Diploma Thesis / Diplomarbeit

3D Drone Tracking

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

Submitted by

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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**, **Ausgangspunk**, **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

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

Ort, Datum Verfasser 1

Ort, Datum Verfasser 1

Contents

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. - Indepedence, 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, incorporating components such as a display and calibration hardware.

1.1.2.2 Secondary Station Housing

Responsible: Prantl Niclas

Design, test, and build housing for secondary stations.

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 [4], 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 [16]. 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 [16, 19].
- **Precision Spraying:** With precise positioning, drones can apply fertilizers, pesticides, and herbicides precisely where needed, reducing chemical usage and minimizing environmental impact [11, 5].
- **Irrigation Management:** Drones assist in detecting variations in soil moisture levels using thermal cameras, helping optimize irrigation systems and conserve water resources [16].
- **Planting and Seeding:** Some drones are designed to plant seeds over large areas efficiently, particularly useful in reforestation efforts and hard-to-reach terrains [4].

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% [19]. 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 [16].
- **Technological Advancements:** Improvements in drone capabilities, such as enhanced sensors and longer flight times, make them more practical for agricultural applications [11].
- **Adoption of Precision Farming Techniques:** Farmers are increasingly using drones for site-specific crop management to optimize resource use and increase yields [19].

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 [16].
- **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 [15].

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 [3]. Additionally, implementing privacy and safety features such as geofencing and privacy-by-design principles ensures compliance with regulations and builds trust among users [17].

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 [18].

- **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 [14, 8]. 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 [13, 12, 10].
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 [6, 7]. In Austria, partners like Drohnenring distribute DJI's products, offering consultation, sales, training, and support [9].
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 [1, 2].

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

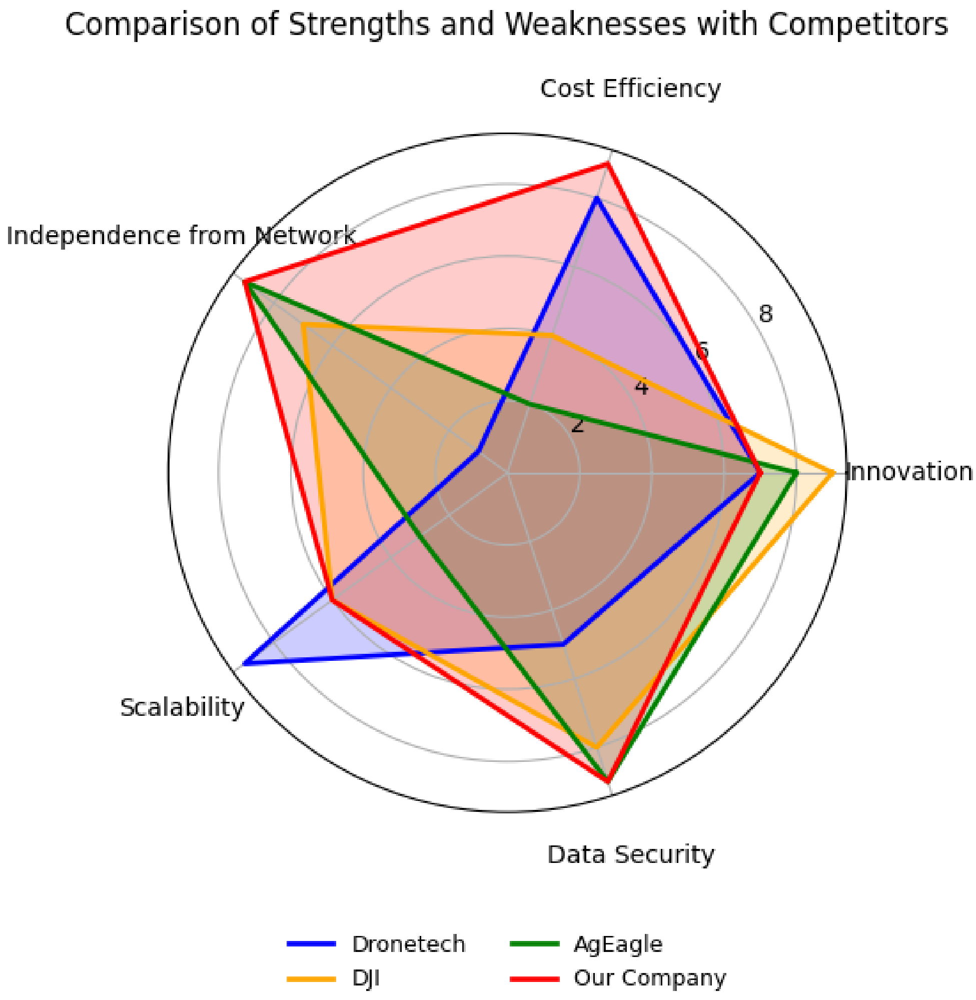

Figure 1: Comparison of Strengths and Weaknesses with Competitors

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 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 is the process of determining the relative positions and orientations of the ground stations, which is essential for accurately calculating the drone's position during operation. Unlike competitors who utilize GNSS with RTK for positioning, this system aims to achieve similar results through a simpler, more cost-effective, and entirely local solution. The calibration hardware, integrated onto a custom PCB, could include components such as:

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

The ToF laser, which is only present in the primary station, is a key component for precise distance measurement. During calibration, approximate directions could be determined using the communication system, supplemented by detailed measurements with the ToF laser. These measurements establish the relative positions and angles of the stations, forming the basis for accurate drone tracking.

3.2 Housing

3.2.1 Primary Station Housing

3.2.2 Secondary Station Housing

3.3 Programming

3.3.1 3D Angle Calculations

3.3.2 Camera Tracking

3.3.3 Data Transfer

3.3.4 Calibration

3.3.5 3D Visualization

4 Solution

4.1 Hardware

4.1.1 Computer

To select the single-board computer, several options were compared based on their processing power, affordability, and compatibility:

- **NVIDIA Jetson Nano:** This board offers strong AI capabilities, with a GPU that supports advanced neural network computations. However, it was significantly more expensive than alternatives and its AI-focused design exceeded the project's requirements for image processing.
- **ASUS Tinker Board S:** While affordable, this board lacked sufficient computational power for real-time image processing tasks, rendering it unsuitable for the project.
- **ArmSom Sige7 (Basic):** This board provided the optimal balance between affordability and processing performance. It supports the necessary image processing workloads while staying within budget.

The ArmSom Sige7 Basic variant was selected due to its sufficient computational power and cost-effectiveness. The Pro Max version, while offering better performance, was deemed unnecessary for this project's scope and budget. Price comparisons and performance benchmarks further confirmed the suitability of the chosen model.

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. The high resolution theoretically extends the effective tracking range, making it ideal for drone detection at longer distances.

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.

Initial issues arose when the power bank intermittently failed to provide a stable output for the ArmSom board, despite meeting technical specifications. The power bank's behavior included unexpected cycling on and off, which necessitated adding two separate start buttons—one for the power bank and one for the ArmSom board. Although a custom power management system would have resolved these issues, time constraints required relying on this solution.

4.1.5 Data Transfer

NRF24L01+ PA + LNA modules with external antennas were used to establish a local radio communication network. These modules replaced smaller NRF24L01 modules with PCB antennas, which failed in the required 3-node mesh configuration. While the updated modules resolved reliability issues, their high transmission power caused interference when modules operated in close proximity. This problem was mitigated by limiting the transmission power to appropriate levels, ensuring stable operation.

4.1.6 Calibration

The calibration hardware ensures precise alignment and positioning of the primary and secondary stations, which is critical for accurate 3D tracking. Each station features a rotatable head capable of moving in two axes (pitch and yaw), while roll adjustments are handled through software corrections based on gyroscope measurements. Although the rotation functionality is not required for the secondary stations, all stations share the same design to streamline production and minimize complexity. The primary station uniquely incorporates a Time-of-Flight (ToF) laser for precise distance measurements, whereas the secondary stations rely solely on their cameras for alignment.

4.1.7 Calibration

The calibration hardware ensures precise alignment and positioning of the primary and secondary stations, which is essential for accurate 3D drone tracking. Each station features a rotatable head capable of moving in two axes (pitch and yaw), while roll adjustments are handled through software corrections using gyroscope measurements. Although the rotation capability is not strictly necessary for the secondary stations, the design was standardized across all stations to simplify production and reduce complexity. The primary station incorporates a Time-of-Flight (ToF) laser for precise distance measurements, while the secondary stations rely on their cameras for alignment.

Components and Functionality

Rotatable Head (Pitch and Yaw Axes): The rotatable head utilizes 28BYJ-48 stepper motors, chosen for their compact size, cost-effectiveness, and sufficient precision for this application. These motors are controlled using ULN2003 driver boards, ensuring reliable step control and compatibility with the system's microcontroller. To limit the movement range of the motors, end-switches are installed in a normally closed configuration. This setup not only detects wiring faults, such as loose connections or damaged cables, but also provides accurate position references for the motors during calibration. Servos were initially considered for their higher torque and precision, but they were ultimately dismissed due to their larger size, higher cost, and additional complexity.

Gyroscope and Compass: The GY-521 gyroscope module provides 6-axis data, combining accelerometer and gyroscope readings. It is essential for real-time tilt measurement and inclination compensation, allowing the system to maintain proper alignment even on uneven terrain. A GY-271 compass module was included to provide absolute rotational data but was eventually excluded from the calibration process due to its unreliable performance. Extensive testing revealed significant inconsistencies between compass readings on different stations and fluctuations during repeated calibration attempts. While the compass remains physically present on the PCB, it is not active in the current calibration setup.

ToF Laser Module: The primary station employs a DFRobot Infrared Laser Distance Sensor capable of measuring distances from 5 centimeters up to 80 meters with millimeter-level accuracy. This sensor plays a critical role in determining the precise distance between stations during calibration. The ToF laser operates using infrared light and requires an unobstructed line of sight to function effectively. It is integrated into the rotatable head alongside the camera and communication modules to facilitate accurate alignment with secondary stations.

Camera for Visual Alignment: Each station is equipped with a 4K camera module, which is used for visual identification and alignment during calibration. The cameras locate the distinct bright orange secondary stations within their field of view, enabling precise positioning. This approach replaces earlier attempts to use radio-based direction finding, which proved unreliable at the short distances required for this application.

Hardware Limitations and Decisions

The calibration hardware relies on the combined functionality of the stepper motors, gyroscope, ToF laser, and cameras. Early designs included motorized feet for roll adjustments and compass-based absolute orientation, but these were discarded due to practical limitations. While the standardization of design across all stations simplified manufacturing, it introduced some redundant functionality, such as the rotatable head on secondary stations, which is rarely used for calibration purposes.

4.2 Housing

4.2.1 Primary Station Housing

4.2.2 Secondary Station Housing

4.3 Programming

4.3.1 3D Angle Calculations

4.3.2 Camera Tracking

4.3.3 Data Transfer

4.3.4 Calibration

4.3.5 3D Visualization

5 Conclusion

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[1] AgEagle [n.d.*a*], 'Agriculture'. Accessed: 2024-09-18.
URL: *https://ageagle.com/industries/agriculture/*

[2] AgEagle [n.d.*b*], 'ebee ag'. Accessed: 2024-09-25.
URL: *https://ageagle.com/wp-content/uploads/2022/06/AgEagle-eBee-AG-EN-2022-2.pdf*

[3] Bundesministerium für Land-und Forstwirtschaft und Regionen und Wasserwirtschaft, A. [2023], 'Die zukunft der landwirtschaft ist digital'. Accessed: 2024-09-18.
URL: *https://info.bml.gv.at/service/presse/landwirtschaft/2023/die-zukunft-der-landwirtschaft-ist-digital-aktionsplan-smart-farming-vorgestellt.html*

[4] Chaundler, R. [2021], 'Can Seeds Planted by Drones Spawn New Forests?', *The New York Times* . Accessed: 2024-09-26.
URL: *https://www.nytimes.com/2021/10/31/climate/deforestation-seeds-environment.html*

[5] Chin, R., Catal, C. and Kassahunw, A. [2023], 'Plant disease detection using drones in precision agriculture', *Precision Agriculture* **24**(5), 1663–1682.
URL: *https://doi.org/10.1007/s11119-023-10014-y*

[6] DJI, A. [n.d.*a*], 'Dji agras t25'. Accessed: 2024-09-25.
URL: *https://ag.dji.com/t25/specs*

[7] DJI, A. [n.d.*b*], 'Dji agras t50'. Accessed: 2024-09-25.
URL: *https://ag.dji.com/t50/specs*

[8] DJI, E. [n.d.*c*], 'Matrice 300 rtk'. Accessed: 2024-09-25.
URL: *https://enterprise.dji.com/matrice-300/specs*

[9] Drohnenring [n.d.], 'Drohnenring Österreich'. Accessed: 2024-09-18.
URL: *https://drohnenring.at/*

[10] DRONETECH, A. [n.d.], 'Smart farming huawei forschungsprojekt'. Accessed: 2024-09-18.
URL: *https://www.dronetech.at/portfolio/smart-farming-huawei-forschungsprojekt*

[11] Guardian, A. [n.d.], 'Guardian agriculture'. Accessed: 2024-09-18.
URL: *https://guardian.ag/*

[12] Huawei [2022*a*], 'Boosting farming yields in austria'. Accessed: 2024-09-18.
URL: *https://www.huawei.com/en/media-center/our-value/boosting-farming-yields-in-austria*

[13] Huawei [2022*b*], 'Huawei and dronetech elevate partnership to facilitate sustainable farming in austria'. Accessed: 2024-09-18.
URL: *https://www.huawei.com/en/news/2022/10/5g-smart-farming-austria-dronetech*

[14] IMMOTECH, A. [n.d.], 'Dronetech'. Accessed: 2024-09-25.
URL: *https://www.instagram.com/dronetech_austria/*

[15] Kuzmenko, M. [2016], 'Drones in agriculture: Potential risks and how to overcome this limitations'. Accessed: 2024-09-24.
URL: *https://www.petiolepro.com/blog/drones-in-agriculture-potential-risks-and-how-to-overcome-these-limitations/*

[16] Nazarov, D., Nazarov, A. and Kulikova, E. [2023], 'Drones in agriculture: Analysis of different countries', *BIO Web Conf.* **67**, 02029. Accessed: 2024-09-26.
URL: *https://doi.org/10.1051/bioconf/20236702029*

[17] Primloc [2024], 'Privacy in the era of drones'. Accessed: 2024-09-24.
URL: *https://www.securedact.ai/articles/privacy-in-the-era-of-drones*

[18] SINUS-Institut [n.d.], 'Sinus-milieus austria'. Accessed: 2024-08-29.
URL: *https://www.sinus-institut.de/en/sinus-milieus/sinus-milieus-oesterreich*

[19] Wankhede, S., Jangra, H. and Mutreja, S. [2021], 'Agriculture drones market size, share, competitive landscape and trend analysis report, by offering, component and application : Opportunity analysis and industry forecast, 2021-2030'. Accessed: 2024-09-26.
URL: *https://www.alliedmarketresearch.com/agricultural-drone-market*