CCA – COMPETENCE CENTRE
HTL Anichstraße

Diploma Thesis / Diplomarbeit

3D Drone Tracking

Image-Driven 3D Drone Tracking employing Multiple Stations for Agricultural Use

Submitted by

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Abstract / Kurzfassung

This diploma thesis explores the development of a ground-based 3D drone tracking system that does not rely on expensive hardware installed on each drone. Three camera-equipped ground stations capture images of drones in flight, calculate their positions in three-dimensional space, and present the results in a user-friendly graphical interface. The project's main goal is to provide a more cost-effective alternative to traditional drone tracking systems, making the technology more accessible for applications such as agriculture, where high costs can be a limiting factor.

Central to this approach is a calibration routine, an approximation algorithm for calculating positions, and local data processing. Early experiments confirmed that relative station angles and coordinates can deliver valid tracking data. However, hardware issues — particularly with the chosen mini-computer — prevented the completion of a fully integrated prototype.

Despite these challenges, the concept demonstrates clear potential for drone tracking without the need for additional modules or external networks. Future improvements could focus on enhancing hardware reliability, developing a weatherproof housing, and further refining accuracy. Overall, this system establishes a foundation for a cost-effective alternative to conventional drone tracking methods and expands the possibilities for broader adoption in cost-sensitive applications.

Diese Diplomarbeit beschäftigt sich mit der Entwicklung eines bodengebundenen 3D-Drohnen-Tracking-Systems, das ohne teure, in der Drohne selbst

verbaute Hardware auskommt. Drei mit Kameras ausgestattete Bodenstationen erfassen Drohnen im Flug, berechnen ihre Position im dreidimensionalen Raum und stellen die Ergebnisse in einer benutzerfreundlichen grafischen Oberfläche dar. Ziel des Projekts ist es, eine kosteneffiziente Alternative zu herkömmlichen Drohnen-Ortungssystemen bereitzustellen und damit den Einsatz dieser Technologie insbesondere in Bereichen wie der Landwirtschaft zu ermöglichen, wo hohe Kosten oft eine Hürde darstellen.

Das Konzept basiert auf einer präzisen Kalibrierung der Stationen, einem Algorithmus zur Positionsberechnung sowie einer lokalen Datenverarbeitung direkt in den Bodenstationen. Erste Tests zeigten, dass sich durch die Winkel- und Distanzmessung zwischen den Stationen eine zuverlässige Grundlage für die Ortung schaffen lässt. Allerdings verhinderten technische Probleme – insbesondere mit dem verwendeten Mini-Computer – die Umsetzung eines vollständig integrierten Prototyps.

Trotz dieser Herausforderungen zeigt das entwickelte Konzept deutlich, dass eine zuverlässige Drohnenortung ohne zusätzliche Module oder externe Netzwerke machbar ist. Künftige Weiterentwicklungen könnten sich auf eine robustere Hardware, ein wetterfestes Gehäuse und eine höhere Genauigkeit konzentrieren. Insgesamt bildet diese Arbeit die Grundlage für eine kostengünstige Alternative zu bestehenden Tracking-Systemen und eröffnet neue Möglichkeiten für eine breitere Nutzung der Drohnentechnologie.

Erklärung der Eigenständigkeit der Arbeit

EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche erkenntlich gemacht habe. Zur sprachlichen und strukturellen Verbesserung wurde das generative KI-Tool ChatGPT als unterstützendes Werkzeug verwendet. Meine Arbeit darf öffentlich zugänglich gemacht werden, wenn kein Sperrvermerk vorliegt.

Ort, Datum Verfasser 1

Ort, Datum Verfasser 2

Contents

1 Introduction

This diploma thesis focuses on developing a ground-based 3D drone-tracking system that avoids the need for specialized onboard hardware. By combining three calibrated stations with local image processing, the system aims to provide a cost-effective alternative for operators who prefer not making any modifications to standard drones. The core research question is whether such a fully ground-based setup can deliver reliable positional data without raising the complexity or costs of each aircraft.

Our motivation arises from an interest in aerial systems and tracking technologies, particularly in settings where budget constraints limit the viability of advanced equipment. By integrating custom hardware design, minimal calibration procedures, and flexible software solutions, we intend to create a practical infrastructure for various applications.

The thesis is organized as follows: “Detailed Task Description” clarifies specific objectives, responsibilities, and deliverables, defining the scope of work. “State of the Art: Market Analysis” then reviews existing commercial and research-based drone-tracking methods, underlining opportunities for saving costs and technical advantages. Next, the “Solution Idea” describes planned hardware, calibration, and networking strategies. The “Solution” chapter discusses practical implementation steps, including prototype testing and preliminary findings. Finally, the "Conclusion" discusses remaining limitations, and proposes directions for future enhancement.

1.1 Detailed Task Description

Main goal: Track drones with multiple ground stations

1.1.1 Hardware

1.1.1.1 Computer

Responsible: Krahbichler Lukas

Select hardware capable of efficiently handling the required image processing.

1.1.1.2 Camera

Responsible: Krahbichler Lukas

Select, acquire, and set up a suitable camera.

1.1.1.3 Display

Responsible: Krahbichler Lukas

Select and integrate a display for visualization, ensuring compatibility with other hardware components.

1.1.1.4 Power Supply

Responsible: Krahbichler Lukas

Design or select a power supply system that meets the requirements of all hardware components to ensure stable and efficient operation.

1.1.1.5 Data Transfer

Responsible: Krahbichler Lukas

Select and test a secure and fast communication medium for data transfer between the stations.

1.1.1.6 Calibration

Responsible: Krahbichler Lukas

Select and integrate calibration hardware essential for precise positioning and synchronization of the stations.

1.1.2 Housing

Responsible: Prantl Niclas

Design, test, and build housing for the primary station and secondary stations, incorporating all components.

1.1.3 Programming

1.1.3.1 Development Environment

Responsible: Prantl Niclas

Ensure a consistent and efficient development setup.

1.1.3.2 Hardware Drivers

Responsible: Prantl Niclas

Develop a modular and reliable driver system.

1.1.3.3 Calibration

Responsible: Krahbichler Lukas

Create software to perform calibration procedures, accurately calculating relative positions and rotations of the stations.

1.1.3.4 Camera Tracking

Responsible: Krahbichler Lukas

Implement software to track drones within the camera's output stream.

1.1.3.5 Data Transfer

Responsible: Krahbichler Lukas

Develop and implement a system to synchronize data transfer from secondary stations to the main station.

1.1.3.6 3D Angle Calculations

Responsible: Prantl Niclas

Develop algorithms to calculate drone positions based on data from the stations.

1.1.3.7 3D Visualization

Responsible: Prantl Niclas

Program a 3D visualization interface to display tracked drones, integrating data from all stations.

2 State of the Art: Market Analysis

2.1 Industry Overview and Market Potential

Drones are transforming agriculture by offering innovative solutions to enhance efficiency and sustainability. As reported by Chaundler in The New York Times [10], companies like CO2 Revolution [9] are using drones to plant seeds in inaccessible areas, showcasing the potential of drone technology in reforestation and agricultural applications.

The global agricultural sector faces significant challenges, including the need to increase food production to meet the demands of a growing population and to address the impacts of climate change [31]. Traditional farming methods are often insufficient, leading to a surge in the adoption of drones for various agricultural purposes.

2.1.1 Applications of Drones in Agriculture

Drones are used in agriculture for a wide range of applications:

- **Crop Monitoring and Mapping:** Drones can provide high-resolution aerial imagery, enabling farmers to monitor crop health, identify pest infestations, and assess soil conditions in real-time [31, 46].
- **Precision Spraying:** With precise positioning, drones can apply fertilizers, pesticides, and herbicides precisely where needed, reducing chemical usage and minimizing its environmental impact [21, 11].

- **Irrigation Management:** Drones assist in detecting variations in soil moisture levels using thermal cameras, helping optimize irrigation systems and conserve water resources [31].
- **Planting and Seeding:** Some drones are designed to plant seeds over large areas efficiently, particularly useful in reforestation efforts and hard-to-reach terrains [10].

2.1.2 Market Growth and Potential

The agricultural drone market is experiencing significant growth. Valued at $0.88 billion in 2020, it is projected to reach $5.89 billion by 2030, with a compound annual growth rate (CAGR) of 22.4% [46]. Key factors contributing to this growth include:

- **Demand for Increased Food Production:** Global population growth drives the need for higher agricultural output, encouraging the adoption of efficient technologies like drones [31].
- **Technological Advancements:** Improvements in drone capabilities, such as enhanced sensors and longer flight times, make them more practical for agricultural applications [21].
- **Adoption of Precision Farming Techniques:** Farmers are increasingly using drones for site-specific crop management to optimize resource use and increase yields [46].

2.1.3 Challenges and Opportunities

While the potential is significant, the adoption of drones in agriculture faces several challenges:

- **Regulatory Barriers:** Strict government regulations on airspace and drone operations can hinder deployment [31].
- **High Initial Costs:** The expense of acquiring and maintaining advanced drones may be prohibitive for small-scale farmers.

- **Privacy and Safety Concerns:** The use of drones can raise privacy issues and pose safety risks to people and animals if not operated correctly [28].

Our solution addresses these challenges by offering cost-effective drone tracking systems that reduce initial costs by eliminating the need for expensive onboard navigation systems. By utilizing ground-based tracking, the drones used for our system can be simpler and more affordable, enhancing operational safety and accessibility for small-scale farmers. Moreover, we can leverage government support initiatives like Austria's "Smart Farming" action plan, which provides funding and resources to integrate digital technologies into agriculture [8]. Additionally, implementing privacy and safety features such as geofencing and privacy-by-design principles ensures compliance with regulations and builds trust among users [39].

2.2 Target Group Definition

Our ideal customers are small to medium-sized agricultural enterprises, individual farmers, and agricultural cooperatives with limited budgets. They seek cost-effective solutions to modernize their farming operations with drone technology without the high expenses associated with advanced onboard systems.

Key Characteristics

- **Demographics**: Farmers and managers aged 35–60 with practical experience in agriculture, often fitting the "Progressive Realists" or "Adaptive-Pragmatic Middle Class" Sinus-Milieus [44].
- **Geographics**: Located in rural agricultural regions such as Lower Austria, Styria, Upper Austria, and Tyrol.
- **Psychographics**: Value efficiency, sustainability, and are open to adopting new technologies that improve their farming practices.
- **Behavioral**: Make purchase decisions based on cost-benefit analysis, attend local agricultural events, rely on recommendations from peers and local networks.

- **Needs**: Affordable and reliable drone tracking systems that are easy to implement and help optimize farming operations.
- **Technographics**: Moderate technological proficiency, use basic agricultural management tools, interested in user-friendly technology solutions.

2.3 Buyer Personas

Persona 1 (Core): Thomas Bauer

- **Age**: 52
- **Role**: Owner of a medium-sized family farm
- **Location**: Lower Austria
- **Goals**: Increase crop yields and operational efficiency through affordable technology
- **Pain Points**: Limited budget for high-end drones; needs cost-effective tracking solutions that don't require extensive technical expertise
- **Behavior**: Reads local agricultural journals, attends regional farming expos, values practical and easy-to-use solutions

Persona 2 (Core): Maria Hofer

- **Age**: 40
- **Role**: Owner of a small organic farm
- **Location**: Graz, Styria
- **Goals**: Implement sustainable farming practices with the help of affordable technology
- **Pain Points**: Needs reliable tracking solutions that align with organic farming principles; constrained by a tight budget
- **Behavior**: Active in local farming communities, follows agricultural trends online, seeks eco-friendly and cost-effective solutions

Persona 3 (Peripheral): Andreas Schneider

- **Age**: 55
- **Role**: Manager of a farming cooperative

- **Location**: Upper Austria
- **Goals**: Enhance productivity for cooperative members through shared resources and technology
- **Pain Points**: Finding affordable technology solutions that can be easily adopted by multiple farmers with varying levels of technical skill
- **Behavior**: Engages with cooperative members, attends agricultural seminars, values solutions that offer collective benefits

2.4 Competitor Analysis

The agricultural drone market in Austria and globally is highly competitive, with key players offering advanced precision farming solutions. This analysis focuses on three major competitors relevant to the Austrian market:

1. **Dronetech by Immotech (Austria):** Dronetech partners with Huawei to develop 5G-enabled smart farming drones. They modify DJI drones, already equipped with Global Navigation Satellite System (GNSS), Real-Time Kinematic (RTK), and obstacle avoidance cameras, adding custom 3D-printed parts to optimize them for agricultural needs [20, 18]. Enhancements include high-resolution cameras and sensors, leveraging Huawei's cloud computing and Artificial Intelligence (AI) for real-time data analysis. This enables precise application of water, fertilizers, and pesticides, reducing waste and environmental impact. A key challenge they face is limited 5G network coverage [23, 22, 24].
2. **DJI - Da-Jiang Innovations Science and Technology Co. (China):** DJI, a global drone leader, offers expensive high-tech agricultural drones like Agras T50, T25, and Mavic 3M for tasks such as spraying, mapping, and crop monitoring. They use GNSS and RTK for precise positioning, radar and vision sensors for obstacle avoidance, and Radio, Wireless Fidelity (WiFi), and Bluetooth for communication. Accessories like DJI Relay enhance their range in complex environments [16, 17]. In Austria, partners like Drohnenring distribute DJI's products, offering consultation, sales, training, and support [19].
3. **AgEagle Aerial Systems Inc. (United States of America (USA)):** AgEagle specializes in agricultural mapping drones like eBee X. Equipped

with GNSS and RTK, they achieve centimeter-level accuracy without ground control points. They communicate via radio links up to 3 km with secure encryption. Light Detection and Ranging (LiDAR) sensors provide obstacle avoidance and controlled landings. AgEagle offers software like eMotion and Measure Ground Control for flight planning and data processing [2, 1].

2.4.1 Competitive Landscape

The Austrian agricultural drone market includes local firms like Dronetech, partnering with global tech companies, and international players like DJI and AgEagle, offering advanced drone technology and services. Competition centers on integrating cutting-edge technologies like 5G, AI, GNSS/RTK positioning, and advanced imaging to enhance precision farming. Competitors offer sophisticated communication systems, precise positioning, and advanced software solutions to meet modern agriculture's needs.

2.4.2 Our Differentiation and Positioning

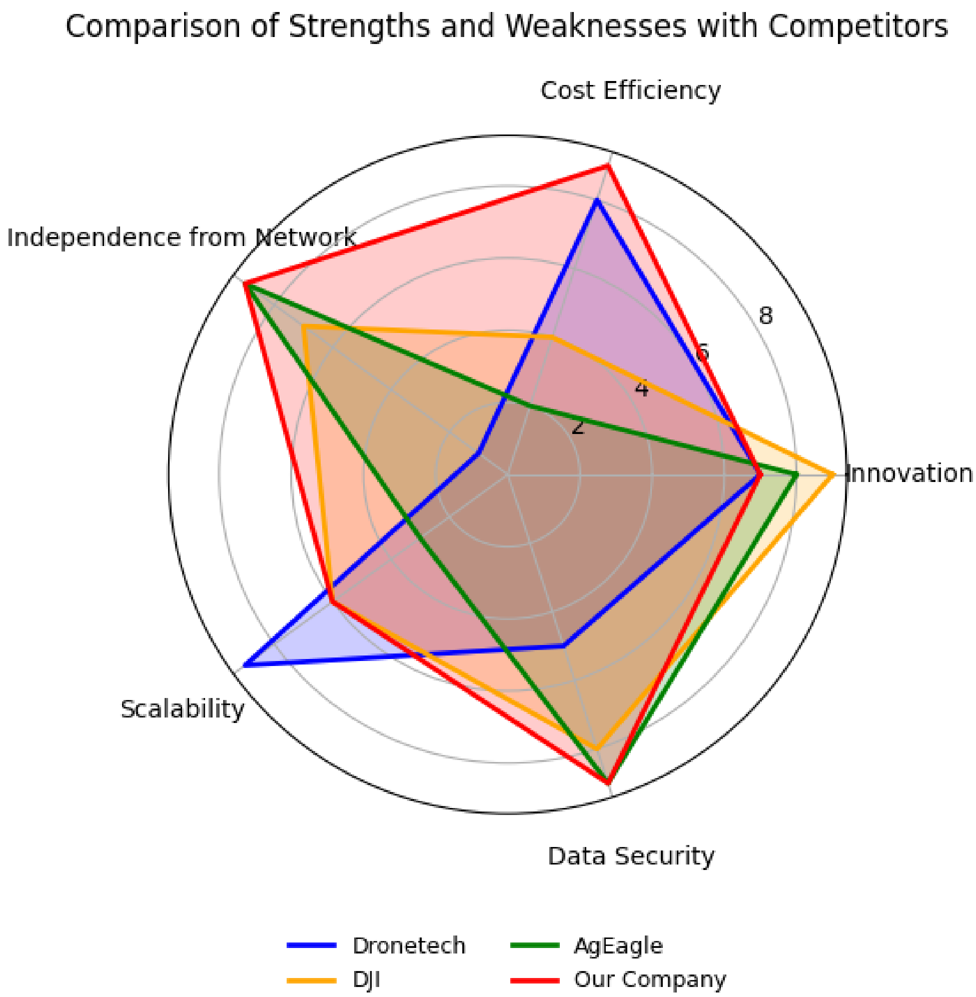

Figure 1: Comparison of strengths and weaknesses with competitors

Source: Own illustration created with Matplotlib in Python

Our ground-based 3D drone tracking system offers an affordable and independent solution for Austria's agricultural sector. By using calibrated ground stations with advanced image processing, we eliminate the need for expensive onboard positioning and obstacle avoidance systems. This allows to deploy simpler drones, reducing costs, maintenance complexities, and payload restrictions. As a result, small to medium enterprises can access modern drone technology, overcoming challenges like network coverage limitations and high equipment costs, making it a practical tool for improving farming operations without substantial investment.

Our approach provides several key benefits:

- **Enhanced Efficiency and Cost Savings:** Without heavy onboard sensors, drones are lighter and consume less energy, thus increasing flight times and coverage area. They can carry more payloads like seeds, fertilizers, or pesticides, enhancing operational efficiency. Reduced complexity lowers maintenance and failure risk, leading to cost savings and making precision agriculture accessible to farmers with limited budgets.
- **Secure, Independent Communication:** Our local communication system operates independently of network infrastructure, ensuring reliability in areas with connectivity issues. Unlike competitors relying on 5G, our system enhances reliability, data security, and privacy by processing tracking data locally.
- **Scalability and Flexibility:** Our ground stations can track multiple drones simultaneously without adding complexity or weight to drones. This enables scalable operations, allowing farmers to expand fleets without significant additional investment.

2.5 Conclusion

The market analysis reveals a significant opportunity for our ground-based 3D drone tracking system in the agricultural sector. As drone adoption in agriculture accelerates, our solution addresses key challenges like high costs, dependence on network infrastructure, and the complexity of onboard systems by eliminating the need for expensive onboard positioning, and obstacle avoidance equipment. By enabling the use of simpler, more affordable drones with increased payload capacity and simplified maintenance, we offer a unique value proposition that differentiates us from competitors relying on complex onboard technologies. Our system aligns with the needs of small to medium agricultural enterprises seeking efficient and sustainable technologies without the barriers of high initial investment and technical complexity. Further research and engagement with industry stakeholders will refine our understanding of target customers and support a successful market entry, positioning us as a competitive player in the agricultural drone market focused on accessibility and practicality.

3 Solution Idea

3.1 Hardware

3.1.1 Computer

The core idea is to perform image processing locally on each unit, thereby eliminating the need to transmit large volumes of raw image data to a central processing unit. This decentralized approach reduces the complexity of high-bandwidth data transfers and ensures that only the essential results, such as computational outputs, are transmitted. By evaluating single-board computers, the goal is to identify a cost-effective option that provides sufficient computational power for these local tasks. This approach not only streamlines data flow but also enhances scalability and independence between the stations.

3.1.2 Camera

The selected camera must be compatible with the chosen single-board computer. A 4K camera is proposed, as a higher resolution theoretically extends the effective range of tracking. This choice balances precision and affordability, ensuring the system's effectiveness without unnecessary costs.

3.1.3 Display

The primary station will include a display for visualizing tracked drone data. The graphical user interface (GUI) is one of the system's primary goals and will be developed as part of the programming section. The parameters for the display, such as resolution (Full HD) and size (8 to 12 inches), are secondary considerations compared to compatibility and affordability. To reduce costs, the display will only be included in the primary station, ensuring that it provides sufficient functionality for monitoring without adding unnecessary expenses.

3.1.4 Power Supply

The proposed solution involves using an off-the-shelf power bank system to supply energy to all components, including the single-board computer, camera, display, and calibration hardware. This approach avoids the complexity of designing and building a custom power supply, saving development time and effort. The power bank should have adequate output to power all components reliably and sufficient capacity to operate the system for a reasonable duration, although extended battery life is not a primary focus.

3.1.5 Data Transfer

The idea is to implement local radio communication as the primary data transfer medium between the stations. This ensures independence from external networks, such as cellular systems, enhancing both security and operational reliability.

3.1.6 Calibration

Calibration determines the relative positions and rotations of the ground stations, essential for accurate 3D drone tracking. Unlike competitors who use GNSS with RTK, our system aims to achieve similar precision through a more cost-effective and fully local approach.

The calibration hardware, integrated onto a custom Printed Circuit Board (PCB), could include:

- Power Delivery
- Time-of-flight (ToF) Laser
- Communication modules
- Stepper motors
- Servo motors
- Gyroscope/Magnetometer/Accelerometer (9 Degrees of Freedom (9DoF))
- End switches
- Microcontroller

During calibration, approximate directions could be determined using the communication system, supplemented by precise distance measurements from a ToF laser.

3.2 Housing

The initial proposition of the housing focuses on the following principles:

- Sturdiness
- Size
- Airflow (Cooling) for the Computer

3.3 Programming

3.3.1 Development Environment

A containerized Debian-based development environment is proposed to standardize dependencies and prevent system-specific issues.

3.3.2 Hardware Drivers

The software should be structured to efficiently manage hardware responsibilities.

3.3.3 Calibration

The calibration process is intended to determine the relative positions and orientations of the ground stations. The calibration hardware will be used for measurements.

3.3.4 Camera Tracking

Being the key element in this project, the cameras should be able to detect and track drones mid air and calculate their relative angle to the ground station. By already knowing the angle the camera is facing, this can be done by reversing the fish-eye effect of the camera and then multiplying the relative x and y position in the image by the cameras field of view (FOV).

3.3.5 Data Transfer

The data transfer system should enable communication between ground stations for synchronization and tracking. A structured protocol is proposed to ensure fast and reliable message transmission.

3.3.6 3D Angle Calculations

Having already calculated the relative angles for each ground station, the individual angles are being combined by using simple trigonometry.

3.3.7 3D Visualization

Decoupled from the tracking logic, the visualization module retrieves positional data through network sockets. It provides a comprehensive real-time display of all three ground stations and their respective cameras. When a target is detected, the system dynamically renders lines extending from each station to the target, visually representing the tracking process. Additionally, a sphere is displayed at the calculated target position, with its size indicating the accuracy of the estimation, ensuring clear situational awareness.

4 Solution

4.1 Hardware

4.1.1 Computer

Several single-board computers were evaluated for this project:

- **NVIDIA Jetson Nano:** Offers strong AI capabilities but is more expensive and exceeds project requirements [35].
- **ASUS Tinker Board S:** Affordable but lacks sufficient computational power for real-time image processing [5].
- **ArmSom Sige7 (Basic):** Balances affordability and performance, supporting necessary image processing tasks [43].
- **Raspberry Pi 4 Model B (8 GB):** Well-supported but has less processing power for image processing compared to other options [38].

The ArmSom Sige7 Basic [43], equipped with a Sige Active Cooling Kit [42], as shown in Fig. 2, was chosen for its adequate performance and cost-effectiveness. However, during development, issues arose: one of the three units failed to boot, and limited documentation and support made troubleshooting difficult. In hindsight, selecting a more widely adopted platform like NVIDIA [35], ASUS [5], or Raspberry Pi [38] would have offered greater reliability and community support.

In the end, this hardware failure was one of the main reasons the project was not fully completed, along with time constraints that prevented further troubleshooting or contacting the manufacturer, and the high costs associated with hardware replacement.

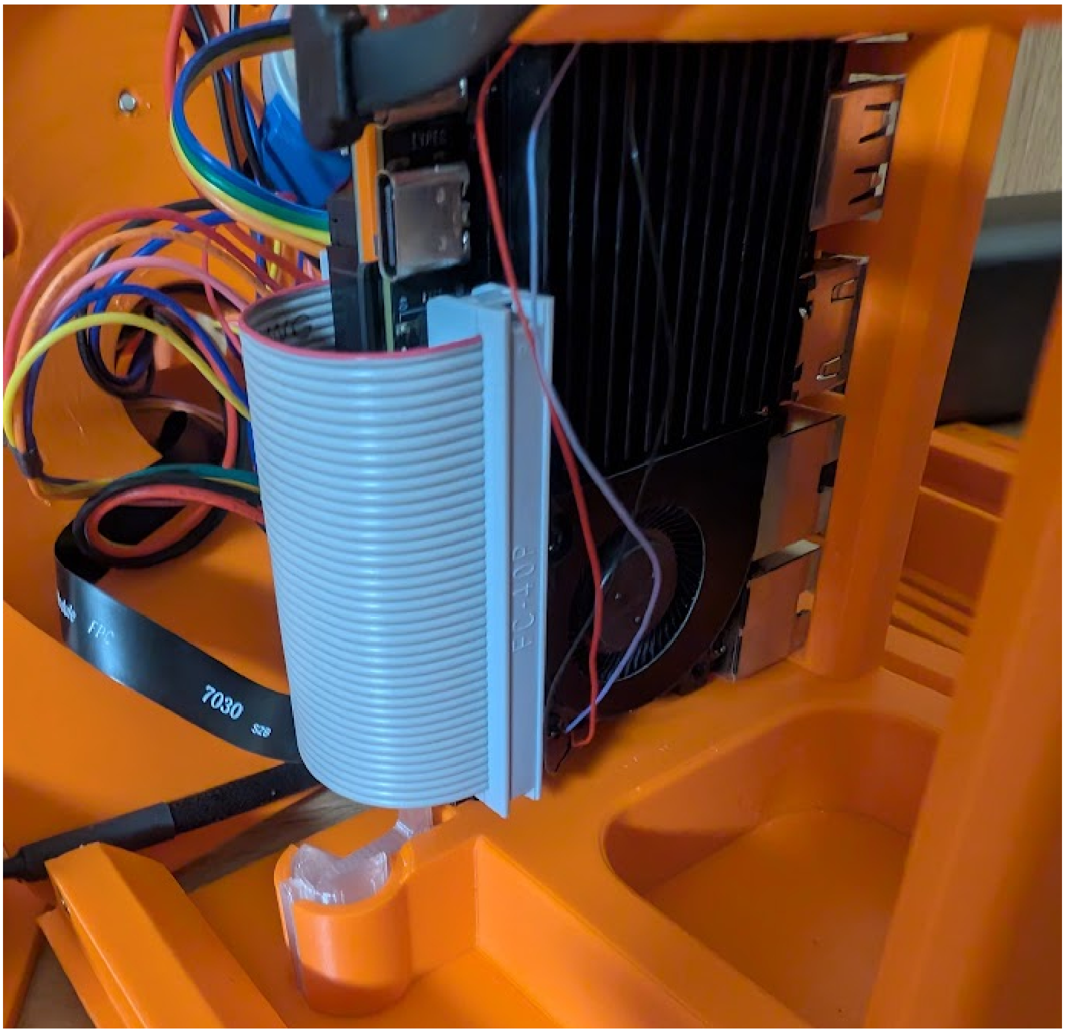

Figure 2: An ArmSom Sige7 Basic, equipped with a Sige Active Cooling Kit, mounted in a secondary station

For heat management, a Noctua NF-A8 5V PWM fan will be integrated into the station to improve cooling performance [32].

4.1.2 Camera

The camera module chosen is ArmSom's 4K model [40], as shown in Fig. 3, specifically designed for seamless integration with the ArmSom Sige7 [43]. This ensured full hardware compatibility and eliminated potential issues with third-party components. The module was selected for its high resolution of 4K, which allows for better tracking accuracy at greater distances. However, during testing, the camera initially produced very dark images. This was traced back to a driver issue, which was quickly resolved with support from the manufacturer.

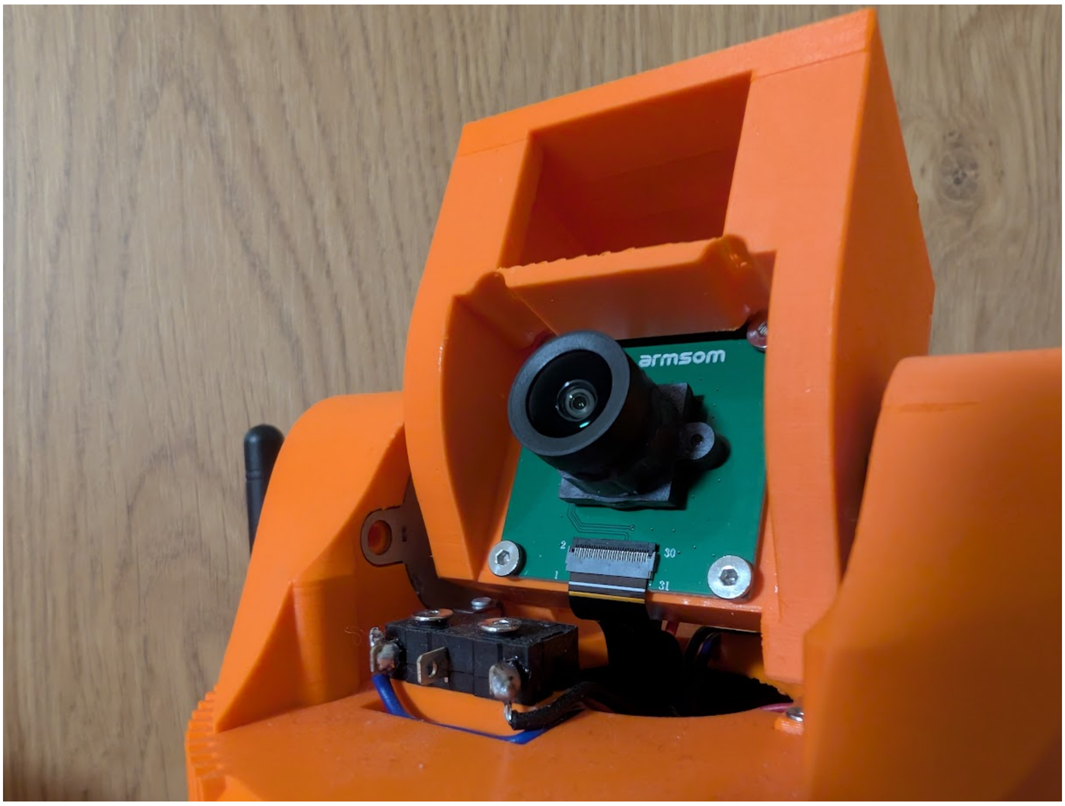

Figure 3: ArmSom's 4K camera integrated into the finalized secondary station

4.1.3 Display

Initially, ArmSom's 10.1-inch Full HD display [41] was integrated into the primary station. The display was chosen for its compatibility with the ArmSom Sige7 [43] and its reasonable price. However, as the project progressed, a redesign of the housing made its removal necessary. Redirecting the visualization to a laptop allowed for a more compact and efficient housing design. This redesign, including the version with the display, is described in detail in Section 4.2.2.

4.1.4 Power Supply

The chosen power supply was a PD 100 W, 20,000 mAh power bank from POWERADD PRO [37] with three Universal Serial Bus (USB) ports. This model met the project's technical requirements as follows:

- Its two USB-C ports support USB Power Delivery (USB-PD), which is essential for powering the ArmSom Sige7 [43]. The ArmSom is connected to the top-left port, as shown in Fig. 4.
- Its 100W output ensures compatibility with all connected components, including the PCB. The PCB is connected to the USB-A port at the bottom left, as shown in Fig. 4.
- It includes three ports, enabling simultaneous connections for the ArmSom board, the PCB, and charging functionality via the unused USB-C port at the top right, as shown in Fig. 4.

Figure 4: Power bank integrated into the finalized secondary station

Despite meeting these specifications, several issues arose while using the power bank. It exhibited unpredictable behavior, intermittently switching on and off. While this occurred less frequently when the power bank was fully or nearly fully charged, the problem was never completely resolved. Additionally, unexpected voltage drops were observed on the PCB, with measurements showing 3.6V instead of the expected 5V from the USB output. This raised concerns about power stability and its impact on system reliability. Furthermore, it is highly likely that our ArmSom computer [43] failed due to unstable voltage levels or power spikes originating from the power bank, though this could not be definitively confirmed. The failure of the ArmSom computer is discussed in more detail in Section 4.1.1.

Additionally, with this setup, the station has two start buttons - one for the power bank and one for the ArmSom - which is not particularly user-friendly.

4.1.5 Data Transfer

Initially, the NRF24L01 [33] modules with PCB antennas, as shown in Fig. 5, were integrated directly onto the PCB to enable local radio communication between stations. However, these modules proved unreliable in the required 3-node mesh system, frequently failing to maintain a stable communication.

To resolve this, the system was upgraded to NRF24L01+ PA + LNA [34] modules with external antennas, as shown in Fig. 6. This change improved signal strength but required modifications to the housing design to accommodate the larger modules. The PCB remained unchanged due to the identical pinout, but the new modules were too large to be mounted directly. Instead, they had to be repositioned and connected via jumper cables.

During testing, the mesh network continued to exhibit failures or functioned only when as were placed in specific orientations. Further research indicated that the high transmission power of the new modules caused interference in close-range operation. Reducing the transmission power resolved these stability issues, allowing the modules to function reliably within the system.

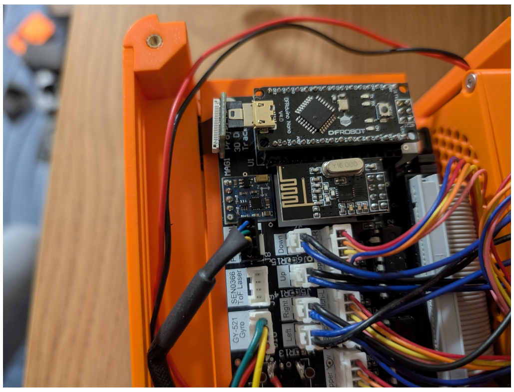

Figure 5: Secondary station with NRF24L01 modules with PCB antennas

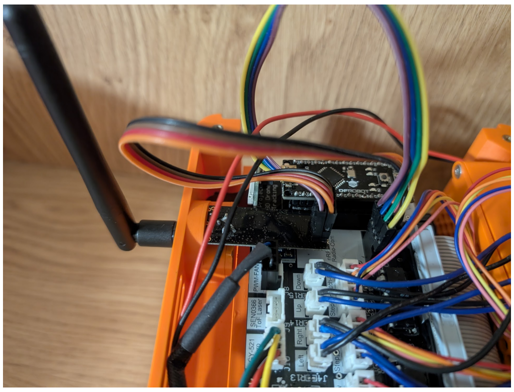

Figure 6: NRF24L01+ PA + LNA [34] modules with external antennas

4.1.6 Calibration

The calibration hardware ensures precise alignment and positioning of the primary and secondary stations for 3D tracking. Each station features a rotatable head for pitch and yaw adjustments, while roll is compensated via gyroscope measurements. Secondary stations share the same design for simplicity, but only the primary station includes a ToF laser for precise distance measurement. Secondary stations rely on camera-based alignment.

Components and Functionality

Rotatable Head (Pitch and Yaw Axes): The system uses compact three 28BYJ-48 stepper motors controlled via ULN2003 drivers [4]. The yaw axis stepper is visible below the gear, and the two pitch axis steppers are positioned on the left and right sides of the head, as shown in Fig. 7. Every station uses four end-switches from InduSKY [25], configured in normally closed mode to detect faults like loose connections. The end-switches are to the left and right of the yaw axis stepper and below the head, as shown in Fig. 7. Servos [30] were initially considered but dismissed due to cost, size, and complexity.

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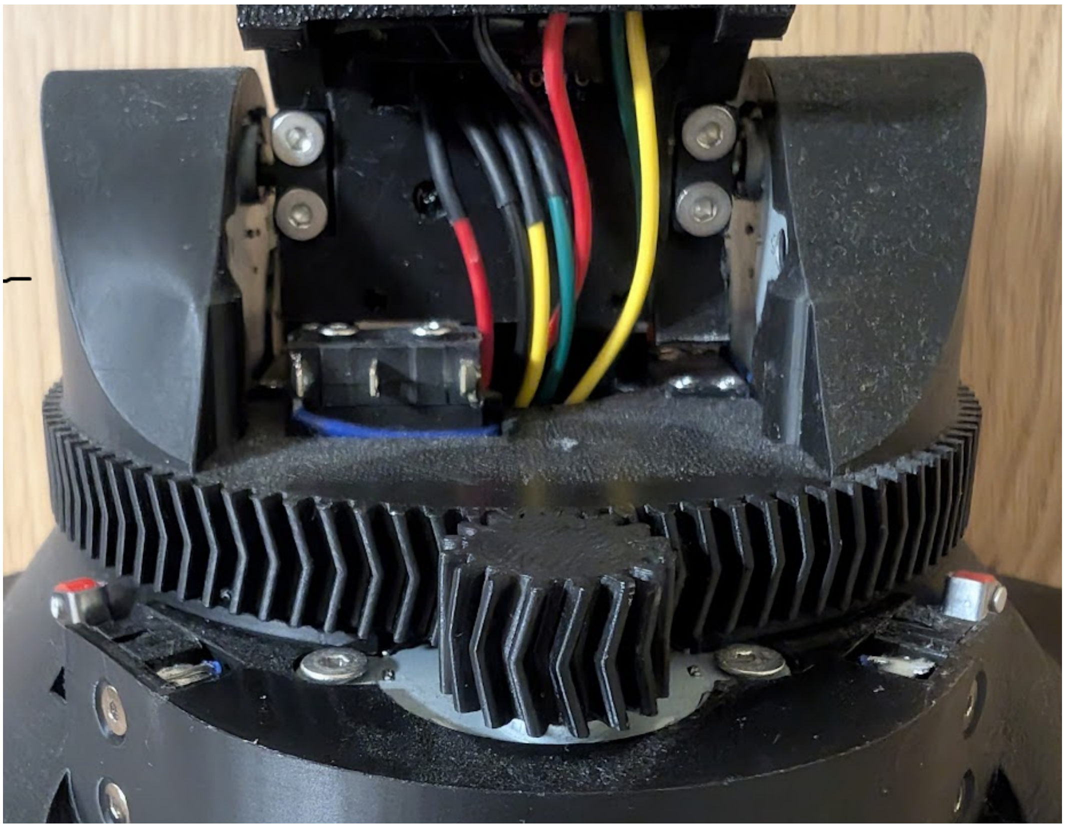

Figure 7: Rotatable head with gear mechanisms of final housing version

Gyroscope and Compass: Initially, we attempted to use a **9DoF sensor module** [48] that integrated a 3-axis 12-bit accelerometer, a 3-axis earth magnet sensor, and a 3-axis 16-bit gyroscope. However, the gyroscope did not function at all, while the accelerometer and magnetometer failed to provide correct data. The earth magnet sensor, in particular, delivered inconsistent readings, fluctuating significantly between measurements and rendering it unreliable for absolute orientation.

As a result, we switched to a **GY-521 gyroscope** [7], which provides 6-axis data for tilt measurement and alignment correction. Additionally, a **GY-271 compass** [6] was initially included for absolute orientation but was later abandoned due to unreliable calibration and inconsistent results. The compass remains on the PCB, as shown in Fig. 9 and 5, but is not actively used in the system.

ToF Laser Module: The primary station features a DFRobot Infrared Laser Distance Sensor [14] with a 5 centimeters to 80 meters range and millimeter-level accuracy. It is used for precise distance measurements and requires an unobstructed line of sight between the stations. Its integrated into the head, positioned above the camera, as shown in Fig. 8.

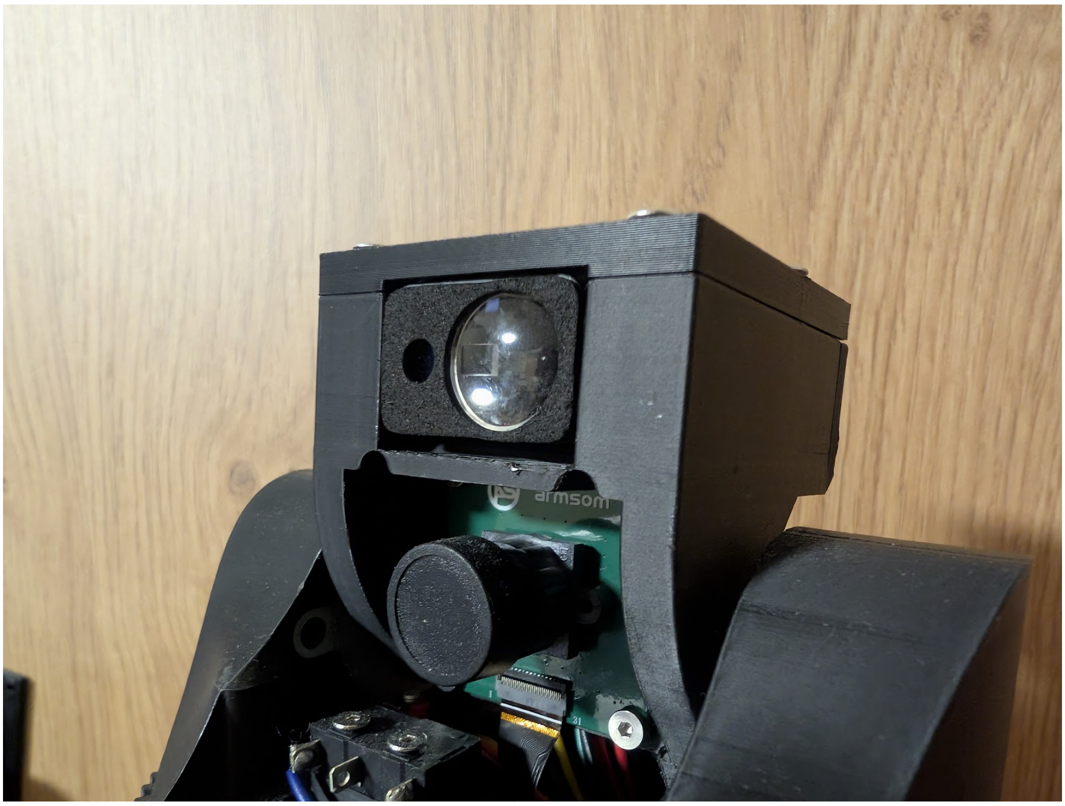

Figure 8: Head of final primary station

Camera for Visual Alignment: Each station's 4K camera [40], located below the ToF laser module, as shown in Fig. 8, identifies and aligns with other stations during calibration. The cameras should track the bright orange secondary stations for positioning, replacing the originally planned but unreliable radio-based direction-finding approach with Long Range (LoRa) modules [45].

PCB: The calibration system relies on a custom-designed PCB, as shown in Fig. 9 and 10, to integrate various components necessary for precise positioning and alignment. The PCB was designed using **Altium Designer 22.11.1** [3], with components sourced from **DigiKey** [15] and the board itself manufactured by **JLCPCB** [27]. Assembly was completed both in the school's workshop and at home.

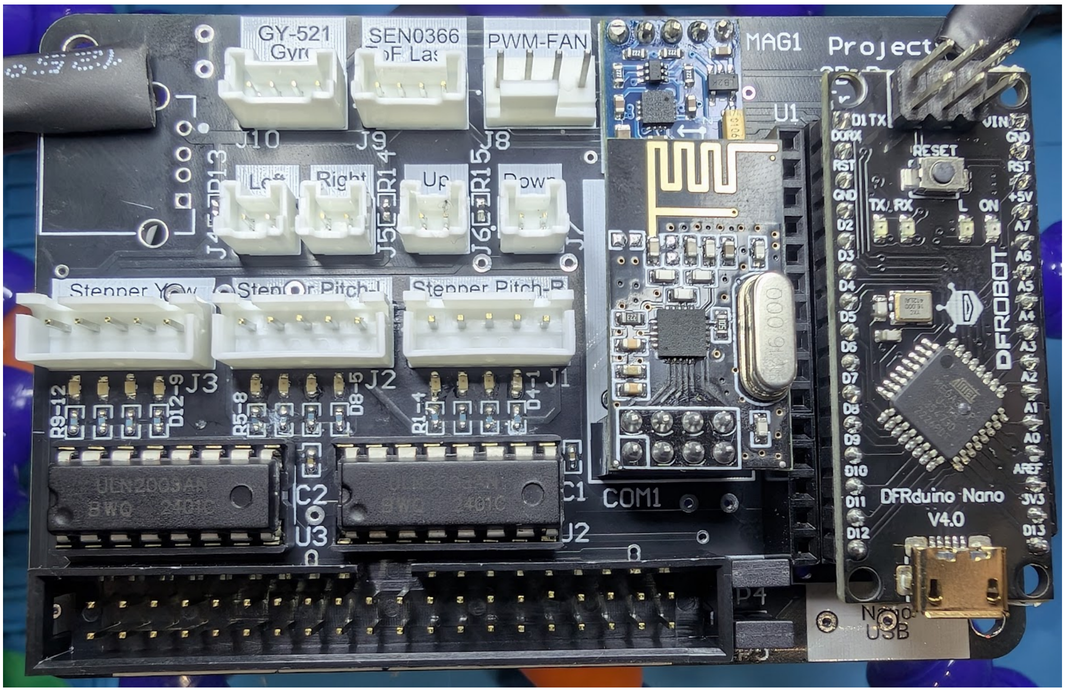

Figure 9: Assembled and soldered PCB with Arduino Nano [12] facing in the wrong direction

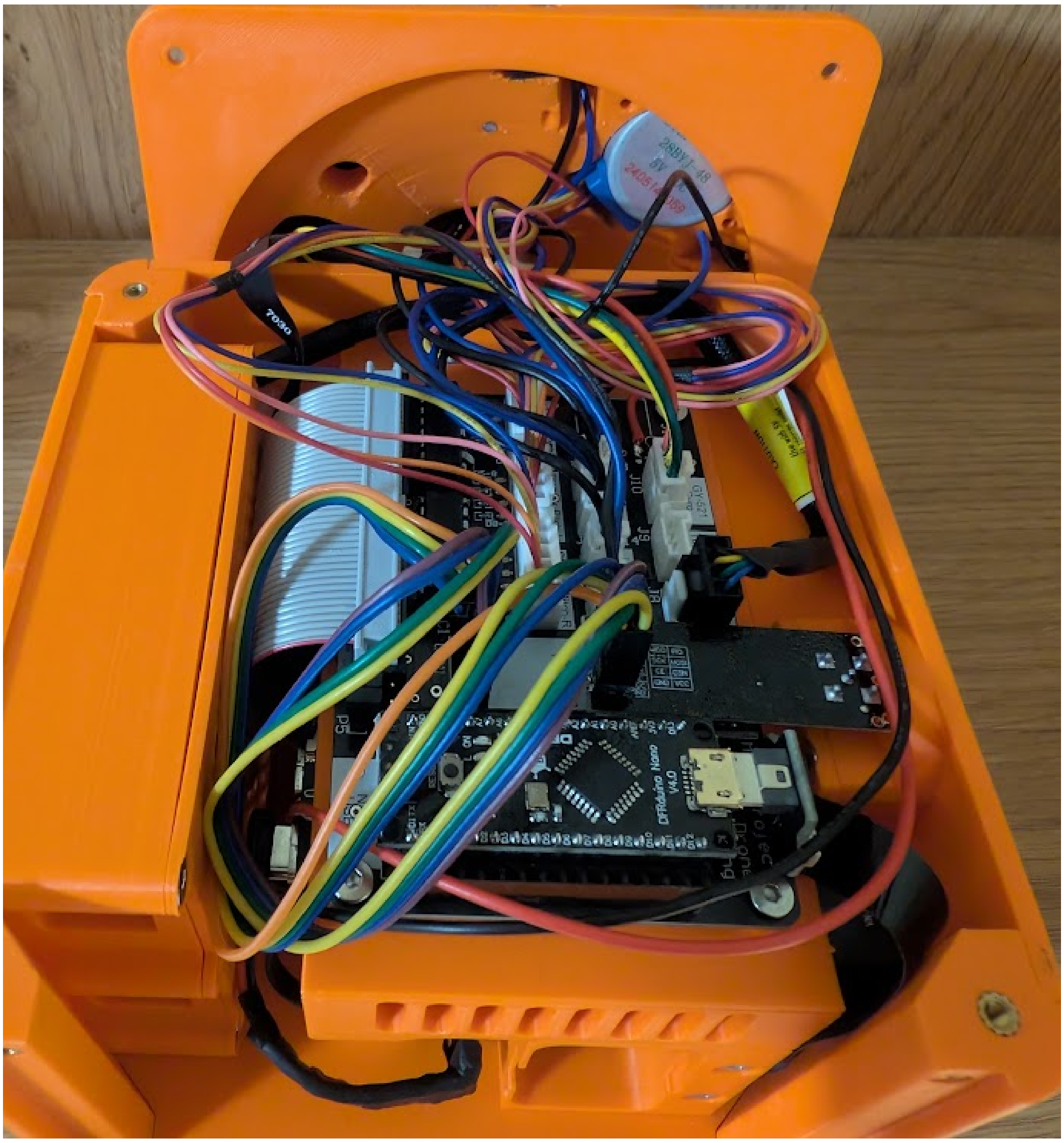

Figure 10: PCB integrated into the final secondary station with all connections except for the laser [14], which secondary stations do not have

The PCB incorporates an **Arduino Nano** by DFRobot [12] as the main microcontroller, as shown in Fig. 9 and 10. However, during development, we encountered program storage limitations, restricting the complexity of the firmware. In hindsight, selecting a microcontroller with more program storage, such as the **Arduino Uno R3** [13], would have provided more flexibility and might have prevented these constraints.

Key Functions of the PCB:

- Provides power distribution to the calibration components.
- Interfaces with the stepper motor drivers for head rotation control.
- Integrates the gyroscope, compass, and ToF laser module.
- Facilitates Light Emitting Diode (LED) indicators for status feedback.

Issues Encountered During Development:

- The **USB input connector** was never soldered, as the cable did not fit inside the housing. Instead, one red and one black wire were soldered directly to the board. As shown in Fig. 10, they are running from the back right of the PCB, around it, and down to the power bank at the front left.
- The **Arduino orientation** in Altium was incorrect, causing the microcontroller to be mounted in the opposite direction than intended. As a result, cable management in the housing design had to be adjusted. As shown in Fig. 10, the microcontroller's USB port faces right, whereas in the production documents it faces the opposite direction.
- The **LED on/off switching functionality** did not work as intended, requiring two additional manual connections to be made on each PCB.
- The **Communication between the Arduino Nano [12] and the ArmSom Sige7 [43]** was initially planned via Inter-Integrated Circuit (I2C). However, this did not work as expected. After unsuccessful troubleshooting attempts, we switched to Universal Asynchronous Receiver Transmitter (UART) communication. This change caused issues with the camera, as both systems could not run simultaneously. Ultimately, we resolved this by using a direct USB connection, running a cable from a USB-A port on the ArmSom board to the Micro-USB port on the Arduino Nano.

Despite these issues, the PCB successfully serves as the central interface for calibration hardware, integrating all necessary sensors and controllers to facilitate the calibration process.

Calibration Hardware Conclusion

While the calibration system was designed to reduce costs compared to GNSS with RTK, the final implementation became expensive. In hindsight, the cost was close to that of RTK-based alternatives used by competitors.

4.2 Housing

4.2.1 First Version

The initial housing design, as shown in Fig. 11, was developed before all hardware components were physically available, relying exclusively on online specifications and measurements provided by the manufacturers. While this approach enabled early prototyping, it also introduced dimensional inaccuracies. One of the most notable issues was an incorrectly sized display cutout, which required significant adjustments and a complete reprint of the housing.

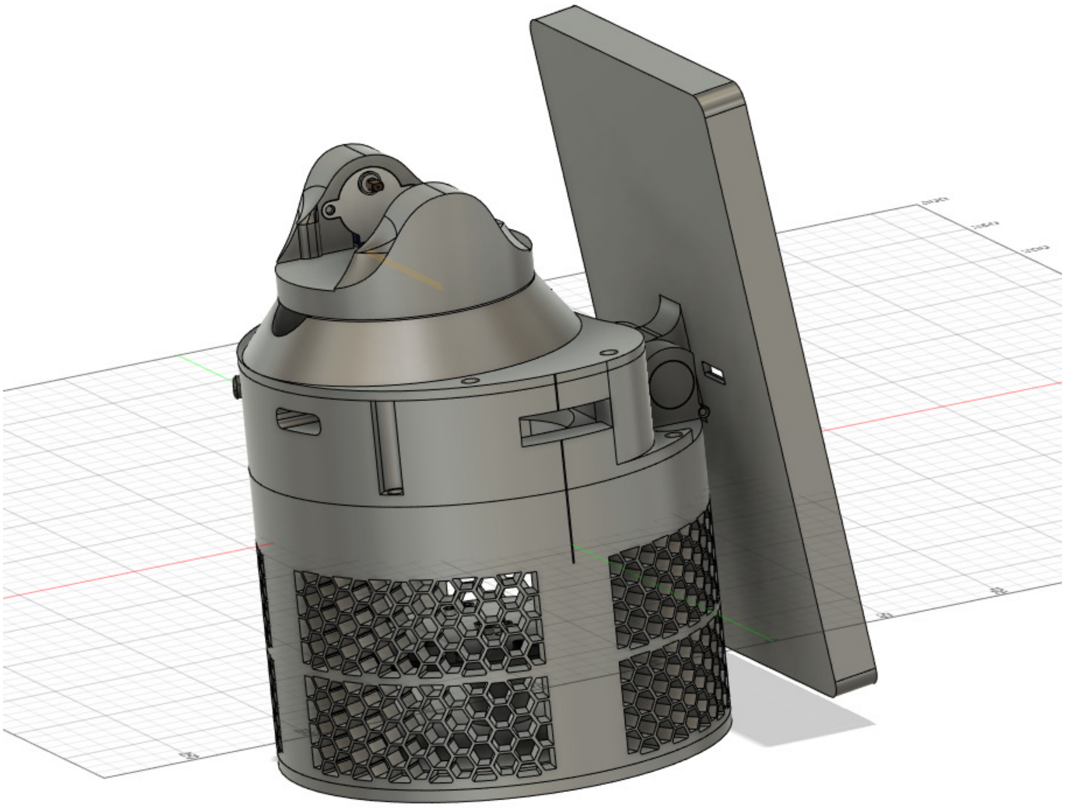

Figure 11: Rendering of first housing version

As the project progressed, multiple redesigns became necessary to refine the housing's functionality and accommodate unforeseen challenges.

Adaptation to Hardware Changes As final hardware selections were made, modifications were required to ensure a proper fit for all parts. Throughout the development process, some components had to be replaced or upgraded, necessitating corresponding adjustments to the housing design. This iterative approach ensured compatibility with the latest hardware configurations while maintaining structural integrity.

Improved Accessibility To facilitate maintenance and future modifications, internal components needed to be more easily accessible. Several design refinements were implemented, including repositioning mounting points, enlarging access openings for connectors, and improving ventilation. These changes simplified servicing and upgrades, reducing downtime and enhancing long-term usability.

Simplified Assembly and Structural Refinements Initial prototypes were complex and time-consuming to assemble. To address this, the design was incrementally refined to minimize the number of assembly steps and reduce the likelihood of errors. Additionally, the housing was structured as a modular system, consisting of multiple interlocking parts. This approach optimized printability within standard 3D printing constraints while also enhancing maintainability, as individual sections could be replaced or upgraded without requiring a complete reprint.

Key Design Challenges and Iterative Improvements Throughout development, several specific design challenges emerged, necessitating further refinements:

- **Countersinks:** Initially too small, requiring adjustments based on print quality to ensure proper screw seating.
- **Screw Holes:** Some holes were oversized, allowing screws to spin freely instead of securing properly. This was addressed by refining tolerances for a precise fit.
- **Tolerance Adjustments:** Various fitment issues arose due to minor dimensional inaccuracies, requiring iterative refinements to achieve optimal compatibility between components.
- **Ventilation:** Early prototypes lacked sufficient airflow, increasing the risk of overheating. Ventilation openings were expanded and repositioned to enhance cooling efficiency.
- **Structural Stability:** Additional reinforcements were implemented to ensure that the housing could withstand vibrations and external forces during operation.

- **Hardware Integration:** Mounting positions were refined to simplify the integration of components, improving ease of assembly and overall usability.
- **Port Accessibility:** The layout was adjusted to provide better access to the computer's ports [43], simplifying connectivity.

These continuous iterations and refinements allowed the first version of the housing to evolve into a more practical and functional design. The lessons learned from this phase directly influenced subsequent iterations, leading to an optimized final version.

4.2.2 Second (Final) Version

Building upon the insights gained from the first housing iteration, the second version introduced several key improvements to enhance functionality, maintainability, and overall design efficiency. A side-by-side comparison is shown in Fig. 12.

Figure 12: Comparison between final (left) and first version (right)

Enhanced Modularity and Accessibility A major focus of the redesign was to improve modularity, simplifying both assembly and maintenance. The revised structure allows for more efficient disassembly, significantly reducing the time required for maintenance and hardware adjustments. Additionally, hardware accessibility was prioritized, ensuring that critical components could be reached without excessive disassembly. This approach is demonstrated by the partially disassembled station, as shown in Fig. 13.

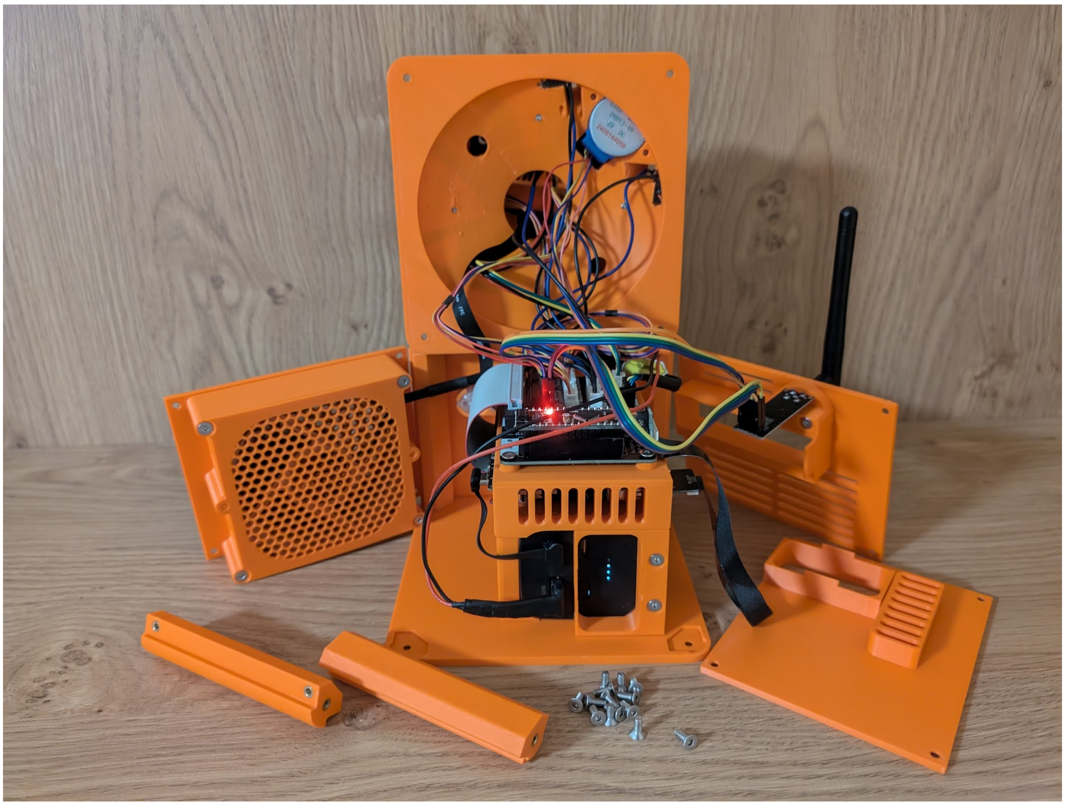

Figure 13: Partially disassembled secondary station

Compact and Optimized Design One of the most impactful changes was the removal of the display, as shown in Fig. 12, which had previously dictated the dimensions of the housing. This adjustment enabled a more compact and streamlined design, optimizing space utilization while maintaining full functionality. Despite these structural changes, the motor mechanism from the first version was retained, reducing development time and ensuring continuity in core functionalities.

Redesigned Bottom Section The bottom section of the housing, which accommodates essential components such as the PCB, computer, power bank, and cooling system, underwent a complete redesign. This revision, as shown in Fig. 12, focused on improving organization, airflow, and ease of access to internal hardware, ensuring more efficient operation and maintenance.

Integration of Threaded Inserts To enhance durability and improve the reliability of screw connections, threaded inserts were introduced. These additions provide several benefits:

- Increased longevity of screw mounts, preventing wear and deformation over multiple assembly cycles.
- Simplified disassembly and reassembly, facilitating faster maintenance and upgrades.
- Enhanced structural integrity, ensuring that fastening points remain secure over time.

Yaw Motor Issue & Gear System Upgrade During testing, the initial yaw motor was found to be underpowered, resulting in performance limitations. To address this issue, a gear system, as shown in Fig. 7, was implemented to increase torque, enabling smoother and more reliable movement. This upgrade ensured that the system could operate effectively under varying conditions without compromising precision or stability.

Refinements to the Bottom Section Even after the major redesign, additional modifications were necessary to further optimize the housing's performance and durability:

- Improved interconnections between housing parts, enhancing structural integrity.
- Optimized airflow channels to improve cooling efficiency and prevent overheating.
- Increased overall stability to withstand vibrations and external forces.
- Adjusted hardware mounting positions for seamless integration and accessibility.
- Enhanced access to the computer's ports, ensuring convenient connectivity.

- Redesigned power button mechanism for a more intuitive and reliable user interface.

By incorporating these refinements, the second housing version achieved a significant leap in reliability, ease of use, and long-term maintainability, making it better suited for real-world deployment. The three finalized stations are shown from the front and back in Fig. 14 and 15.

Figure 14: Front view of all three final stations: two secondary (orange) and one primary (black, center)

Figure 15: Rear view of all three final stations showing fan outlets and head-mounted components

4.2.3 3D Printing Process

The housing components were fabricated using a **Bambu Lab P1S** 3D printer, chosen for its high-speed printing capabilities and reliable output quality. The material selection varied throughout the development phase to balance rapid prototyping needs with long-term durability requirements.

Prototyping with PLA During the initial prototyping stage, **polylactic acid (PLA)** was used due to its ease of printing and fast turnaround time. This enabled rapid iteration and testing of design modifications without significant material costs. However, PLA's mechanical properties and limited environmental resistance made it unsuitable for the final application.

Final Production with PETG For the final version, **polyethylene terephthalate glycol (PETG)** was selected due to its superior durability, higher temperature resistance, and suitability for outdoor conditions. Unlike PLA, PETG offers improved impact resistance and reduced brittleness, ensuring a more robust enclosure for long-term use.

Considerations for Printing with PETG Although PETG generally requires longer print times and more careful tuning compared to PLA, the use of **High-Flow (HF)** filament allowed for efficient production without a significant increase in cost or time. To ensure optimal print quality, PETG filament was dried for **eight hours** in a filament dryer before printing. This step was necessary to prevent moisture absorption, which can negatively impact layer adhesion and overall print strength.

By leveraging the strengths of both materials at different development stages, the housing design was iteratively refined while maintaining efficiency in the fabrication process.

4.3 Programming

4.3.1 Development Environment

To facilitate efficient and consistent development of the ArmSom codebase, a **custom development environment** was created. This environment builds upon and extends the previously developed system by FrenchBakery [29], incorporating various improvements to enhance usability, maintainability, and cross-platform compatibility.

Containerized Development Approach A **Debian-based development container** was employed to provide a standardized environment for **C++ development and cross-compilation**. By using containerization, all necessary dependencies, libraries, and toolchains are encapsulated within a controlled environment, ensuring that every developer operates under identical conditions, regardless of the underlying host system.

Cross-Platform Consistency One of the primary motivations for adopting a containerized approach was the need to support development across multiple systems, each running different operating systems. Without a uniform environment, discrepancies in library versions, compiler behavior, and system dependencies could introduce inconsistencies, leading to potential compatibility issues. By utilizing a **Debian-based development container**, the project ensures:

- **Improved Repeatability:** Code behaves identically across all development machines, eliminating system-dependent discrepancies.
- **Stable and Predictable Development Workflow:** Developers can work with a predefined toolset, reducing setup time and potential conflicts.
- **Seamless Cross-Compiling:** The containerized approach streamlines cross-compilation, allowing code to be developed on one system while being compiled for another target architecture.

By leveraging this structured development environment, the project benefits from enhanced collaboration, reduced debugging overhead, and a more streamlined deployment process. This approach not only improves efficiency but also ensures long-term maintainability and scalability of the development workflow.

4.3.2 Hardware Drivers

A significant portion of the software development effort was dedicated to implementing robust and efficient hardware drivers. These drivers facilitate seamless communication between various hardware components and ensure reliable operation of the system. The hardware control is primarily divided between two processing units: the **ArmSom** (main computer) [43] and the **Arduino Nano** [12], each responsible for different aspects of device management.

- **ArmSom (Main Computer)**
  - Stepper motor drivers [4]
  - Serial communication with Arduino Nano
- **Arduino Nano**
  - RF24 Mesh networking [33, 34]
  - Pulse Width Modulation (PWM)-based fan control [32]
  - ToF laser module [14]
  - Compass and gyroscope integration [6, 7],
  - Communication with the ArmSom

ArmSom The ArmSom [43] is responsible for controlling the stepper motors [4], ensuring precise movement across both horizontal and vertical axes. A dedicated stepper driver interface provides comprehensive support for various motion parameters, including:

- Half-stepping and gear ratio compensation for smooth motion.
- Absolute and relative positioning in both steps and angular degrees.
- Speed control with acceleration management.
- Continuous positional awareness to maintain accurate alignment.

To establish a robust communication link with the Arduino Nano [12], a serial interface was developed, incorporating acknowledgment mechanisms to ensure reliable data transmission. This approach verifies the successful execution of commands and prevents the loss of critical control signals. While the ArmSom serves as the central processing unit, it interacts with key hardware components—such as the cooling fan [32], sensors [6, 7, 25], and RF24-based networking modules [33, 34]—indirectly through the Arduino Nano, which acts as an intermediary for hardware control and data acquisition.

Arduino Nano The Arduino Nano [12] is responsible for handling auxiliary hardware tasks and serves as a bridge between the ArmSom [43] and various peripheral components.

RF24 Mesh Networking The RF24 Mesh protocol provides reliable wireless communication between ground stations. The implementation ensures efficient data transfer and message routing across the mesh network. For further details, refer to Section 4.3.5.

PWM Fan Control A simple PWM control system is used to regulate the cooling fan speed. The Noctua fan [32] is controlled via a single PWM pin, enabling dynamic adjustments based on temperature or other system conditions.

ToF Laser The ToF laser module [14] is responsible for distance measurements station alignment. A custom serial-based communication interface was developed due to limitations in existing libraries, providing additional functionalities such as:

- Checksum validation for data integrity.
- Adjustable range and resolution settings.
- Laser diode power control (on/off).
- Automatic re-request mechanism in case of transmission errors.

Serial Communication with ArmSom A dedicated serial communication link between the Arduino Nano [12] and the ArmSom [43] allows efficient data exchange. Key features of this communication system include:

- Buffered message storage for incoming network data until requested by the ArmSom.
- Memory-efficient design to account for the Nano's limited random access memory (RAM) capacity.
- Integrated debugging capabilities, enabling the Nano to send diagnostic data to the ArmSom's command-line interface (CLI).

This modular hardware driver implementation ensures stable, reliable, and maintainable operation across all system components.

4.3.3 Calibration

The calibration process was only implemented in a basic form. Only tests were made, where the relative positions of the stations had to be manually input by the user, after which the laser [14] was used to measure distances. Due to our critical hardware failures, as described in Section 4.1.1, further development towards automation was not possible. While the conceptual framework was outlined, practical validation and refinement beyond manual calibration could not be completed.

4.3.4 Camera Tracking

The implementation of the camera tracking system progressed to the conceptual and initial development stages. The intended approach was outlined, and preliminary considerations were made regarding tracking accuracy and computational feasibility. However, due to hardware constraints, as described in Section 4.1.1, further refinement and real-world validation could not be completed within the project's timeframe.

4.3.5 Data Transfer

Protocol Overview: To ensure reliable and efficient data transmission, a structured JavaScript Object Notation (JSON)-based communication protocol was developed. Each message is encapsulated in a **parent message**, containing a type, unique identification (ID), and timestamp. The message type can be one of the following:

- **req** – Requests information or an action.
- **ack** – Confirms successful execution of an action.
- **repl** – Provides responses to requests.
- **data** – Transmits tracking or station-related information.

This way each message type has a specific schema. In case the message type is **data**, it can be further separated in:

- **Target Result (tres)**: Contains object tracking data, including camera angles and object IDs.
- **3D Target Result (tres3)**: Extends **tres** with precise 3D position.
- **Station Information (sinf)**: Provides metadata on ground stations, including position, direction, and camera specifications.

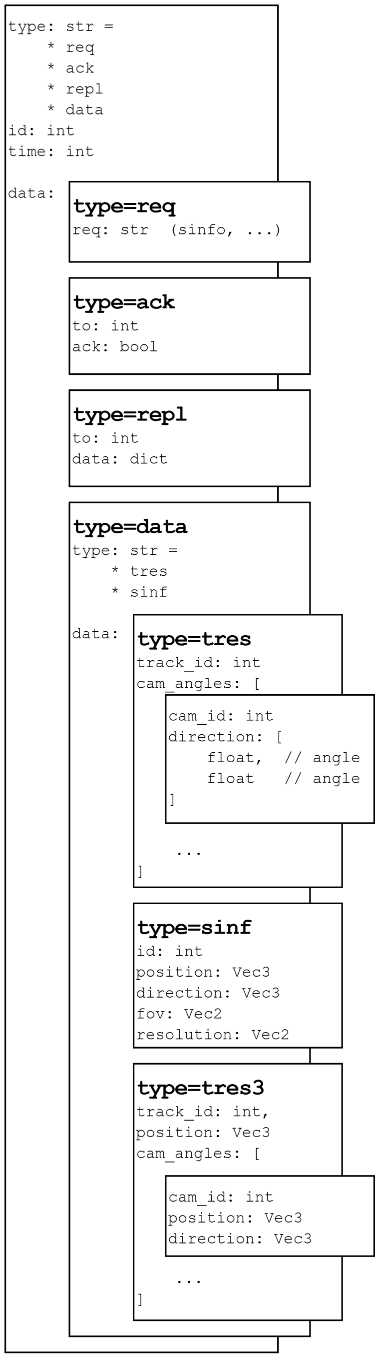

Figure 16: Message structure

Source: Own illustration created with draw.io [26]

Protocol Advantages: The protocol ensures:

- **Efficiency**: Predefined schemas enable fast parsing and low-latency communication.
- **Scalability**: The modular design allows for future extensions.
- **Reliability**: The acknowledgment system provides valuable feedback for handling errors.

This structured approach enables seamless coordination between ground stations, visualization tools, and tracking algorithms.

Theoretical Solution: To establish a robust and efficient communication framework, all three ground stations are integrated into a **Mesh network**, where the **primary station** assumes the role of the central server, while the **secondary stations** operate as clients.

During system initialization, the primary station enters a **standby state**, waiting for all secondary stations to establish a connection. Once all connections are confirmed, the system initiates a calibration procedure, synchronizing positional data and aligning reference frames to ensure precise tracking and analysis.

For standard operation, the primary station transitions into a **listen-only mode**, except for sending essential acknowledgments. This strategic design significantly reduces computational overhead and minimizes RAM usage, allowing the system to maintain high efficiency even under demanding conditions. By limiting active processing on the primary station, the architecture optimizes real-time data handling while ensuring rapid and reliable communication between all networked components.

This approach not only enhances the system's scalability but also improves fault tolerance by enabling seamless reconnections in case of temporary communication disruptions.

Code Implementation: The implementation of the communication framework was significantly streamlined by leveraging the `RF24Network` and `RF24Mesh` libraries, which provide a robust abstraction layer for interfacing with the `NRF24L01+ PA + LNA` modules [34]. These libraries handle much of the low-level networking functionality, including packet routing, automatic retransmissions, and dynamic addressing, thereby reducing development complexity and allowing for a more structured and maintainable architecture.

However, to fully integrate the system's requirements, a modular software interface had to be developed, capable of supporting both **server** (primary station) and **client** (secondary station) nodes. This involved designing a flexible communication framework that could dynamically handle various message types, manage connections efficiently, and ensure reliable data transfer.

A key aspect of the implementation was integrating the previously defined **custom network protocol**, which structures and organizes all transmitted data. The protocol was designed to handle distinct message types, including requests, replies, acknowledgments, and data transmissions. Within data messages, further categorization enables the transmission of tracking results and station-specific information.

By adopting this structured approach, the system benefits from improved scalability, reduced processing overhead, and enhanced reliability, making it well-suited for real-time applications with stringent performance requirements.

4.3.6 3D Angle Calculations

Approach: In contrary to the initially proposed "simple trigonometry", the calculations are being done using an approximation algorithm. This approach was chosen, because the vectors from each station to the target will never be fully accurate, so in the real world the three Vectors would never meet, which makes solving it using trigonometry impossible. Approximation works, by specifying a "rule set" (a function returning an integer) and trying to achieve the lowest possible output value, using a three dimensional position as input parameter.

Code Solution: In Python, this approximation is performed using `scipy.optimize.minimize`. The objective function calculates the sum of distances to each line, with lower values indicating points closer to the center of the vector system. The second parameter, `x0`, defines the starting point for the approximation algorithm, set as the center of our coordinate system, which coincides with the center of our ground station array. Since this function also depends on `lines`, it must be provided as an argument in `minimize`. Additionally, the fourth parameter, `method`, is specified as `"BFGS"`.

Broyden–Fletcher–Goldfarb–Shanno algorithm:
The Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm is an iterative method for solving unconstrained nonlinear optimization problems. It preconditions the gradient with curvature information, gradually approximating the Hessian matrix using a generalized secant method. Unlike Newton's method, BFGS avoids matrix inversion, reducing computational complexity to O(n2)O(n2) instead of O(n3)O(n3). The L-BFGS variant is efficient for large-scale problems, while BFGS-B handles box constraints. Named after Broyden, Fletcher, Goldfarb, and Shanno, it remains widely used in numerical optimization.[47]

Listing 4.1: Example of 3D Angle Calculation

```python
lines: list[tuple[np.array, np.array]] = ...


def objective(
    point: np.array,
    lines: list[tuple[np.array, np.array]]
) -> float:
    """
    calculate the sum of the distances to each line
    """
    return sum(distance_to_line(
        point, line[0], line[1]
    ) for line in lines)

```

```
result = minimize(
    objective,
    x0=np.array([0.0, 0.0, 0.0]),
    args=(lines,),
    method='BFGS'
)
```

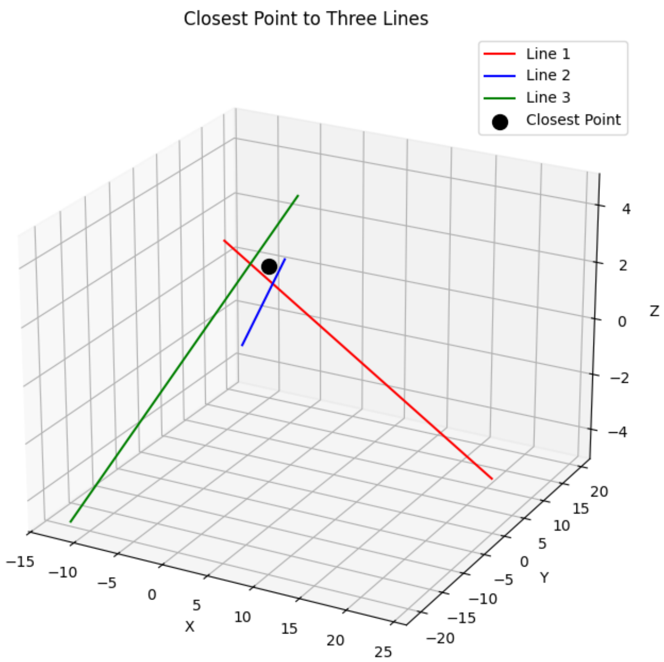

Figure 17: Example visualization of the algorithm

Source: Own illustration created with Matplotlib in Python

As shown in the illustration above, when given three lines in random orientations, the algorithm successfully identifies their center. Testing revealed that the code executes in approximately 400 to 600 µs, which is more than fast enough for our use case.

Tracking To enhance target tracking, each identified object is assigned a unique 'track ID,' which allows it to be consistently identified at any given time. Additionally, every calculated position of the object is recorded throughout its movement. This comprehensive data logging makes it possible to fully reconstruct the object's flight path, providing a detailed history of its trajectory and enabling further analysis if needed.

4.3.7 3D Visualization

Network Protocol To ensure broad compatibility and accessibility, the visualization application was designed to run on a wide range of devices, including user-provided hardware. As a result, a dedicated network communication protocol was required to facilitate seamless data exchange between the tracking system and the visualization client.

To achieve this, the previously defined network protocol was not only reused but also further refined and optimized for this specific application. Unlike a purely request-based system, the server is also capable of broadcasting updates autonomously, ensuring that clients receive critical tracking information in real time. This hybrid approach balances efficiency and responsiveness, allowing visualization clients to both request specific data when needed and passively receive updates without constant polling.

The refined protocol structure enables the efficient transmission of tracking and calibration data while minimizing network overhead. The updated communication procedure is outlined below:

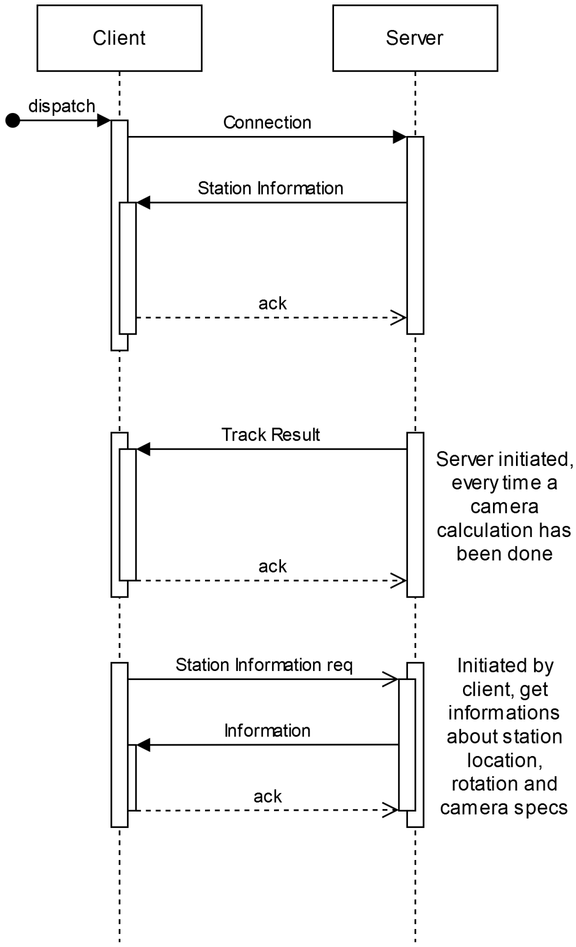

Figure 18: Simplified network protocol

Source: Own illustration created with draw.io [26]

Rendering Engine Given that the 3D tracking component was already developed in Python, it was a logical decision to implement the visualization system in Python as well to maintain consistency and streamline integration. For this purpose, I selected **Ursina**, a lightweight yet powerful three-dimensional (3D) rendering engine designed for Python. My prior experience with **Ursina** further reinforced this choice, as it enables the efficient rendering of simple 3D models with minimal development overhead. Its intuitive API and ease of use makes it well-suited for rapidly prototyping and displaying real-time visualizations while ensuring smooth performance.

5 Conclusion

This diploma thesis focused on the development of a ground-based 3D drone tracking system using three camera-equipped stations. The primary goal was to track drones without the need for expensive onboard tracking hardware, making drone applications more accessible and cost-effective for agricultural use. The system was designed to determine drone positions by processing images from three ground stations and displaying tracking data through a 3D visualization interface.

Compared to existing solutions, our approach eliminates the need for costly GNSS/RTK systems or onboard tracking modules, significantly reducing operational costs and hardware complexity. The use of ground-based tracking enhances scalability, allowing multiple drones to be monitored without additional modifications. Furthermore, independence from external network infrastructure, such as 5G, ensures reliability in remote agricultural areas.

The significance of this work lies in its potential to lower the cost barrier for implementing drone tracking technology, making precision farming more accessible to small and medium-sized agricultural enterprises. Additionally, it explores methods for accurate multi-station synchronization and 3D position calculation.

Key findings from this work include the successful implementation of a custom approximation algorithm for determining 3D positions based on known station locations and relative angles. The modular software architecture ensures adaptability for further enhancements, such as refining calibration procedures or integrating alternative tracking methods.

Despite these achievements, challenges limited the completion of a fully functional prototype. Hardware issues, including an unreliable single-board computer and power supply inconsistencies, hindered full system integration and testing. Additionally, the current design is not waterproof, which presents limitations for outdoor agricultural use. Future improvements should focus on selecting a more reliable computing platform, and enhancing system durability.

The developed system lays a foundation for further research and industrial applications. With refinement, it could be deployed in areas such as drone-based surveillance, automated infrastructure monitoring, or environmental analysis. Our findings contribute to ongoing advancements in ground-based tracking technologies, paving the way for cost-effective and scalable solutions.

Acknowledgments

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We are also profoundly thankful to our families, especially our parents, for their continuous support, both emotionally and financially, which has made it possible for us to pursue our education at this institution. Living away from home during the week in a student dormitory, due to the significant distance from our school, has presented its own set of challenges.

Lastly, we extend our appreciation to our classmates, especially Reiter Matteo, and friends who have been a source of inspiration and assistance throughout this project.

Acronyms

3D three-dimensional. 4, 9, 11, 12, 16, 27, 35, 41, 47, 53

AI Artificial Intelligence. 9, 10, 21

GNSS Global Navigation Satellite System. 9, 10, 16, 33

ID identification. 47, 52

PCB Printed Circuit Board. 16, 24, 25, 26, 27, 29, 30, 31, 32, 38, 63
PETG polyethylene terephthalate glycol. 42
PLA polylactic acid. 41, 42
PWM Pulse Width Modulation. 44, 45

RTK Real-Time Kinematic. 9, 10, 16, 33

ToF Time-of-flight. 17, 27, 29, 32, 44, 45

USB Universal Serial Bus. 24, 25, 32

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Appendix

Attachment	Description
Arduino Nano Firmware	Code running on the Arduino Nano (C++)
Documentation	LaTeX source files of the documentation
GUI	Three-dimensional visualization interface that renders the ground stations and tracked drone positions (Python, Ursina)
Hardware-Drivers	Hardware interface drivers for the station (C++)
Housing	3D model files of the stations (STLs)
PCB	Altium Designer project files and Gerber exports for manufacturing the custom PCB
Python-Tools	Common libraries and modules containing shared data types, vector operations, and support functions for both tracking and visualization
Tracking-Software	Executed on the primary station to gather and combine data from all stations for drone position calculation (Python)
Mind Map	Initial brainstorming document outlining project ideas and scope (PDF)

Table 1: List of Appendices and Files

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