

Diploma Thesis / Diplomarbeit

3D Drone Tracking

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

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Submitted to

Höhere Technische Bundeslehr- und Versuchsanstalt Anichstraße

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Innsbruck, March 2025

Submission Notice:

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Date:

Kurzfassung / Abstract

Eine Kurzfassung ist in deutscher sowie ein Abstract in englischer Sprache mit je maximal einer A4-Seite zu erstellen. Die Beschreibung sollte wesentliche Aspekte des Projektes in technischer Hinsicht beschreiben. Die Zielgruppe der Kurzbeschreibung sind auch Nicht-Techniker! Viele Leser lesen oft nur diese Seite.

Beispiel für ein Abstract (DE und EN)

Die vorliegende Diplomarbeit beschäftigt sich mit verschiedenen Fragen des Lernens Erwachsener – mit dem Ziel, Lernkulturen zu beschreiben, die die Umsetzung des Konzeptes des Lebensbegleitenden Lernens (LBL) unterstützen. Die Lernfähigkeit Erwachsener und die unterschiedlichen Motive, die Erwachsene zum Lernen veranlassen, bilden den Ausgangspunkt dieser Arbeit. Die anschließende Auseinandersetzung mit Selbstgesteuertem Lernen, sowie den daraus resultierenden neuen Rollenzuschreibungen und Aufgaben, die sich bei dieser Form des Lernens für Lernende, Lehrende und Institutionen der Erwachsenenbildung ergeben, soll eine erste Möglichkeit aufzeigen, die zur Umsetzung dieses Konzeptes des LBL beiträgt. Darüber hinaus wird im Zusammenhang mit selbstgesteuerten Lernprozessen Erwachsener die Rolle der Informations- und Kommunikationstechnologien im Rahmen des LBL näher erläutert, denn die Eröffnung neuer Wege zur orts- und zeitunabhängiger Kommunikation und Kooperation der Lernenden untereinander sowie zwischen Lernenden und Lernberatern gewinnt immer mehr an Bedeutung. Abschließend wird das Thema der Sichtbarmachung, Bewertung und Anerkennung des informellen und nicht-formalen Lernens aufgegriffen und deren Beitrag zum LBL erörtert. Diese Arbeit soll einerseits einen Beitrag zur besseren Verbreitung der verschiedenen Lernkulturen leisten und andererseits einen Reflexionsprozess bei Erwachsenen, die sich lebensbegleitend weiterbilden, in Gang setzen und sie somit dabei unterstützen, eine für sie geeignete Lernkultur zu finden.

This thesis deals with the various questions concerning learning for adults – with the aim to describe learning cultures which support the concept of live-long learning (LLL). The learning ability of adults and the various motives which lead to adults learning are the starting point of this thesis. The following analysis on self-directed learning as well as the resulting new attribution of roles and tasks which arise for learners, trainers and institutions in adult education, shall demonstrate first possibilities to contribute to the

implementation of the concept of LLL. In addition, the role of information and communication technologies in the framework of LLL will be closer described in context of self-directed learning processes of adults as the opening of new forms of communication and co-operation independent of location and time between learners as well as between learners and tutors gains more importance. Finally the topic of visualisation, validation and recognition of informal and non-formal learning and their contribution to LLL is discussed.

Gliederung des Abstract in **Thema, Ausgangspunkt, Kurzbeschreibung, Zielsetzung**.

Projektergebnis Allgemeine Beschreibung, was vom Projektziel umgesetzt wurde, in einigen kurzen Sätzen. Optional Hinweise auf Erweiterungen. Gut machen sich in diesem Kapitel auch Bilder vom Gerät (HW) bzw. Screenshots (SW). Liste aller im Pflichtenheft aufgeführten Anforderungen, die nur teilweise oder gar nicht umgesetzt wurden (mit Begründungen).

Erklärung der Eigenständigkeit der Arbeit

EIDESSTÄTTLICHE 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. Meine Arbeit darf öffentlich zugänglich gemacht werden, wenn kein Sperrvermerk vorliegt.

Ort, Datum

Verfasser 1

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1 Introduction

Current drone tracking systems often rely on onboard equipment, requiring expensive hardware installations on each drone. This thesis focuses on developing a ground-based 3D tracking system capable of monitoring "dumb" drones—those without onboard tracking systems—using calibrated and synchronized ground stations equipped with image processing technology.

The goal of this project is to design and implement a functional prototype consisting of three ground stations that can accurately track drones in three-dimensional space. The system aims to calculate drone positions by processing images captured by the ground stations and display the tracked drones through a 3D visualization interface.

This topic is important because it addresses the high costs and limitations associated with current drone tracking methods. By eliminating the need for onboard tracking hardware, the proposed system could make drone tracking more accessible and cost-effective. The problem of tracking drones without onboard systems is significant, as it could expand the usability of drones in various industries where cost and simplicity are critical factors.

Solving this problem is crucial for reducing operational costs and enhancing the scalability of drone applications. Existing research primarily focuses on onboard tracking solutions or GPS-based methods, which may not be feasible for all situations due to cost or technical constraints. This thesis aims to contribute to the field by providing an alternative ground-based tracking solution, potentially filling a gap in current drone tracking technologies.

This topic was chosen because it combines practical engineering challenges with significant potential benefits in the field of drone technology. By developing a ground-based tracking system, we aim to offer a viable alternative to existing methods, addressing a current need in the industry.

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 and running the 3D-GUI.

1.1.1.2 Camera

Responsible: Krahbichler Lukas

Select, procure, 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. -
Independence, security

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

1.1.2.1 Primary Station 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 3D Angle Calculations

Responsible: Prantl Niclas

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

1.1.3.2 Camera Tracking

Responsible: Krahbichler Lukas

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

1.1.3.3 Data Transfer

Responsible: Krahbichler Lukas

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

1.1.3.4 Calibration

Responsible: Krahbichler Lukas

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

1.1.3.5 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 [?], companies like CO2 Revolution 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 climate change impacts [?]. 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 [? ?].
- **Precision Spraying:** With precise positioning, drones can apply fertilizers, pesticides, and herbicides precisely where needed, reducing chemical usage and minimizing environmental impact [? ?].
- **Irrigation Management:** Drones assist in detecting variations in soil moisture levels using thermal cameras, helping optimize irrigation systems and conserve water resources [?].
- **Planting and Seeding:** Some drones are designed to plant seeds over large areas efficiently, particularly useful in reforestation efforts and hard-to-reach terrains [?].

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% [?]. 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 [?].
- **Technological Advancements:** Improvements in drone capabilities, such as enhanced sensors and longer flight times, make them more practical for agricultural applications [?].
- **Adoption of Precision Farming Techniques:** Farmers are increasingly using drones for site-specific crop management to optimize resource use and increase yields [?].

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 [?].
- **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 [?].

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, our drones 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 [?]. Additionally, implementing privacy and safety features such as geofencing and privacy-by-design principles ensures compliance with regulations and builds trust among users [?].

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 [?].

- **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 Three-Dimensional (3D)-printed parts to optimize them for agricultural needs [? ?]. Enhancements include high-resolution cameras and sensors, leveraging Huawei's cloud computing and 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 [? ? ?].
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, WiFi, and Bluetooth for communication. Accessories like DJI Relay enhance their range in complex environments [? ?]. In Austria, partners like Drohnenring distribute DJI's products, offering consultation, sales, training, and support [?].
3. **AgEagle Aerial Systems Inc. (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. LiDAR sensors provide obstacle avoidance and controlled landings. AgEagle offers software like eMotion and Measure Ground Control for flight planning and data processing [? ?].

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

Comparison of Strengths and Weaknesses with Competitors

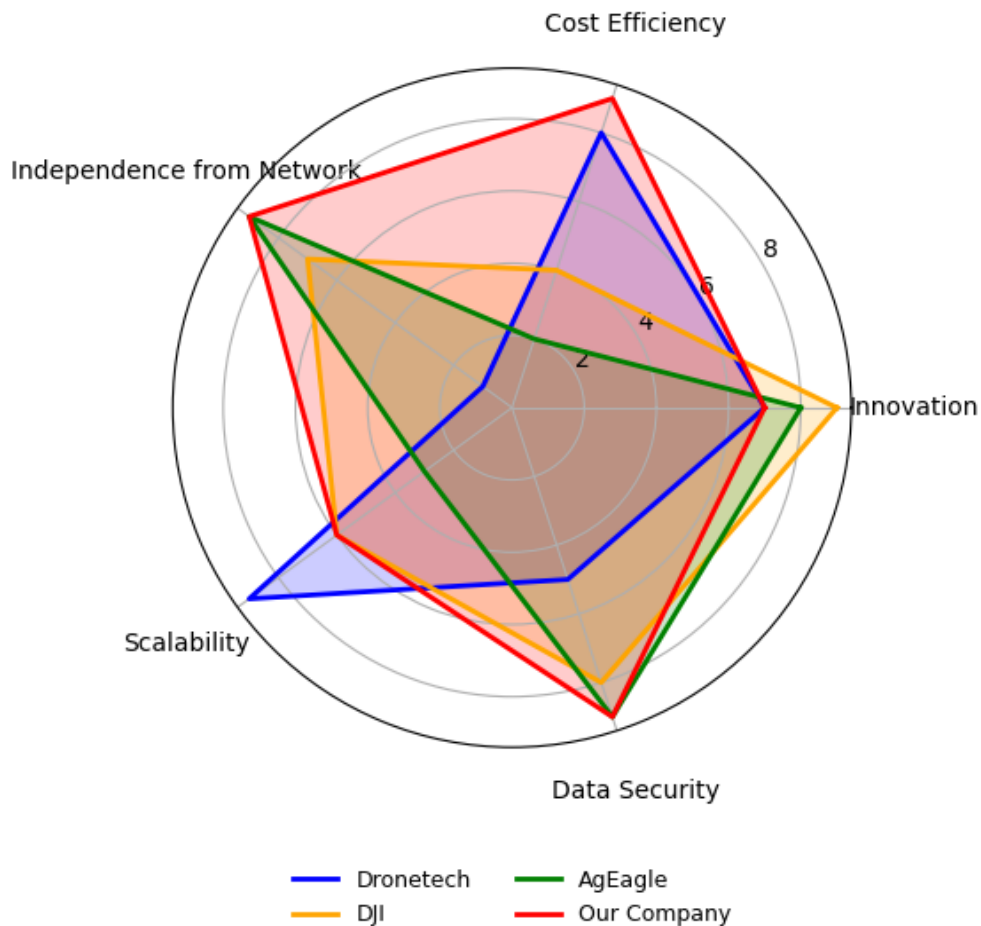


Figure 1: Comparison of Strengths and Weaknesses with Competitors

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 us 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, 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 and provide high resolution to enable accurate tracking over greater distances. A 4K camera is proposed, as 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 visualization 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), were 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 battery management system, 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. By avoiding reliance on external infrastructure, the system becomes more robust and adaptable to various operational scenarios.

3.1.6 Calibration

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

The calibration hardware, integrated onto a custom PCB, could include:

- Power Delivery
- Time-of-Flight (ToF) Laser
- Communication modules
- Stepper motors
- Servo motors
- Gyroscope/Magnetometer/Accelerometer (9DOF)
- End switches
- Microcontroller

During calibration, approximate directions could be determined using the communication system, supplemented by precise distance measurements from the ToF laser. These measurements define the relative positions and angles of the stations, forming the foundation for accurate drone tracking.

3.2 Housing

The initial proposition of the housing focused on following principles:

- Sturdiness

- Size
- Airflow (Cooling) for the Computer

?? wtf should i write about dis

3.3 Programming

3.3.1 Calibration

3.3.2 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 FOV.

3.3.3 Data Transfer

3.3.4 3D Angle Calculations

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

3.3.5 3D Visualization

Operating independently from the tracking suite, the visualization system retrieves 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.
- **ASUS Tinker Board S:** Affordable but lacks sufficient computational power for real-time image processing.
- **ArmSom Sige7 (Basic):** Balances affordability and performance, supporting necessary image processing tasks.
- **Raspberry Pi 4 Model B (8GB):** Well-supported but has less processing power for image processing compared to other options.

The ArmSom Sige7 Basic 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, ASUS, or Raspberry Pi would have offered greater reliability and community support.

In the end, the combination of hardware failures, time constraints preventing further troubleshooting or contacting the manufacturer, and the costs associated with replacing the hardware contributed to the project not being fully completed.

4.1.2 Camera

The camera module chosen was the 4K model from ArmSom, specifically designed to integrate seamlessly with the ArmSom Sige7. This decision prioritized compatibility and reduced integration risks, avoiding potential issues with third-party hardware.

TODO: Document problems with the camera (like when the image was too dark and how we solved it)

4.1.3 Display

Initially, a 10.1-inch Full HD display from ArmSom was integrated into the primary station. The display was chosen for its compatibility with the ArmSom Sige7 and its reasonable price. However, as the project progressed, a redesign of the housing necessitated its removal. Redirecting the visualization to a laptop allowed for a more compact and efficient housing design. This change eliminated the need for a larger primary station housing, optimizing portability and practicality.

4.1.4 Power Supply

The chosen power supply was a PD 100 W, 20,000mAh power bank with USB-C output. This model met the project's technical requirements as follows:

- It supports USB-PD, essential for powering the ArmSom Sige7.
- Its 100W output ensures compatibility with all connected components, including the PCB.
- It has three ports, enabling simultaneous connections for the ArmSom board, the PCB, and charging functionality.

Despite meeting these specifications, several issues arose during use. The power bank exhibited unpredictable behavior, intermittently cycling 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.

The two separate start buttons—one for the power bank and one for the ArmSom board—were implemented purely due to the independent power controls of both components, ensuring that shutting off the power bank did not abruptly cut power to the ArmSom. Furthermore, it is highly likely that one of the ArmSom computers failed due to unstable voltage levels or power spikes originating from the power bank, though this could not be definitively confirmed.

4.1.5 Data Transfer

Initially, the NRF24Lo1 modules with PCB antennas 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 stable communication.

To resolve this, the system was upgraded to NRF24Lo1+ PA + LNA modules with external antennas. 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 antennas 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.

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 Time-of-Flight (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 28BYJ-48 stepper motors controlled via ULN2003 driver boards. End-switches, configured in normally closed mode, detect faults like loose connections and set position limits. Servos were initially considered but dismissed due to cost, size, and complexity.

Gyroscope and Compass: The GY-521 gyroscope provides 6-axis data for tilt measurement and alignment correction. A GY-271 compass was initially included for absolute orientation but was abandoned due to inconsistent calibration results. The compass remains on the PCB but is not in use.

ToF Laser Module: The primary station features a DFRobot Infrared Laser Distance Sensor with a 5 cm to 80 m range and millimeter-level accuracy. It is used for precise distance measurements and requires an unobstructed line of sight between the stations.

Camera for Visual Alignment: Each station's 4K camera 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.

Calibration PCB: The calibration system relies on a custom-designed PCB to integrate various components necessary for precise positioning and alignment. The PCB was designed using **Altium Designer**, with components sourced from **DigiKey** and the board itself manufactured by **JLCPCB**. Assembly was completed both in the school's workshop and at home, with components manually soldered.

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 LED indicators for status feedback.

Issues Encountered During Development: - The **USB input connector** was never soldered because the cable would not fit inside the housing. Instead, wires were directly soldered to the board. - The **Arduino orientation** was incorrect in the Altium design, resulting in the microcontroller being mounted in the opposite direction than originally planned. - The **LED on/off switching functionality** did not work as intended, requiring two additional manual connections to be made on each PCB.

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.

Hardware Limitations and Decisions

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 was developed before all hardware components were physically available, relying exclusively on online specifications and manufacturer-provided measurements. 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.

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 components. Throughout the development process, some components were 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, 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.

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.

Compact and Optimized Design One of the most impactful changes was the removal of the display, 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 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 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.

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, **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, **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 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 French Bakery [?], 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) and the **Arduino Nano**, each responsible for different aspects of device management.

- **Armsom (Main Computer)**
 - Stepper motor drivers
 - Serial communication with Arduino Nano
- **Arduino Nano**
 - RF24 Mesh networking
 - PWM-based fan control
 - Time-of-Flight (TOF) laser module
 - Compass and gyroscope integration
 - Communication with the Armsom

Armsom The Armsom is responsible for controlling the stepper motors, 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, 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, sensors, and RF24-based networking modules—indirectly through the Arduino Nano, which acts as an intermediary for hardware control and data acquisition.

Arduino Nano The Arduino Nano is responsible for handling auxiliary hardware tasks and serves as a bridge between the Armsom 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 pulse-width modulation (PWM) control system is used to regulate the cooling fan speed. The fan is controlled via a single PWM pin, enabling dynamic adjustments based on temperature or other system conditions.

Time-of-Flight (TOF) Laser The TOF laser module 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 and the Armsom 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 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

4.3.4 Camera Tracking

4.3.5 Data Transfer

Protocol Overview: To ensure reliable and efficient data transmission, a structured JSON-based communication protocol was developed. Each message is encapsulated in a **parent message**, containing a type, unique 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.

with each message type having a specified 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.

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 error handling.

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

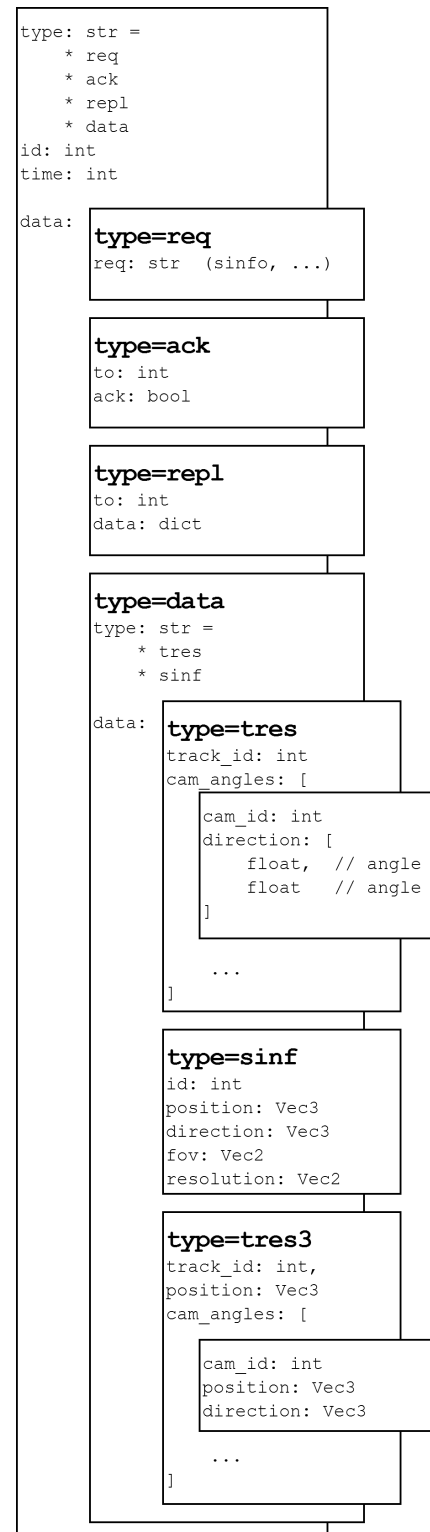


Figure 2: Message Structure

Source: Own illustration created with Draw.io

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. 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 needed 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 $O(n^2)O(n^2)$ instead of $O(n^3)O(n^3)$. 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.[?]

```

1 lines: list[tuple[np.array, np.array]] = ...
2
3
4 def objective(
5     point: np.array,
6     lines: list[tuple[np.array, np.array]]
7 ) -> float:
8     """
9     calculate the sum of the distances to each line
10    """
11    return sum(distance_to_line(
12        point, line[0], line[1]
13    ) for line in lines)
14
15
16 result = minimize(
17     objective,
```

```
18 x0=np.array([0.0, 0.0, 0.0]),  
19 args=(lines,),  
20 method='BFGS',  
21 )
```

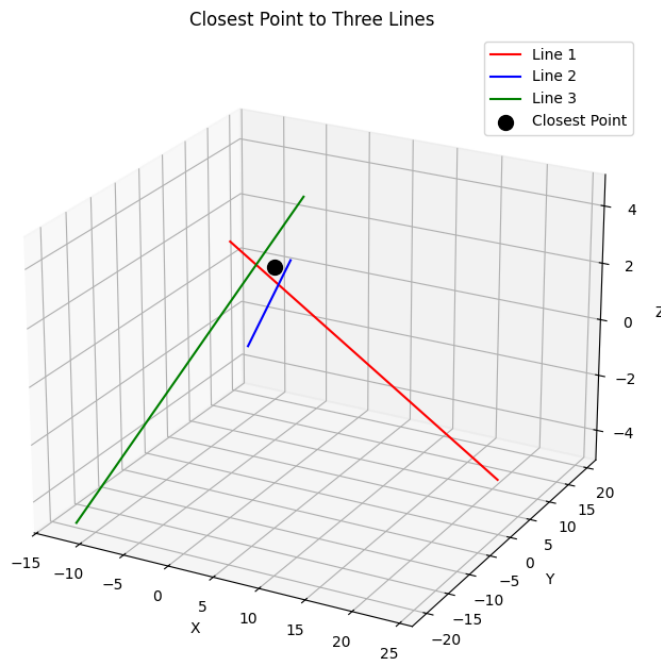


Figure 3: Example Visualization of the algorithm

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:

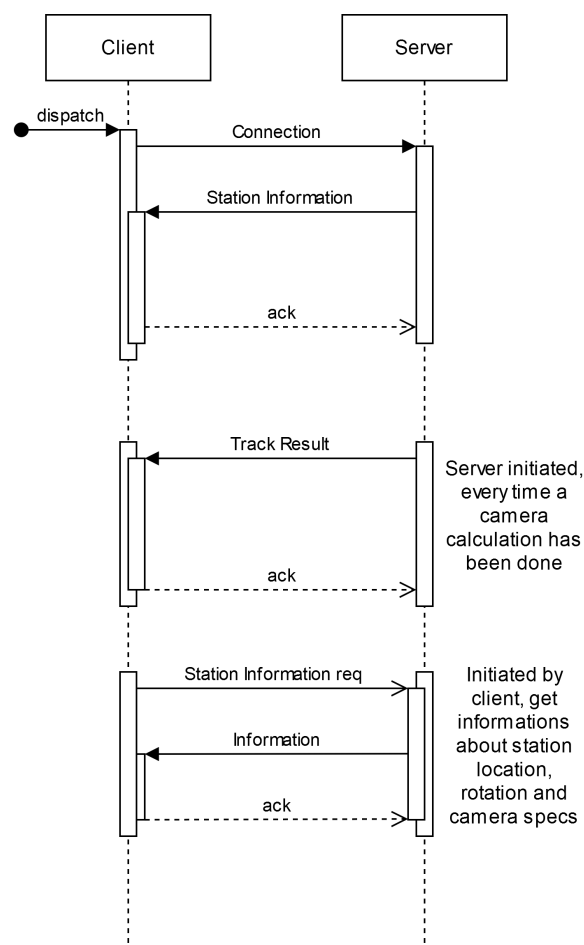


Figure 4: Simplified Network Protocol

Source: Own illustration created with Draw.io

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 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

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