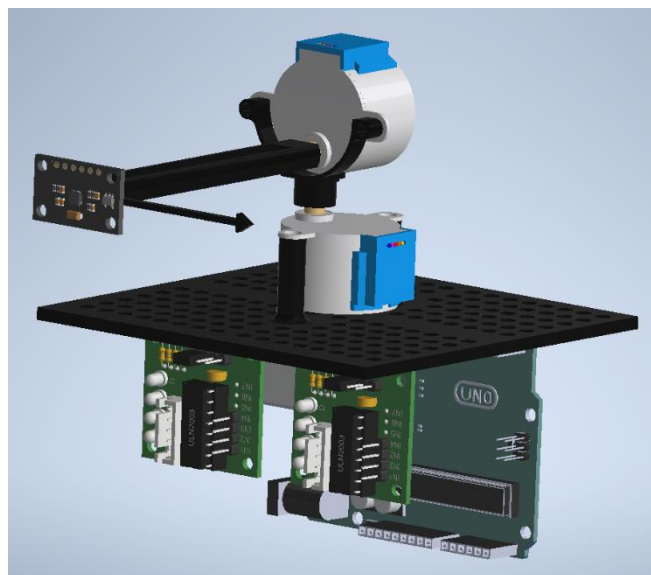
## 1.4 Conclusion and Future Work

A generalized satellite test bench demonstrator for optical space communication was designed and implemented in the laboratory and tested to verify the requirements laid out in section 1.1.2. All requirements were successfully verified. The Nodes are able to communicate with each other with no noticeable telemetry issues and able to relay the positional data through a multiple node system.

The node selected for testing the ATP successfully carried out the maneuver for pointing the test laser at the other node that relayed its position to the test node. By this, a feeble attempt was made on decentralizing the pointing process since there are no ground stations involved. The satellite are capable of determining their own orientations in a reference inertial frame and use that data to determine the positions in space.

For future work, It would be nice to have;

1. **Better Motors.** Replacing the existing Servo motors with 28BYJ-48 Stepper motors with a dedicated motor driver board such as ULN003 and see if the introduction of step control, that is the ability to control the angular velocity, as shown in Figure 1.4.1. This will help simulate the actual rotation capability of the spacecraft. But, they require considerably more power and input pins than the motors used for the Test Bench. The power budget trade-off will be required.



**Figure 1.4.1:** Autodesk Inventor CAD Model with a stepper motor configuration Test Bench

2. **Introducing Node Motion.** Adding the translational DOF into the system so the nodes are in motion. This can be done by introducing rail systems for the nodes. It is unclear if a circular, scaled down orbit rail system would be more appropriate or the linear

translation rails. This would require an additional control loop to feed back the updated positions in space with respect to time.

3. **Improving Pointing Accuracy.** For the purpose of developing a more robust, accurate and reliable Test Bench, the introduction of FSM would considerably reduce the pointing errors. The design of the required FSM would involve precise understanding of redirecting the signal on the mirror.

In summary, the work intends to converge on a solution to decentralize the framework for space communication. The focus was made on FSO to enable the highest data rate transfer of the LASER based communication systems.

## 2 Chapter 2: Literature Review

### 2.1 Free space Optical Overview

The development of free space optical communication systems can be traced back to the mid-19th century, when scientists began experimenting with the use of light to transmit information [10]. One of the earliest pioneers for the FSO technology was Alexander Graham Bell, who in 1880, invented the photophone, a device that used light to transmit sound signals over a distance [11]. However, the technology was limited in its application due to the lack of suitable light sources and the inability to focus light over long distances. It wasn't until the 1960s that the first practical application of FSO systems emerged. This was in the form of laser communication links used by NASA for inter-satellite communication. The advantage of using FSO systems over traditional radio frequency communication was the ability to transmit data at much higher rates and with greater security [12]. FSO systems were also less susceptible to interference from other sources of electromagnetic radiation.

Over the next few decades, FSO technology continued to evolve, with the development of more powerful and efficient lasers [13], better optical components [14], and the use of advanced signal processing techniques [15]. One of the key breakthroughs in FSO technology was the development of adaptive optics, which enabled the system to compensate for atmospheric disturbances and maintain a stable beam over long distances [16].

In the 1990s, FSO technology began to be commercialized, with the first applications being in the telecommunications sector [17]. FSO systems were used to provide high-speed data links between buildings, eliminating the need for expensive fiber optic cabling [18]. The technology was also used in military applications, providing secure communication links that were resistant to interception. [19]

In recent years, FSO technology has gained renewed interest due to the rapid growth in data traffic and the need for high-speed communication links that can be quickly deployed [20]. FSO systems are seen as an ideal solution for providing high-speed links in urban environments where traditional cabling or RF systems are impractical or expensive [21]. One of the key areas of research in FSO technology is the development of more advanced directivity concepts. Directivity refers to the ability of the system to maintain a stable beam over long distances and in adverse weather conditions. Advanced directivity concepts such as beam steering and spatial filtering are being developed to enhance the performance of FSO systems and increase their range [22].

### 2.2 Distributed Satellite Systems Overview

Distributed satellite systems (DSS) are a type of satellite system that involves multiple small satellites working together to accomplish a common mission or objective. The idea behind DSS is to create a more flexible and cost-effective alternative to traditional monolithic satellite systems.



One of the key advantages of DSS is its ability to provide greater coverage and redundancy compared to monolithic satellite systems. By using multiple smaller satellites, DSS can be designed to cover a wider area and provide better global coverage. Additionally, the use of redundant systems ensures that if one satellite fails or experiences issues, other satellites can continue to provide service, reducing the risk of service disruptions. Another advantage of DSS is its flexibility in terms of mission configuration. DSS can be designed to perform a variety of missions, including Earth observation, communications, and scientific research. By using modular designs and standardized components, DSS can be easily configured and reconfigured to meet the specific needs of a mission.

DSS technology has been a topic of research for many years, and there have been numerous studies and experiments conducted to explore its feasibility and potential benefits. For example, the European Space Agency has conducted studies on DSS for Earth observation, with the aim of developing a low-cost alternative to traditional Earth observation satellite systems [23]. In recent years, there has been a growing interest in DSS for communication purposes, particularly for providing global internet connectivity. Companies such as SpaceX and OneWeb have launched or plan to launch large constellations of small satellites to provide internet connectivity to underserved areas around the world [24].

### 2.3 Advantages of using FSO over RF in space

There are noticeable differences between the two technologies but the former has its modern perks that makes it a suitable and more attractive alternative to the older RF based communication. These are;

1. FSO systems are highly optimized in the sense of power consumption. They consume much less power compared to RF-based communication systems because FSO systems use infrared light for communication, which requires less power to generate compared to RF signals.
2. FSO systems have higher directivity than RF based systems.
3. FSO systems offer significantly higher bandwidth compared to RF-based communication systems. This is because FSO systems operate in the optical spectrum, which has a much higher frequency range compared to RF. As a result, FSO can support higher data rates, making it ideal for applications that require high-speed data transfer.
4. FSO systems are Immune to electromagnetic interference. Radio waves are susceptible to EMI from other RF sources or electronic devices. This interference can cause signal degradation or complete loss of communication. FSO systems therefore are more reliable in space environments with with high EMI.
5. FSO signals experience low attenuation in the atmosphere, allowing them to travel long distances without significant signal loss. This is in contrast to RF signals, which can be absorbed, reflected, or scattered by obstacles such as buildings, trees, and hills.



6. FSO communication is highly secure because the optical signal does not penetrate walls or other solid objects. This makes it difficult for eavesdroppers to intercept the signal without being detected or secure data to be intercepted.
7. FSO systems can be less expensive to install and maintain compared to traditional RF-based communication systems. This is because FSO systems use off-the-shelf components such as lasers, detectors, and optical fibers, which are readily available and affordable, like it was used in this internship report.
8. FSO communication is a green technology because it does not require the use of radio waves, which can cause electromagnetic pollution. Additionally, FSO systems use less energy compared to RF-based communication systems, making them more environmentally friendly.

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## A. Appendix

### A.1 Propagator Model for Test Bench

There is an attempt to integrate a propagator model to the Test Bench setup so that the model will be able to feed in the ephemeral data directly to the Test Bench. That way, the test bench in essence can simulate the pointing of an example mission and verify the pointing process. The left window shows the a propagator model using the Two body method written in Python script where the inertial frame is in reference to ECI. The right window depicts the STK that verifies the performance of the same system with the standard Two Body propagator done on STK Free license.

