Master Thesis

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Department of Measurement

Design and verification of a system for remote control of an unmanned system

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MASTER'S THESIS ASSIGNMENT

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II. Master's thesis details

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Design and verification of a system for remote control of an unmanned system

Master's thesis title in Czech:

Návrh a ověření systému pro vzdálené řízení bezpilotního systému

Guidelines:

The aim of the work is the development of the control system of the unmanned aircraft and the research of the status of freely available control systems such as PX4 or iNAV. The control system generally consists of three parts: on-board software, ground control station software, and antenna panning flight tracking software.
The work will include a comparison of the usability of freely available systems against the requirements and possibilities arising from the realization of one's own unmanned vehicle. These are specific requirements for aircraft capabilities, focus on control algorithms, creation of secure and encrypted communication, integration of flight planning functions, camera view display, image processing for navigation and a robust map framework.
Test the control system as a whole using a flight simulator and explore the possibilities of real use and possibly test the solution in real operation.
From the point of view of controlling the aircraft, the task is to select or design algorithms that control the flight systems of the given UAV (flight stabilization in automatic and manual mode). Describe the possibilities of image processing for navigation and the possibilities of connecting algorithms for navigation in an environment without GPS and connecting their outputs to the PX4 or iNAV system. Suggest options for generating a flight plan in which a safety back-up solution can be specified.
In the case of a ground station, describe the possibilities of existing solutions such as QGC and their disadvantages when used with your own solution. Specifically, explore the possibilities of self-control and monitoring of UAV systems, flight planning, camera image display and position display using a robust map background.
The connection between the aircraft and the ground station depends on the data link. At work, explore the various possibilities of implementing a reliable data connection. The goal is to ensure stable communication with the UAV, which is encrypted and takes place in real time.

Bibliography / sources:

1) Flight Control Systems: Practical Issues in Design and Implementation (Control, Robotics and Sensors) R.Pratt
2) Fundamentals of Aerodynamics (MECHANICAL ENGINEERING) 6 by Anderson Jr., John D
3) Mechanics of flight Kermode, A.C.; Barnard, R.H.; Philpott, D.R
4) Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems Paul. D. Groves
5) Aided Navigation: GPS with High Rate Sensors
6) Projektová dokumentace systému PX4 a iNAV

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Thanks for Grammarly proof-reading service.

Declaration

I declare that the presented work was developed independently and I have listed all sources of information used within it by the methodical instructions for observing the ethical principles in the preparation of university theses.

In Prague, January 2024

Abstract

This thesis pioneers the design and development of an advanced UAV system, focusing on software, electronics, onboard components, and ground equipment. It conducts an extensive review of existing UAV technologies in control, navigation, guidance, datalink, and video systems, laying the groundwork for identifying crucial requirements. The research progresses to custom system realization, achieving full autonomy and successful validation through flight simulator testing and real-world autonomous flights. Notably, the thesis explores GNSS-denied navigation, enhancing adaptability in GNSS-challenged environments. By bridging gaps in UAV technology, this work offers a comprehensive blueprint for creating sophisticated UAVs, poised to advance autonomy and operational adaptability across diverse applications.

Keywords: unmanned system, fixed wing aircraft, remote control, autonomous control, navigation, GNSS-denied navigation, datalink, WiFi, video system, camera, RTSP, H265, maps, coordinate systems, software

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Abstrakt

Tato práce se zabývá vývojem pokročilého systému dálkového řízení bezpilotního letounu se zaměřením na software, elektroniku, palubní komponenty a pozemní vybavení. Provádí rozsáhlou rešerši stávajících technologií v oblasti řízení, navigace, datového spojení a videosystémů, čímž pokládá základy pro identifikaci klíčových požadavků. Výzkum postupuje k realizaci vlastního systému, dosažení plné autonomie a úspěšnému ověření prostřednictvím testování při použití leteckého simulátoru a reálných autonomních letů. Práce také stručně seznamuje možnostmi navigaci bez GNSS, které zvyšují bezpečnost, robustnost a adaptabilitu pro provoz v těchto prostředí. Díky komplexní integraci systémů a technologií klíčových v oblasti bezpilotních letounů nabízí tato práce komplexní plán pro vytvoření sofistikovaného systému, který je připravem pro plnou autonomii a odemyký možnosti dalšího výzkumu.

Klíčová slova: bezpilotní systém, letadlo s pevným křídlem, dálkové řízení, autonomní řízení, navigace, navigace bez GNSS, datalink, WiFi, video systém, kamera, RTSP, H265, mapy, souřadnicové systémy, software

Překlad názvu: Návrh a ověření systému pro vzdálené řízení bezpilotního systému

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Chapter 1

Introduction

1.1 Motivation

Unmanned Aerial Vehicles (UAVs) are proving to be increasingly valuable across diverse industries. In agriculture, they are used for crop monitoring, precision farming, and pesticide spraying, leading to higher yields and greater efficiency. In conservation, UAVs aid in wildlife tracking, habitat monitoring, and anti-poaching efforts, ultimately contributing to the preservation of biodiversity. In disaster management, they help assess affected areas quickly, deliver aid, and support search and rescue missions. Infrastructure inspection is also transformed by UAVs, enabling safer and more comprehensive assessments of bridges, pipelines, and buildings. Beyond these uses, UAVs also serve critical roles in cinematography, aerial photography, and parcel delivery services, demonstrating their adaptability across both entertainment and logistics sectors.

In recent years, the use of unmanned aerial vehicles UAVs has skyrocketed due to impressive technological advancements. With drones now being more affordable, efficient, and versatile than ever before, they have become increasingly popular across a broad range of industries. The miniaturization of sensors, improved battery life, and enhanced autonomy have expanded their capabilities, making them accessible to an even broader range of users. Governments around the world have adopted regulatory frameworks that make it easier to operate them, fueling their rise. This has led to innovative applications across various sectors, driving research and development toward more specialized and sophisticated UAV designs. The rapid evolution of

UAV technology continues to push new boundaries, promising even more groundbreaking uses and advancements in the years ahead.

The inspiration for selecting this particular topic for my thesis stems from my two significant passions: aviation and technology. As a passionate pilot, I have been actively involved in aviation, experiencing the intricacies and wonders of flight firsthand. Furthermore, my enthusiasm for technology has been an ongoing journey, exploring its advancements and applications in various domains. The intersection of these passions forms the cornerstone of my interest, presenting a compelling crossover. This thesis serves as an attempt to merge my expertise as a pilot with my fascination for technology, delving into the intersection where innovation meets the skies, creating a rich and promising terrain for exploration.

As a pilot, I bring a distinctive perspective to my technical aerospace education. My firsthand experience of flying enriches my understanding and imbues my technical knowledge with practical depth and a visceral sensation that cannot be found in textbooks alone. This combination of real-world insight and formal education has honed my approach to academic pursuits, affording me a comprehensive and multidimensional understanding of the intricate nuances within the aviation realm.

My current job has been a great opportunity for me to combine my passions for aviation and technology. I've been able to use these interests to create practical solutions that have greatly influenced my thesis. The connection between my work and academic pursuits has provided me with valuable resources and firsthand insights that have been instrumental in bringing my thesis aspirations to life.

1.2 Outline

The culmination of the work is a comprehensive end-to-end UAV solution, encompassing meticulous hardware selection and the intricate realization of software for both onboard and ground equipment. My work encompasses a comprehensive spectrum of elements crucial to the seamless operation of unmanned systems. The output of my efforts culminates in an integrated UAV ecosystem where hardware components synergize seamlessly with meticulously crafted software. This complete solution ensures a robust, reliable, and adaptable UAV system capable of undertaking diverse missions while empowering operators with efficient control and comprehensive oversight.

At the heart of the system lies a cohesive integration of critical components: the onboard software, the ground control station software, and the antenna panning flight tracking software. The onboard software serves as the operational brain, orchestrating and managing the UAV's in-flight functionalities, ensuring seamless navigation, data acquisition, and mission execution. The ground control station software acts as the nerve center, facilitating real-time communication, control, and monitoring of the UAV's activities from a centralized location, enabling operators to oversee and intervene as necessary. Complementing these, the antenna panning flight tracking software plays a pivotal role in ensuring precise and continuous tracking of the UAV's flight path, enabling accurate data transmission and reception by dynamically aligning the antenna with the UAV's movements. This trifecta of software components forms a robust and interconnected core, fostering efficient, reliable, and coordinated operations within the UAV system.

The objective of this thesis is to delve into the realm of a specific domain, scrutinizing the current solutions that exist and comparing and contrasting them in detail to discern their strengths and weaknesses. Through meticulous evaluation, my aim is to gain valuable insights into the current state-of-the-art practices, while critically analyzing their efficacy, limitations, and areas for potential improvement. By conducting an exhaustive analysis of these solutions, I will highlight their advantages and disadvantages. Based on this analysis, my work aims to propose a unique and innovative solution that addresses the identified limitations and builds on the strengths of the existing methodologies. By incorporating the best aspects and mitigating shortcomings, proposed solution intends to introduce a fresh and more effective approach, contributing to the evolution and betterment of the field.

Starting with the hardware aspect, the work involves strategically selecting electronics components, ensuring they align seamlessly to create a robust and efficient UAV system. This includes carefully considering flight and navigation computers, communication modules and ground control station equipment essential for system UAV performance.

From the software part which is the core of the works I focus on developing control, navigation, and guidance algorithms, meticulously engineered to optimize flight dynamics and ensure precise maneuvering in diverse operational environments. A focal point of my expertise lies in establishing secure and encrypted communication protocols, fand ortifying data transmissions to safeguard critical information from potential cyber threats. Additionally, I specialize in integrating sophisticated flight planning functions, enabling strategic mission execution. Moreover, my contributions extend to crafting robust ground station interfaces, equipped with multifaceted control options, comprehensive camera views, system-wide oversight, and a resilient map framework. This holistic approach creates an interconnected ecosystem, fostering efficient and secure unmanned system operations while empowering users with comprehensive control and situational awareness.My primary focus encompasses the domain of system design and software implementation, where I specialize in the conceptualization, architectural structuring, and practical realization of complex systems. My expertise lies in meticulously crafting design frameworks and blueprints that underpin the development of software solutions. It's noteworthy that the hardware infrastructure vital to these endeavors is facilitated through my ongoing work, providing the foundational support necessary for the software to function optimally. This collaboration between hardware and software elements harmonizes seamlessly, fostering the creation of comprehensive and innovative solutions. This symbiotic relationship ensures that software intricately interfaces and operates within the context of the hardware environment, aligning with the fundamental principles of robust system development and implementation.

Ensuring the utmost safety and reliability in unmanned systems is paramount, considering the absence of a human pilot as a failsafe and the limitations of manual control in unexpected scenarios, especially when the data link might be compromised. Therefore, comprehensive and rigorous testing procedures are absolutely crucial. The inherent risks associated with flying unmanned systems necessitate meticulous testing protocols to mitigate potential hazards. Integration with flight simulators is pivotal, providing a controlled environment to replicate real-world scenarios and thoroughly assess system responses, without risking physical assets or endangering lives. This connection to simulators facilitates exhaustive emulatinging for the emulation of various flight conditions, failure simulations, and system malfunctions, thereby ensuring that the unmanned system's functionalities are thoroughly vetted and capable of handling unforeseen circumstances. By conducting robust testing that mirrors real-life situations in a simulated, controlled environment, I strive to fortify the reliability and safety of these systems, significantly reducing risks in actual flight operations.

Chapter 2

Theoretical part

2.1 Available software solutions

The following sections describe market available software solutions for UAVs operation, their comparison and highlighs disadvantages and limitations.

2.1.1 Onboard control software

PX4

PX4 [7] is a versatile and adaptable open-source autopilot software suite that effectively controls UAVs for various applications. It offers a comprehensive platform that efficiently manages the flight dynamics and operations of drones, making it ideal for hobbyists, researchers, and industry professionals alike. Created through the collective efforts of a global community of experts, PX4 represents the epitome of cutting-edge technology and collaborative innovation, fostering an ecosystem that constantly pushes the boundaries of autonomous flight.

PX4 is renowned for its powerful and flexible flight control system, boasting a diverse range of control algorithms, sensor interfaces, and stabilization mechanisms. This robust core provides UAVs with the precision, stability, and adaptability required to operate seamlessly across varied environments and mission profiles.

A standout feature of PX4 is its modular design, allowing for effortless integration with a broad spectrum of hardware platforms - from commercial off-the-shelf components to specialized systems. This flexibility empowers users to customize their UAV configurations according to their specific needs, ensuring compatibility with different sensors, communication modules, and airframes. PX4's adaptability extends to accommodating various vehicle types, including multirotors, fixed-wing aircraft, VTOLs, and hybrid configurations.

PX4's mission planning and execution tools are equally impressive, providing sophisticated functionalities that enable users to design complex mission paths, define waypoints, execute autonomous flight maneuvers, and collect data with precision. This comprehensive mission planning framework is integral to aerial surveys, search and rescue operations, environmental monitoring, and other applications.

PX4's collaborative and open-source approach is central to its success, fostering an active community of developers, researchers, and enthusiasts. This community-driven ethos encourages continuous improvement, innovation, and knowledge sharing, resulting in a dynamic ecosystem that continually evolves to meet emerging challenges and technological advancements.

In conclusion, PX4 is a cornerstone of the UAV technology industry, offering a comprehensive, adaptable, and extensible platform for developing, deploying, and advancing autonomous flight systems. Its robust capabilities, commitment to openness, and community-driven ethos continue to drive innovation, shaping the future of unmanned aerial vehicles across industries and applications worldwide.

iNav

iNAV [2] is another prominent open-source flight control software tailored explicitly for multirotor and fixed-wing UAVs. Renowned for its user-friendly interface and robust capabilities, iNAV serves as a comprehensive platform catering to both enthusiasts and professional drone operators. Developed collaboratively by a dedicated community of developers and enthusiasts, iNAV focuses on delivering a streamlined and accessible solution for autonomous flight and navigation.

At its core, iNAV encompasses a suite of features that empower UAVs with precise and reliable flight control. This includes advanced stabilization algorithms, sensor integration, and navigation systems that facilitate stable and accurate flight across various mission profiles. The software's emphasis on user-friendliness is evident in its intuitive configuration interface, making it accessible for users with diverse skill sets, from beginners to experienced pilots.

One of iNAV's distinguishing traits is its specialization in multirotor platforms, providing tailored support and optimization for these vehicles. It includes a range of flight modes optimized for multirotor operation, enabling functionalities like position hold, altitude hold, return-to-home, and autonomous missions with ease.

Moreover, iNAV offers extensive mission planning capabilities, allowing users to define waypoints, set flight paths, and execute complex missions autonomously. This functionality is instrumental in aerial photography, surveying, and mapping applications, where precise and automated flight paths are crucial.

The software's adaptability and flexibility extend to its compatibility with various hardware components commonly used in UAVs. This versatility enables users to integrate iNAV with various flight controllers, GPS modules, sensors, and other peripherals, allowing for various configurations tailored to specific needs.

The collaborative nature of iNAV's development fosters a supportive and engaged community of users and contributors. This collaborative environment encourages knowledge sharing, continual improvement, and the evolution of the software to meet the evolving demands of the drone industry.

In essence, iNAV is a comprehensive and accessible open-source solution, empowering users with the tools and functionalities necessary for stable, autonomous, and precise flight control in multirotor and fixed-wing UAVs. Its user-friendly interface, specialized features for multi rotors, and extensive mission planning capabilities make it a valuable asset for drone enthusiasts and professionals seeking a reliable and adaptable flight control system.

Ardupilot

Ardupilot [1] is an open-source autopilot system that is widely known for its versatility, robustness, and extensive capabilities in governing various unmanned vehicles. It is developed by a global community of developers, researchers, and enthusiasts, and powers diverse aerial and ground-based vehicles, including multirotors, fixed-wing aircraft, helicopters, rovers, and boats.

At its core, Ardupilot is equipped with a sophisticated and adaptable flight control system that offers a wide range of features essential for autonomous flight and navigation. This includes advanced control algorithms, sensor fusion, GPS integration, and stabilization mechanisms that collectively ensure precise and stable flight across different environments and mission profiles.

One of Ardupilot's unique attributes is its modular architecture, which allows seamless integration with a wide range of hardware components and configurations. This flexibility enables users to customize their vehicles with various sensors, communication modules, and peripherals, adapting the system to suit their specific requirements and vehicle types.

Ardupilot's rich assortment of flight modes and mission planning tools also stands out as a testament to its capabilities. It offers an extensive range of flight modes, including autonomous, manual, and assisted modes, empowering users to execute missions with ease. Additionally, the mission planning functionality allows users to define complex flight paths, set waypoints, and perform automated missions for applications such as aerial surveying, mapping, and data collection.

Furthermore, the software's user-friendly Ground Control Station (GCS) interface provides operators with comprehensive control and monitoring capabilities. This interface allows real-time telemetry, parameter adjustments, and mission monitoring, enhancing situational awareness and control during flight operations.

Ardupilot's open-source nature fosters a vibrant and collaborative community, encouraging contributions, knowledge sharing, and continuous advancements. This collective effort results in a constantly evolving ecosystem that adapts to emerging technological trends and challenges in the unmanned systems domain.

In summary, Ardupilot is a versatile and robust open-source solution that provides a comprehensive suite of features and functionalities for autonomous flight control across various unmanned vehicle platforms. Its adaptability, rich feature set, and community-driven development approach continue to position it as a leading choice for enthusiasts, researchers, and industry professionals seeking reliable and advanced autopilot systems for unmanned vehicles.

2.1.2 Mavlink

Micro Air Vehicle Link (MAVLink) is a communication protocol that enables the exchange of information between unmanned systems components. It is a lightweight, efficient, and standardized way of communication, providing seamless interactions between various onboard and ground-based systems within the MAVLink ecosystem.

Overview

MAVLink is a protocol that is designed to be lightweight, allowing for efficient data exchange with minimal overhead. This makes it ideal for use in environments that have limited resources and require fast communication between components. Additionally, MAVLink is versatile and platform-independent. It is compatible with various hardware and software setups, and can be integrated with different autopilot systems, ground control stations, onboard computers, and peripherals. MAVLink operates on a message-based structure, which enables various modules or components to exchange information in a structured and standardized format.

Features

MAVLink is a protocol that enables the exchange of telemetry data between an autopilot system and ground control stations. With MAVLink, users can monitor real-time vehicle status, sensor readings, and other vital information. It also facilitates the transmission of commands from the ground control stations to the vehicle, enabling operators to execute specific actions such as mode changes, waypoints, or mission-related instructions. Additionally, MAVLink allows for remote configuration and adjustment of vehicle parameters, enabling users to fine-tune settings without direct physical access to the vehicle. Finally, it supports the transmission of mission plans or waypoints from ground control stations to the vehicle, enabling autonomous execution of predefined tasks or routes.

Advantages

The MAVLink protocol offers a standardized approach to facilitate efficient communication between unmanned systems. Its interoperability capabilities foster seamless integration of components and systems, regardless of their origin. The lightweight design of MAVLink makes it an ideal option for exchanging data in resource-constrained environments. Moreover, the message-based framework of MAVLink is incredibly versatile, enabling the inclusion of new message types or features in response to changing needs.

Disadvantages

Despite its adaptability and lightweight design, there are some limitations to keep in mind. In situations with restricted bandwidth, such as long-range communication or high data rate requirements, transmitting large amounts of data with MAVLink may prove challenging. Additionally, as an open protocol, it's important to address potential security vulnerabilities in the implementation of MAVLink. While widely adopted, it's crucial to consider bandwidth limitations and security concerns in certain applications.

2.1.3 Ground control software

Managing and monitoring unmanned systems is made possible through Ground Control Software (GCS), which provides a centralized interface for vehicle interaction. Here's an overview of GCS for PX4, iNAV, and Ardupilot flight computers:

PX4's Ground Control Software

QGroundControl [8] stands as the primary GCS for PX4-powered vehicles. It offers a comprehensive and user-friendly interface for mission planning, real-time telemetry monitoring, vehicle setup, and firmware updates. QGroundControl is compatible with various operating systems, including Windows, macOS, Linux, and Android, catering to diverse user preferences.

iNAV's Ground Control Software

The iNAV Configurator [3] is a highly intuitive GCS that empowers users to customize and optimize multirotor flight controls. Tailored specifically to iNAV-powered drones, this GCS is accessible via desktop application and is compatible across multiple operating systems including Windows, macOS, and Linux. Notably, while the iNAV Configurator excels in pre-flight configuration and tuning, it does not offer real-time monitoring options such as camera views.

Ardupilot's Ground Control Software

Mission Planner [6] and QGroundControl [8]: Ardupilot is compatible with multiple GCS options, including Mission Planner and QGroundControl. Mission Planner, primarily used for Windows-based systems, offers extensive mission planning tools, configuration options, and real-time telemetry monitoring for Ardupilot-powered vehicles. QGroundControl also supports Ardupilot vehicles, providing a user-friendly interface for mission planning, setup, and monitoring across various operating systems.

Summary

The interface between users and their UAVs is essential, and the GCS for PX4, iNAV, and Ardupilot plays a critical role in facilitating this communication. These platforms - QGroundControl for PX4, iNAV Configurator for iNAV, and Mission Planner/QGroundControl for Ardupilot - use the MAVLink protocol to establish a reliable connection between the GCS and the autopilot system on the vehicle. Through this link, users can access telemetry data, configure parameters, plan missions, and interact with their drones in real-time. This level of control and oversight is vital for ensuring the safe and effective operation of unmanned systems. While QgroundControl and MissionPlanner provide a wealth of in-flight monitoring and control options, iNav is more geared towards preflight setup and tuning.

2.1.4 Integration of video systems

When integrating video systems with autopilot solutions such as PX4, iNAV, and Ardupilot, it's often necessary to establish a separate communication pathway specifically for video transmission. This additional pathway is necessary in addition to the primary telemetry and control channels. To accomplish this, there are various datalink and transmission protocol options available that offer sufficient bandwidth (discussed in later sections of the thesis). Additionally, some GCS software may offer integration or plugins that allow for viewing or recording of the video stream. However, it's important to keep in mind that the primary function of GCS software is to handle telemetry data and mission planning, rather than managing the video stream itself.

Numerous UAV users still prefer to use separate video channels with analog transmission, but this method poses challenges for onboard video processing due to the lack of direct integration capabilities offered by digital transmission. Consequently, it's challenging to smoothly integrate the video feed into both onboard systems and ground software. By adopting digital transmission, UAV systems become more efficient and streamlined, enabling direct integration of the video feed into both onboard and ground software. This approach enhances compatibility and communication among the various components, optimizing the overall performance and functionality of UAV systems.

2.1.5 Comparison

In the world of unmanned aerial vehicles (UAVs), open-source frameworks such as PX4, iNAV, and ArduPilot are highly sought-after due to their flexibility and customizability. These frameworks incorporate MAVLink, which enables efficient communication and control between various UAV components. PX4 stands out for its advanced capabilities and reliable groundstation software, making it an excellent choice for mission planning and control. Meanwhile, iNAV boasts a lightweight design that prioritizes simplicity, although it may not be suitable for complex operations. ArduPilot offers a wealth of features that cater to a wide range of user preferences, although some may find it overwhelming. Regardless, each platform plays a vital role in the UAV ecosystem, providing users with diverse options and seamless communication through MAVLink.

2.2 Limitations of available systems

These systems offer a wide range of capabilities but their complexity makes it difficult to develop custom features. Their extensive codebases can be challenging to understand fully, and while they provide comprehensive functionalities, they may be overwhelming for some users who are limited by the boundaries set by the maintainers. In general, most UAV applications do not use all of their options, and the remaining code can result in unexpected behavior and unnecessary complexity, which can complicate development and safe operation.

Based on my research and experiments, I have found some notable limitations in areas such as advanced flight plan guidance, custom self-check protocols, video stream integration, and limited options for failsafe measures, all of which are important for specialized applications. Additionally, support for automated takeoffs and landings remains significantly restricted, which limits the potential for more sophisticated autonomous functionalities.

2.3 Datalink

The utilization of Radio Frequency (RF) technologies is crucial for establishing reliable data links for UAVs. These technologies enable seamless communication between the UAV and ground control stations or other connected devices. It's worth noting that each technology has its own unique set of benefits and drawbacks when it comes to factors such as range, data rate, power consumption, and suitability for various applications.

2.3.1 WiFi (IEEE 802.11)

Wireless Fidelity (Wi-Fi) is a commonly used RF technology for UAV data links. It operates in the 2.4 GHz and 5 GHz frequency bands, offering relatively high data rates and good throughput capable of video stream transmission for short to medium-range communication. Wi-Fi provides reliable connections for real-time video streaming, telemetry, and control signals. However, its range is limited compared to some other technologies.

Standards

Wi-Fi networks rely on their standards, which are protocols that outline the rules and specifications for wireless communication. By enabling devices to connect and exchange data over local area networks, these standards offer distinct enhancements in data rates, frequency bands, modulation techniques, and features. Their importance lies in determining the speed, range, and overall performance of wireless networks, as well as in ensuring compatibility and promoting connectivity across diverse devices and applications.

802.11b

Introduced in 1999, it operates in the 2.4 GHz band and offers a maximum bandwidth of 11 Mbps.

802.11a

Also introduced in 1999, it operates in the 5 GHz band and provides higher data rates up to 54 Mbps. However, its shorter range compared to 802.11b in the 2.4 GHz band limited its widespread adoption.

802.11g

Introduced in 2003, it operates in the 2.4 GHz band and offers data rates up to 54 Mbps. It's backward compatible with 802.11b.

802.11n

Introduced in 2009, it operates in both 2.4 GHz and 5 GHz bands and supports Multiple Input Multiple Output (MIMO) technology. It offers higher throughput, reaching up to 600 Mbps.

802.11ac

Introduced in 2013, it operates in the 5 GHz band and supports wider channels and more spatial streams than 802.11n. It can provide multi-station WLAN throughput of over 1 Gbps and is known as Wi-Fi 5.

802.11ah

IEEE 802.11ah, known as Wi-Fi HaLow, operates in the Sub-1 GHz band, offering extended range and lower power consumption tailored for Internet of Things (IoT). It covers several kilometers, conserves power for battery-operated devices, and delivers reasonable data rates (up to several Mbps) suitable for IoT applications like smart homes, agriculture, and industrial IoT.

802.11ax (Wi-Fi 6)

Introduced in 2019, it operates in both the 2.4 GHz and 5 GHz bands and introduces Orthogonal Frequency Division Multiple Access (OFDMA) and Multi-User Multiple Input Multiple Output (MU-MIMO) technologies. It offers higher efficiency, capacity, and performance in crowded environments and can support multi-gigabit speeds.

802.11be (Wi-Fi 7)

Expected to be the next generation, Wi-Fi 7 aims to improve speed, capacity, and latency further, focusing on advancements like more advanced MIMO, improved efficiency, and higher frequency operation.

Although newer Wi-Fi standards, such as 802.11ac or 802.11ax Wi-Fi 6), offer faster data rates, older standards like 802.11n may be more effective for long-range connectivity because they support more durable modulation schemes and are compatible with older devices. Generally, newer standards provide wider channel widths and higher throughput, resulting in greater bandwidth. However, in situations where stability is more important than maximum speed, using older standards with narrower channels can be beneficial. Older standards often offer more robustness and compatibility in challenging environments, while newer standards provide higher performance and efficiency in optimal conditions.

Channel Width

The Wi-Fi channel's width is a crucial factor that determines the performance and data capacity of a wireless network. It refers to the spectrum bandwidth range assigned for wireless data transmission within the network and dictates the available space for information transmission. The width typically ranges from 20 MHz to 160 MHz and plays an essential role in determining the network's efficiency.

While wider channel widths can support higher data rates, they are more susceptible to interference. Conversely, narrower widths offer better resistance to interference, more channels, and are ideal for robust connections over longer distances. Choosing the optimal channel width is crucial to achieving the right balance of data throughput, range, and network reliability across various wireless environments.

Long Range

Narrower channel widths (20 MHz or less) are often more suitable for long-range Wi-Fi. They experience less interference, propagate better through obstacles, and can provide more robust connections over extended distances.

Bandwidth

Narrower channel widths typically offer lower overall bandwidth compared to wider channels. However, in scenarios where long-range communication is a priority, sacrificing some bandwidth for a more reliable connection might be preferred.

Robustness

Narrower channels tend to be more robust in environments with interference or signal congestion since they have more available channels and experience less interference from neighboring networks.

Modulation

The process of Wi-Fi modulation involves transforming data into radio waves, which are then transmitted wirelessly. It is a crucial component of wireless communication that determines how information is encoded onto the radio signal. Modulation techniques, such as Binary phase-shift keying (BPSK), Quadrature phase-shift keying (QPSK), and Quadrature amplitude modulation (QAM), manipulate the amplitude, phase, or frequency of the signal to represent digital information. These modulation schemes play a significant role in determining data transfer rates, signal strength, and the ability to transmit data over specific distances. Selecting the appropriate modulation scheme is essential for optimizing data transmission efficiency and reliability in Wi-Fi networks across various environments and usage scenarios.0

Long Range

Modulation techniques like BPSK or QPSK are more robust and can maintain connections over longer distances compared to more complex modulations like high-order QAM (256-QAM, 1024-QAM), especially in environments with lower signal-to-noise ratios.

Bandwidth

More advanced modulation schemes offer higher data rates but might be less reliable over longer distances or in environments with obstacles or interference.

Robustness

Robust modulation schemes can handle interference and signal degradation better, ensuring a more stable connection, albeit potentially at the expense of maximum data rates.

Security

Wi-Fi security involves a range of measures aimed at protecting wireless networks from unauthorized access, data breaches, and various cyber threats.

Here are key aspects of Wi-Fi security:

Encryption Protocols

WPA3/WPA2: Wi-Fi Protected Access (WPA) protocols establish encrypted connections between devices and networks, ensuring that data transmitted over the network remains confidential and secure. WPA3 is the latest and most secure protocol, offering stronger encryption than its predecessor WPA2.

Authentication Mechanisms

Pre-Shared Key (PSK) Often used in home networks, PSK requires a passphrase or key for devices to authenticate and access the network.

Enterprise Authentication (EAP) Common in business settings, EAP involves a centralized authentication server (like RADIUS [9]), requiring individual user credentials for network access.

Network Segmentation

Virtual Local Area Networks (VLANs) Segmentation divides networks into separate segments, restricting access between them. It limits the impact of a breach by containing it within a specific segment.

Firewalls and Intrusion Detection/Prevention Systems (IDS/IPS)

Firewalls Control and monitor incoming and outgoing network traffic, blocking unauthorized access and filtering potential threats.

IDS/IPS Detect and respond to suspicious activities, alerting administrators or taking automated actions to prevent security breaches.

Regular Software Updates

Keeping routers, access points, and connected devices up-to-date with the latest security patches and firmware helps address known vulnerabilities and protect against potential exploits.

Access Control Measures

MAC Address Filtering Restricts network access to devices with approved MAC addresses, though it's not foolproof due to address spoofing.

Strong Password Policies Enforcing complex, unique passwords reduces the risk of unauthorized access by preventing easy guessing or brute-force attacks.

Disabling Unnecessary Services

Turning off unnecessary features like Wi-Fi Protected Setup (WPS) or remote management minimizes potential entry points for attackers.

User Education and Awareness

Educating users about common threats like phishing attacks, emphasizing the importance of secure passwords, and raising awareness about the risks associated with connecting to unsecured networks helps mitigate human-related security risks.

Regular Security Audits and Monitoring

Conducting periodic security audits and continuously monitoring network traffic helps identify vulnerabilities and potential security breaches, allowing for proactive measures to strengthen security.

Wi-Fi security involves a multi-layered approach, implementing various measures to create a robust defense against potential threats and vulnerabilities, ensuring the confidentiality, integrity, and availability of wireless networks and the data transmitted over them.

Wi-Fi as UAV datalink

Wi-Fi technology stands as an excellent choice for UAV datalink applications due to its adaptable nature, offering a balanced combination of range, bandwidth, and versatility. With the ability to provide reliable connectivity over considerable distances, Wi-Fi ensures effective communication between UAVs and ground control stations. Its versatility accommodates various mission needs, delivering ample bandwidth for real-time video streaming, telemetry, and control signals. Wi-Fi's adaptability allows for seamless integration of UAV systems, optimizing performance while offering the flexibility needed to navigate diverse operational environments.

Potential threads

The use of Wi-Fi to communicate with UAVs introduces a number of potential security risks. These risks include the possibility of unintentionally disclosing the UAV's presence or location, as well as threats to the security of data transmission and the UAV's overall operational security. While Wi-Fi signals can offer high data rates, their relatively short range makes them susceptible to interception or tracking. This vulnerability can be exploited by adversaries to intercept UAV signals and potentially uncover sensitive information about the UAV's location or flight path. Additionally, Wi-Fi networks are vulnerable to cyber attacks, such as unauthorized access, signal jamming, or data interception, which can compromise control signals or sensitive mission data. To ensure the safety and confidentiality of UAV operations, it is crucial to secure Wi-Fi-enabled UAVs with robust encryption, secure authentication mechanisms, regular security updates, and measures to minimize location exposure.

2.3.2 LoRa (Long Range)

Long Range (LoRa) is a low-power, wide-area networking technology that operates in sub-GHz bands. It boasts excellent long-range communication capabilities, covering distances ranging from several to tens of kilometers, all while maintaining low data rates. LoRa is particularly useful for applications that require low bandwidth, such as environmental monitoring, remote sensing, or low-frequency telemetry. Its low power consumption ensures a longer battery life.

Key components

Technology and Range

LoRa utilizes spread spectrum modulation techniques, operating in unlicensed frequency bands (such as 433 MHz, 868 MHz, or 915 MHz), enabling long-range communication. It can cover several kilometers in urban environments and even more in rural settings with low power consumption.

Low Power and Battery Efficiency

LoRa devices are energy-efficient, allowing battery-operated sensors and devices to operate for extended periods, making it ideal for applications requiring long-lasting, low-maintenance connectivity, such as smart agriculture, asset tracking, or environmental monitoring.

Network Topology

LoRa supports various network topologies, including point-to-point, star, and mesh networks. Its flexibility enables connectivity between devices (nodes) directly to gateways or through intermediate nodes, providing scalability and adaptability to different deployment scenarios.

Data Rates and Payload

While LoRa offers long-range connectivity, its data rates are lower compared to other technologies like Wi-Fi or cellular networks. It's well-suited for applications transmitting small packets of data intermittently rather than continuous high-bandwidth requirements.

Security

Long Range Wide Area Network) (LoRaWAN), built on top of LoRa technology, incorporates robust security features. It employs encryption and authentication mechanisms to secure data transmission, ensuring the confidentiality and integrity of information exchanged over LoRa networks.

Applications

LoRa finds applications across various industries, including smart cities (for smart metering, waste management), agriculture (crop monitoring, livestock tracking), logistics (asset tracking, supply chain management), and environmental monitoring (air quality, water management).

Open Standard and Ecosystem

LoRa is an open standard, fostering a diverse ecosystem of devices, gateways, and network providers. This openness promotes interoperability and allows for innovation and customization in IoT deployments.

Adjustable parameters

In LoRa technology, similar to Wi-Fi, there are adjustable parameters that can be configured to optimize communication based on the specific requirements of the application. Two significant adjustable parameters in LoRa are:

Spreading Factor

Spreading factor determines how data is modulated before transmission. LoRa uses a modulation technique called Chirp Spread Spectrum, and the spreading factor controls the chirp rate. Lower spreading factors (e.g., SF7) result in faster data rates but shorter range, while higher spreading factors (e.g., SF12) allow for longer range but lower data rates. Adjusting the spreading factor enables optimization between range and data rate based on the application's needs.

Bandwidth

LoRa allows for adjustable bandwidths ranging from 125 kHz to 500 kHz. Bandwidth selection affects the amount of spectrum used for transmission. Narrower bandwidths lead to longer transmission times but offer better signal robustness and range, whereas wider bandwidths allow higher data rates but may reduce the signal's robustness and coverage.

LoRa as UAV datalink

The innovative LoRa technology proves to be a viable and versatile solution for long-range, small bandwith, low-power communication in UAVs. Its extended range transmission capabilities, coupled with energy conservation, make it the ideal choice for UAVs requiring reliable connectivity over expansive areas.

What's more, LoRa can penetrate obstacles and is robust against interference, ensuring seamless transmission of critical telemetry, control commands, and sensor data in remote or challenging terrains. Its flexibility in supporting diverse network topologies and cost-effectiveness render it a compelling option for UAV datalinks, enabling extended flight missions and ensuring consistent communication throughout the UAV's operation.

Potential threads

Employing LoRa as a datalink for UAVs presents distinct security challenges, including the potential revelation of the UAV's location. While LoRa offers extended range and low-power communication, its signals, if intercepted, could expose the approximate location of the UAV. Malicious entities might exploit this vulnerability to track or compromise the UAV's operations. Additionally, LoRa networks, though robust, are susceptible to signal interception, manipulation, or even jamming, potentially compromising the UAV's telemetry data or control commands. Securing LoRa-enabled UAVs necessitates robust encryption, authentication protocols, and vigilance against potential signal interception to safeguard against location exposure and protect sensitive mission details.

2.3.3 LTE

Long-Term Evolution (LTE) is a critical technological advancement in wireless communication that has become a standard for 4G networks. This network standard is known for its exceptional speed, efficient use of spectrum, and low latency. Thanks to advanced techniques like MIMO, OFDMA, and carrier aggregation, LTE provides a seamless streaming experience, speedy internet browsing, and strong connectivity across various mobile devices. Its widespread availability and technical sophistication make it an essential component of modern telecommunications, paving the way for the evolution of 5G networks and revolutionizing global connectivity for individuals and industries. Moreover, LTE-enabled UAVs can efficiently transmit high-quality video streams and large data sets over longer distances, making them ideal for high-bandwidth data transfer applications such as surveillance or emergency response.

Closed system

When compared to other technologies like Wi-Fi and LoRa, LTE functions within a relatively closed system. Unlike Wi-Fi, which commonly operates in unlicensed spectrum, LTE generally operates within licensed frequency bands. This means that strict regulatory compliance and operator control is required, which restricts widespread access and deployment. The closed nature of LTE means that it is mostly managed and operated by telecom carriers or licensed entities. In contrast to LoRa, which operates on open standards, LTE infrastructure and technology are proprietary. This means that specific licensing, certifications, and specialized equipment are necessary. As a result, the closed ecosystem of LTE limits flexibility and ease of deployment, making it more centralized and controlled in terms of network operation and expansion.

Security

LTE networks utilize a variety of security measures to safeguard communication, with a focus on preserving data confidentiality and connection security. These measures include the use of strong encryption standards like AES, mutual authentication, and key agreement protocols, ensuring data remains secure during transmission. To further enhance security, firewalls, intrusion detection, and network segmentation are employed to prevent unauthorized access and identify potential threats. Additionally, LTE networks implement subscriber identity privacy, secure handover procedures, and SIM/USIM security cards to provide additional layers of protection, enhancing their resilience against cyber threats and data breaches.

LTE as UAV datalink

Utilizing LTE as a datalink for UAVs is an optimal solution for fast and dependable communication. LTE boasts a robust and expansive infrastructure that allows for seamless transmission of telemetry, high-definition video feeds, and control signals over long distances. Its high bandwidth and low latency facilitate real-time data exchange, which is imperative for mission-critical tasks. The availability of LTE networks is widespread, ensuring consistent coverage, allowing UAVs to operate in diverse terrains and remote regions. Furthermore, LTE's evolving standards, including LTE-A and LTE-A Pro, guarantee continuous enhancements in data rates and network efficiency. By employing LTE as a UAV datalink, communication becomes more efficient and secure, ensuring uninterrupted connectivity throughout the mission.

Potential threads

The use of LTE as a datalink for UAVs poses potential security risks, including the inadvertent exposure of the UAV's location. Although LTE offers reliable and high-speed communication, its signals can be intercepted, revealing the UAV's location and compromising operational security. Malicious actors could exploit this vulnerability to track or disrupt UAV operations. Moreover, LTE networks are vulnerable to potential threats such as signal interception, manipulation, or jamming, which could jeopardize the confidentiality of the UAV's telemetry data or control commands. To safeguard sensitive information transmitted over LTE datalinks during UAV operations, it is critical to implement robust encryption, stringent access controls, and continuous monitoring.

2.3.4 5G

The newest cellular network technology, 5G, offers remarkable data rates, reduced latency, and improved capacity compared to LTE. It functions in both sub-6 GHz and mmWave frequency bands. For UAVs, 5G provides ultra-reliable, low-latency communication that enables real-time control and critical data transmission. With its exceptional throughput and low latency, 5G is an excellent choice for applications such as autonomous flight, remote inspection, and high-definition video streaming.

Closed system

The 5G technology system operates differently from Wi-Fi and LoRa, as it is relatively closed and relies on licensed spectrum. Unlike Wi-Fi, which operates on open standards and unlicensed spectrum, 5G requires strict regulatory compliance and centralized control from telecom operators. As a result, access and deployment are often restricted to licensed entities. Conversely, LoRa operates on open standards, allowing for more flexible deployment. The proprietary nature and licensing requirements of 5G networks may limit accessibility and deployment flexibility. 5G's closed approach emphasizes centralized control and regulatory adherence, whereas Wi-Fi and LoRa prioritize more open and adaptable structures.

5G as UAV datalink

The utilization of 5G as a datalink for UAVs has the potential to revolutionize communication during flight operations. With its ultra-low latency, high bandwidth, and superior reliability, 5G networks empower UAVs with real-time, high-definition data transfer, allowing for seamless transmission of telemetry, high-resolution imagery, and mission-critical commands. The multi-gigabit speeds and network slicing capabilities of 5G enable tailored network configurations, ensuring dedicated and secure channels for UAV communication, which ultimately enhances operational efficiency and safety. Moreover, 5G's ability to handle numerous connections concurrently assures reliable connectivity, enabling UAVs to navigate diverse environments and execute complex tasks with heightened responsiveness. The integration of 5G technology as a UAV datalink promises transformative possibilities for advanced and dynamic aerial missions as 5G technology continues to evolve.

Potential threads

Using 5G as a datalink for UAVs has some security concerns, such as accidentally revealing the UAV's location. Although 5G has excellent connectivity and low latency, intercepted signals could expose the UAV's whereabouts, potentially compromising operational security. This loophole could be exploited by malicious entities to track or disrupt the UAV's missions. The complexity of 5G networks also poses risks such as signal interception, manipulation, or jamming, which could jeopardize the confidentiality of the UAV's telemetry data or control signals. To address these risks, stringent encryption, robust authentication protocols, and constant monitoring are necessary to prevent location exposure and safeguard sensitive information transmitted over 5G networks during UAV operations.

2.3.5 Antennas

Antennas are crucial for establishing communication between a UAV and the ground station or other devices. A number of factors need to be considered when designing an effective antenna system for UAV datalinks. These include antenna type, gain, frequency, and amplification.

Antenna Types

Omni-directional Antennas

These antennas radiate and receive signals equally in all directions, providing a spherical coverage pattern. They are suitable for scenarios where the UAV might change orientation frequently during flight.

Directional Antennas

These antennas focus their radiation pattern in a specific direction, offering higher gain and longer range but with a narrower coverage area. They are beneficial for long-range communication where maintaining a constant direction of transmission is possible.

Gain

Antenna gain refers to the ability of an antenna to concentrate and direct radio frequency energy to a specific direction with precision. This property is measured in decibels (dB). Antennas with higher gain provide better performance and range, especially in directional antennas.

Antennas rely on the science of electromagnetic radiation and reception. When an electrical current flows through the antenna, it generates an electromagnetic field that propagates through space as radio waves. If these waves come across another antenna tuned to the same frequency, they induce a similar electrical current, enabling communication between the transmitting and receiving antennas.

Amplifiers

Datalink systems frequently employ amplifiers to increase the range of communication or reinforce weak signals. Low Noise Amplifiers are a popular choice as they enhance the signal-to-noise ratio and overall system performance by strengthening weak incoming signals before they reach the receiver.

To create a dependable and efficient antenna system, it's essential to consider a variety of factors to ensure reliable communication between the UAV and its connected devices, including the ground station. Careful consideration of the antenna type, frequency, gain, and other components, such as amplifiers, is necessary to meet the specific requirements and limitations of the UAV's mission.

2.3.6 Summary

Selecting the appropriate RF technology for UAV datalinks is a critical consideration that involves weighing a variety of factors, such as range, data rate, power usage, regulatory restrictions, and environmental conditions. WiFi technology is an excellent option that strikes a good balance between range and bandwidth, satisfying diverse UAV communication requirements. Implementing omnidirectional antennas in the air and directional antennas on the ground creates a robust configuration that optimizes signal coverage and strength. Depending on the particular application, some may demand long-distance communication with minimal energy consumption, such as LoRa for environmental monitoring, while others may prioritize fast data rates and low latency, like 5G for real-time video streaming in surveillance. Moreover, integrating multiple RF technologies or adopting hybrid solutions can enhance the overall effectiveness and dependability of UAV communication systems.

2.4 Camera

The camera settings of UAVs with cameras are crucial in capturing high-quality and precise aerial imagery. These settings are a complex combination of intrinsic and extrinsic parameters that impact the camera's internal characteristics and spatial relationship with the UAV. Intrinsic parameters like focal length, principal point, and lens distortion define the camera's internal characteristics, while extrinsic parameters like position, orientation, and field of view determine the camera's spatial relationship with the UAV. To ensure accurate spatial mapping and reliable aerial imagery, calibration procedures are necessary. These procedures involve using checkerboard patterns and computational tools like Matlab. This thesis delves into these parameters, their calibration methodologies, and their critical role in improving the precision and effectiveness of aerial imaging using UAV-mounted cameras.

2.4.1 Intrinsics parameters

The internal settings of a camera mounted on a UAV are referred to as intrinsic parameters, and they play a critical role in creating high-quality images. These parameters include the focal length, principal point, and lens distortion types, all of which affect image quality and perspective. Additionally, pixel size and aspect ratio are important factors in determining image resolution and shape. The intrinsic matrix combines all of these parameters to convert 3D world coordinates into 2D image coordinates, making it a crucial element in creating accurate images. Calibration procedures, such as checkerboard calibration, refine these parameters, eliminating distortions and optimizing accuracy. Understanding and precisely calibrating intrinsic parameters are necessary for tasks like image rectification and geometric analysis, ensuring that the information gathered from the UAV's camera imagery is reliable and precise.

2.4.2 Extrinsics parameters

In the realm of UAV-mounted cameras, extrinsic parameters hold great significance as they determine the camera's spatial position in relation to its surroundings. These parameters consist of the camera's position and orientation with respect to the UAV's frame of reference, which includes movement along the X, Y, and Z axes, as well as roll, pitch, and yaw angles. The field of view (FOV), characterized by horizontal and vertical angles, determines the scope of the captured scene. Precise calibration and understanding of these parameters are essential to achieve accurate spatial mapping and geometric precision in the captured imagery.

To align different reference frames, such as those of the UAV, camera, and world coordinates, transformation matrices are crucial. The accurate determination and refinement of these extrinsic parameters are vital for various applications, including photogrammetry, 3D reconstruction, and spatial analysis. Such precision ensures the dependability and authenticity of data obtained through UAV-captured imagery.

2.5 Video streaming

The act of transmitting live video footage captured by unmanned aircraft or drones to a ground station or remote device in real-time is known as video streaming. This advanced technology has become increasingly popular in a variety of industries, such as filmmaking, agriculture, surveillance, and disaster management, thanks to its exceptional capacity to offer aerial perspectives and real-time data.

2.5.1 Basic system overview

Camera and Drone Setup

UAVs can capture high-quality video with cameras that range in quality and specialization based on mission.

Video Transmission Systems

Unmanned aerial vehicles, commonly known as drones, possess video transmission systems that leverage wireless communication technologies, including for instance Wi-Fi and cellular networks. These systems enable the live streaming of video feeds to a ground station or remote device, with the quality and range of transmission varying based on the drone's features and intended purpose..

Ground Station or Remote Device

The live video feed is received and displayed on a ground station, computer, tablet, or smartphone. The users can then view, analyze, and act upon the footage in real-time.

Data Processing and Analysis

Advanced UAV systems may have onboard data processing to analyze live video feed, extract valuable information via object detection, image recognition, or other forms of analysis.

2.5.2 Challenges

Bandwidth and Range

For seamless video streaming, a reliable and high-speed internet connection is required. The range limitations can impact the quality and consistency of video transmission, while signal interference from environmental factors or other electronic devices can disrupt video transmission. Furthermore, any delays in video streaming can impede immediate decision-making in crucial scenarios.

2.5.3 Streaming protocols

The focus of this thesis is on the practical application of WiFi datalink capabilities for video streaming. It delves into the complex relationship between WiFi infrastructure, video streaming protocols, and encoding techniques. Specifically, the section narrows its focus to explore video streaming protocols and encoding methodologies that are intricately intertwined with WiFi transmission. By examining this symbiotic relationship, the objective is to dissect and illuminate the fundamental underpinnings, intricacies, and optimizations that are crucial for ensuring seamless, high-quality video delivery over Wi-Fi networks. Through this specialized lens, the theoretical discourse aims to unravel the critical components that shape the efficiency, reliability, and fidelity of video streaming within the domain of Wi-Fi datalink. This forms the foundation for practical implementation and informed technological advancements.

RTSP and RTP

The Real-Time Streaming Protocol (RTSP) is a crucial tool for managing the delivery of real-time media, including audio and video. It functions atop other communication protocols, such as Transmission Control Protocol (TCP) or User Datagram Protocol (UDP), and provides essential functionality for configuring, managing, and transmitting real-time data streams. One key point to keep in mind is that RTSP is not responsible for handling the actual transfer of media. Rather, it enables communication between a client and a server to determine the optimal method of media transmission.

Key Components of RTSP

Session Control: RTSP sets up and controls media sessions, allowing users to initiate, pause, play, or stop streaming media. It manages session control aspects without actually transmitting the media content itself.

Media Streaming Control: It handles the specifics of how media is streamed, including format negotiation, playback control, and managing different streams within a session (e.g., multiple audio channels, different video qualities).

URL Structure: RTSP uses URLs to identify media streams. These URLs often include information about the server, media type, and specific stream parameters.

Interoperability: It's designed to be highly interoperable with various media delivery systems, making it versatile for use across different platforms and devices.

Client-Server Interaction: RTSP operates on a client-server model, where the client initiates commands to the server for actions related to media stream setup and control.

Use Cases:

Live Streaming: RTSP is often used in live streaming scenarios, such as video conferences, live sports broadcasts, or live event streaming.

On-Demand Media: It's also used for on-demand media delivery, facilitating the control and delivery of stored media files.

Relation between RTSP and RTP

RTSP (Real-Time Streaming Protocol) and RTP (Real-Time Transport Protocol) are closely related protocols used for real-time media streaming but serve different purposes in the streaming process.

RTSP (Real-Time Streaming Protocol):

RTSP acts as a control protocol that facilitates the setup and control of media sessions between a client and server. It doesn't handle the actual transport of media data but focuses on session initiation, control commands (play, pause, stop), and metadata exchange. It operates on top of other protocols such as TCP and UDP and is responsible for negotiating the parameters of the media streams but doesn't transmit the media itself.

RTP (Real-Time Transport Protocol):

RTP, on the other hand, is responsible for the actual transmission of the multimedia data, such as audio or video streams. It handles the packetization, transmission, and reception of real-time data. RTP works in tandem with RTSP, delivering the media content in packets, each tagged with sequence numbers, timestamps, and payload types to ensure proper reconstruction and synchronization of the transmitted data on the receiving end. RTP typically uses UDP as its transport protocol due to its low-latency and real-time nature, but it can also work over TCP in some scenarios where reliable transmission is needed.

UAV-specific Considerations:

Real-time streaming of video feeds captured during flights can be facilitated by UAVs using RTSP. This protocol is especially useful for managing and controlling media sessions, making it an ideal solution for scenarios where quick access to live video feeds from aerial platforms is necessary for monitoring, surveillance, or navigation purposes. In essence, RTSP is a flexible protocol that prioritizes the establishment and management of media sessions, a critical factor in enabling real-time streaming applications across a range of fields, including UAV operations that demand efficient and interactive media transmission.

HLS

The HTTP Live Streaming (HLS) protocol was created by Apple to facilitate the distribution of live and pre-recorded multimedia content over the internet using regular HTTP web servers. This protocol splits multimedia files into smaller segments, allowing for adaptive bitrate streaming. HLS is a great solution for a variety of network situations, particularly those faced by UAVs where connectivity can be inconsistent or varied.

Benefits and Applications:

Adaptive Bitrate Streaming: HLS adapts to varying network conditions, providing a seamless viewing experience across different devices and network speeds.

Compatibility: Its use of HTTP enables straightforward integration with existing web infrastructure.

Live Streaming and VOD: Suitable for both live streaming events and on-demand video content delivery.

UAV-specific Considerations:

In the realm of UAVs, HLS is an invaluable tool due to its ability to enable adaptive bitrate streaming. Essentially, this means that the video quality can automatically adjust in real-time to accommodate changes in network conditions that may occur during flights. By offering multiple quality versions of the video, HLS ensures that the video playback remains seamless and uninterrupted, even when the network bandwidth experiences fluctuation. As a versatile streaming protocol, HLS is ideal for a range of applications, including UAV operations where network conditions may be less predictable. With its efficient and reliable multimedia streaming capabilities, HLS is a wise choice for UAV pilots seeking to optimize their video streaming experience.

MPEG-DASH

Dynamic Adaptive Streaming over HTTP (DASH) (MPEG-DASH) is a streaming protocol standardized by the Moving Picture Experts Group (MPEG) that enables adaptive bitrate streaming of multimedia content over HTTP servers, similar to HLS. It focuses on delivering high-quality video content to various devices and network conditions by dynamically adjusting the bitrate and resolution of video segments during playback.

Benefits and Applications:

Dynamic Adaptation: MPEG-DASH enables smooth playback by dynamically adjusting video quality based on changing network conditions.

Interoperability: Its standardized nature fosters compatibility across a wide range of devices, browsers, and streaming platforms.

Codec Flexibility: Supports multiple codecs, allowing content providers to choose the most suitable codec for their content.

UAV-specific Considerations:

MPEG-DASH plays a crucial role in UAV systems, particularly for its adaptive bitrate streaming capability. This feature enables the system to seamlessly adjust video quality in response to real-time changes in network conditions during flights. With multiple video quality versions available, MPEG-DASH ensures uninterrupted video playback by efficiently adapting to fluctuations in network bandwidth. Its flexibility and reliability make it an ideal streaming protocol for a wide range of applications, especially in UAV operations where network stability can be unpredictable. By providing efficient and dependable multimedia streaming, MPEG-DASH is a smart choice for UAV pilots looking to enhance their video streaming capabilities.

2.5.4 Encoding/Decoding

MJPEG

Motion JPEG (MJPEG) is a video compression format that treats each frame of a video sequence as a separate JPEG image. Unlike other video codecs like H.264/AVC or H.265/HEVC that use inter-frame compression, MJPEG encodes each frame individually without inter-frame dependencies.

Key Elements and Functions of MJPEG:

Frame-by-Frame Compression: Each frame in a video sequence is compressed as an individual JPEG image. This frame-by-frame approach simplifies the encoding process, as each frame is compressed independently without considering information from previous or future frames.

Simple Encoding and Decoding Process: MJPEG encoding and decoding processes are relatively straightforward, making it less computationally intensive compared to some other video compression standards. As each frame is compressed independently, decoding any specific frame doesn't require accessing other frames, simplifying random access and editing.

Quality and Bitrate Control: Offers control over the quality of each frame independently, allowing for consistent quality across frames. Bitrate control can be managed by adjusting the quality settings for individual frames.

Compatibility and Interoperability: MJPEG is widely supported across various platforms, devices, and software due to its simplicity and reliance on the JPEG compression standard.

Significance for UAVs:

When it comes to transmitting videos via UAVs, the MJPEG codec can be a wise choice. MJPEG compresses each frame separately, making decoding simple and efficient, which is especially advantageous in scenarios where computational resources are scarce. However, it's important to note that MJPEG may result in larger file sizes compared to more advanced codecs such as H.264/AVC or H.265/HEVC, which could pose a problem if bandwidth or storage space is restricted.

H264

Advanced Video Coding, or H.264/AVC, is a widely adopted video compression standard that was developed by the Joint Video Team (JVT) of the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG). Its efficient compression algorithms have made it a popular choice for video recording and streaming applications.

Key Elements and Functionalities of H.264/AVC:

High Compression Efficiency: H.264/AVC achieves significant compression while maintaining reasonable video quality. It efficiently reduces the file size of video content without substantial loss of visual fidelity.

Block-Based Compression: Utilizes block-based motion compensation and predictive coding techniques, breaking frames into smaller blocks to encode motion information efficiently. Implements inter-frame and intra-frame compression, capturing both spatial and temporal redundancies in the video data.

Multiple Profiles and Levels: Offers various profiles and levels, each with specific capabilities and constraints, catering to different applications and devices. Profiles include Baseline, Main, High, etc., providing options for encoding complexity and feature sets.

Support for Various Resolutions and Bitrates: Accommodates a wide range of resolutions and bitrates, making it adaptable to different display sizes and network bandwidths.

Compatibility and Adoption: Widely adopted across various devices, platforms, and software due to its efficiency, leading to its prevalence in video streaming, broadcasting, Blu-ray discs, and more.

Low Complexity for Decoding: Although encoding can be computationally intensive, decoding H.264/AVC videos is relatively less demanding, allowing playback on a wide array of devices, including those with limited processing power.

H.264/AVC for UAVs:

H.264/AVC proves to be the preferred codec among UAVs for its balanced compression efficiency and computational requirements. Its exceptional capability to reduce video file sizes while preserving high-quality standards is of utmost importance when streaming video feeds from aerial platforms where bandwidth may be limited. This codec enables the efficient transmission of superior video data, which is a vital aspect for real-time monitoring, surveillance, and numerous other UAV applications.

H265

H.265/HEVC, standing for High-Efficiency Video Coding, is the successor to H.264/AVC and represents a more advanced video compression standard developed by the Joint Collaborative Team on Video Coding (JCT-VC). It was designed to address the shortcomings of its predecessor while offering improved compression efficiency.

Key Elements and Functions of H.265/HEVC:

Enhanced Compression Efficiency: H.265/HEVC significantly improves compression efficiency compared to H.264/AVC, allowing for substantial reductions in file sizes without compromising on video quality. Achieves better compression by using more advanced encoding techniques, such as larger block sizes and more sophisticated motion compensation.

Increased Block Sizes and Coding Tools: Utilizes larger block sizes for encoding, allowing more efficient representation of complex areas in video frames. Incorporates advanced coding tools like improved intra prediction, better motion compensation, and enhanced entropy coding.

Support for Higher Resolutions and Bit Depths: H.265/HEVC efficiently handles higher resolutions, including 4K and even 8K, making it suitable for ultra-high-definition content. Supports higher bit depths, enabling a broader range of colors and enhancing visual fidelity.

Multiple Profiles and Levels: Similar to H.264/AVC, H.265/HEVC offers various profiles and levels catering to different applications and device capabilities.

Wide Adaptation and Compatibility: While its adoption is not as widespread as H.264/AVC, H.265/HEVC is increasingly supported across various platforms, devices, and software.

Significance for UAVs:

When it comes to UAVs, H.265/HEVC provides numerous benefits, especially in situations involving high-resolution video feeds or limited bandwidth. Compared to H.264/AVC, its compression efficiency is superior, enabling UAVs to transmit high-quality video with a reduced need for bandwidth. This is crucial for real-time video transmission during flight operations. With its support for higher resolutions and enhanced compression capabilities, H.265/HEVC is a promising option for optimizing video transmission from UAVs. It maintains a balance between high-quality video output and efficient data handling, making it a suitable choice for UAV applications.

H265+

H.265+ is an enhanced version or an optimized variant of the H.265/HEVC standard, designed to further improve video compression efficiency while maintaining high-quality video encoding.

Key Elements and Functions of H.265+:

Enhanced Compression Efficiency: H.265+ builds upon the foundation of H.265/HEVC by introducing additional optimizations in compression techniques, resulting in improved efficiency in reducing video file sizes.

Smart Encoding Algorithms: Utilizes advanced algorithms and optimizations, such as improved motion estimation and sophisticated prediction methods, to further reduce redundant information in video frames. Incorporates intelligent scene analysis to identify and encode specific areas or details more efficiently.

Reduction in Bitrate and Storage Requirements: Offers even more substantial bitrate savings compared to H.265/HEVC, enabling significantly reduced storage requirements without compromising video quality.

Improved Processing Efficiency: While maintaining high compression efficiency, H.265+ aims to optimize the computational workload, ensuring that the decoding process is manageable and efficient.

Compatibility and Adoption: While not as widely adopted as H.265/HEVC, H.265+ is increasingly being supported by some hardware and software manufacturers, especially in surveillance and security applications.

Significance for UAVs:

When utilized in UAV applications, H.265+ boasts several advantages, particularly in scenarios where bandwidth and storage efficiency are crucial. This codec provides superior compression efficiency when compared to H.265/HEVC, which is especially advantageous for UAVs that transmit high-quality video feeds in real-time while optimizing bandwidth usage. Its capacity to decrease bitrate without sacrificing quality makes it an ideal choice for UAV operations that require the optimal use of limited resources. However, it is worth noting that the degree of acceptance and support for this codec may differ depending on the specific hardware and software configurations available for UAV systems.

2.6 Navigational computing

For aerospace and robotics systems to achieve precise navigation, a strong computing framework is essential. This framework must seamlessly incorporate various coordinate systems like WGS84, ECEF, and NED, which serve distinct purposes but are interconnected. By doing so, accuracy and reliability in determining positions and guiding navigation are ensured.

To create an efficient UAV system, it is essential to comprehend several fundamental concepts. These include the variances in altitudes, distinguishing between heading and track, and understanding the differences between airspeed and true airspeed.

2.6.1 Coordinate systems and projections

For UAVs to navigate and move precisely, they rely on coordinate systems and world frames. These frameworks offer standardized ways to define positions and orientations in three-dimensional space, enabling UAVs to plan their flight paths and carry out maneuvers efficiently. Global frames, such as World Geodetic System 1984 (WGS84) or Earth-Centered Earth-Fixed (ECEF), provide a universal reference for positioning over long distances, while local frames like NED assist in localized control and maneuvering. These frameworks are instrumental in UAV operations as they ensure accurate spatial representation and facilitate effective aerial operations.

To accurately navigate, map, and use location-based technologies, projections like WGS84 are indispensable. Maps are two-dimensional, while the Earth is a three-dimensional sphere, making it challenging to represent its surface accurately. Projections solve this problem by transforming the spherical Earth onto a flat surface, preserving important properties like angles, shapes, distances, and areas. WGS84 is a widely used projection that defines a global reference system for GPS and mapping, providing a consistent framework to represent locations worldwide accurately. These projections are essential for various applications, ensuring precise spatial representation despite the Earth's curved surface.

WGS84

WGS84, or World Geodetic System 1984 [10], stands as a global standard for defining Earth's shape, size, and position. It's a geodetic reference system crucial for GPS navigation, mapping, and various location-based technologies. WGS84 utilizes a three-dimensional model to describe the Earth's surface, employing latitude, longitude, and ellipsoidal height to pinpoint locations. This system provides a consistent and precise global framework, allowing for accurate positioning on a planetary scale. WGS84 serves as the foundation for GPS systems, satellite imagery, cartography, and diverse geospatial applications, ensuring uniformity in location representation across the globe.

Following formula defines WGS84 point:

$$\boldsymbol{p}^{\text{WGS84}} \in \mathbb{R}^3 \tag{2.1}$$

where $p_1^{\text{WGS84}} = \text{latitude}$, $p_2^{\text{WGS84}} = \text{longitude and } p_3^{\text{WGS84}} = \text{altitude}$

WGS84 Ellipsoid parameters

In this section, fundamental WGS84 parameters essential for navigation computations are presented: the semi-major axis and flattening. These core parameters form the bedrock of geodetic reference systems.

parameter	symbol	value
`semi-major axis`	a	6378137.0 [m]
`flattening`	f	1/298.257223563 [-]

Table 2.1: WGS84 Ellipsoid parameters.

Normal radius

Normal radius of WGS84 Ellipsoid is *Latitude* dependend variable crutial for coordinate conversions.

$$n = \frac{a}{\sqrt{1 - ((f(2-f) - \sin(lat)^2}} \tag{2.2}$$

where a and f are parameters defined in Tab.: 3.1.

Tangent plane

Tangent plane of WGS84 ellipsoid is *Latitude* and *Longitude* dependend variable crutial for coordinate conversions represented by rotation matrix.

$$\boldsymbol{R}^{\text{WGS84}} = \begin{bmatrix} -\sin(lat)\cos(lon) & -\sin(lat)\sin(lon) & \cos(lat) \\ -\sin(lon) & \cos(lon) & 0 \\ -\cos(lat)\cos(lon) & \cos(lat)\sin(lon) & -\sin(lat) \end{bmatrix} \tag{2.3}$$

.

ECEF

The Earth-Centered, Earth-Fixed (ECEF) [10] coordinate system is a standardized, global three-dimensional framework used to precisely represent positions in relation to the Earth's center. The system employs Cartesian coordinates (X, Y, Z), with the origin situated at the Earth's geometric center. Applications that rely on the ECEF system include satellite-based navigation systems, geodesy, and aerospace engineering. This system enables accurate localization and provides a consistent framework for spatial representation on a global scale. ECEF coordinates are essential for satellite positioning, including GPS, and for precise calculations involving Earth's surface or orbits. Overall, the ECEF system serves as a fundamental reference for accurate positioning worldwide.

$$\boldsymbol{p}^{\text{ECEF}} \in \mathbb{R}^3 \tag{2.4}$$

where $p_1^{\text{ECEF}} = \text{x}$, $p_2^{\text{ECEF}} = \text{y}$ and $p_3^{\text{ECEF}} = \text{z}$

ECEF provides a global Cartesian coordinate system centered at Earth's center, enabling precise positioning relative to the planet's geometric center. It's crucial for satellite navigation systems like GPS and in aerospace engineering for satellite tracking, orbit calculations, and satellite positioning.

NED

The NED (North-East-Down) coordinate system [10] is widely used in fields like aerospace, robotics, and vehicle dynamics for localized navigation and control. Essentially, this system establishes positions relative to a specific reference point, which is often an aircraft, drone, or vehicle. The NED axes are oriented toward North, East, and Down directions from the perspective of the reference point. Due to its ability to provide a frame of reference relative to the object's orientation, NED simplifies calculations and control strategies, making it particularly useful for local maneuvering and control algorithms. In various applications where precise maneuvering, stabilization, and control are necessary, NED proves beneficial for local navigation and positioning.

$$\boldsymbol{p}^{\text{NED}} \in \mathbb{R}^3 \tag{2.5}$$

where $p_1^{\text{NED}} = \text{n}$, $p_2^{\text{NED}} = \text{e}$ and $p_3^{\text{NED}} = \text{d}$

NED is a local Cartesian coordinate system used for localized navigation, control, and maneuvering. It's beneficial in aerospace, robotics, and vehicle dynamics, providing a local frame of reference relative to a moving object's orientation for precise maneuvering and control.

Conversions

In this subsection, conversions between coordinate systems are presented. Conversions between WGS84 and NED frames use ECEF frame as a middle-man.

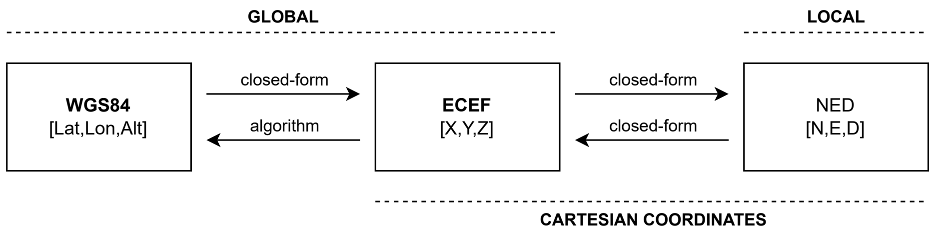

Figure 2.1: Coordinate systems - conversions.

WGS84 to ECEF

Following formula defines conversion from WGS84 frame to ECEF frame as a function $f : \boldsymbol{p}^{\text{WGS84}} \rightarrow \boldsymbol{p}^{\text{ECEF}}$ defined in 2.1 and 2.4 that is:

$$\begin{aligned} x &= (n + alt)\cos(lat)\cos(lon) \\ y &= (n + alt)\cos(lat)\sin(lon) \\ y &= (n(1 - (f(2 - f)) + alt)\sin(lat) \end{aligned} \tag{2.6}$$

where n is normal radius 2.2 and f is WGS84 Ellipsoid flattening 3.1.

ECEF to NED

Following formula defines conversion from ECEF frame to NED frame as a function $f : \boldsymbol{p}^{\text{ECEF}} \rightarrow \boldsymbol{p}^{\text{NED}}$ defined in 2.4 and 2.5 that is:

$$\boldsymbol{p}^{\text{NED}} = \boldsymbol{R}^{\text{WGS84}}\left(\boldsymbol{p}^{\text{ECEF}}_{\text{target}} - \boldsymbol{p}^{\text{ECEF}}_{\text{reference}}\right) \tag{2.7}$$

where $\boldsymbol{R}^{\text{WGS84}}$ is tanget plane rotation matrix 2.3.

NED to ECEF

Following formula defines conversion from NED frame to ECEF frame as a function $f : \boldsymbol{p}^{\text{NED}} \rightarrow \boldsymbol{p}^{\text{ECEF}}$ defined in 2.5 and 2.4 that is:

$$\boldsymbol{p}^{\text{NED}} = \left((\boldsymbol{R}^{\text{WGS84}})^{T}\boldsymbol{p}^{\text{ECEF}}_{\text{target}}\right) + \boldsymbol{p}^{\text{ECEF}}_{\text{reference}} \tag{2.8}$$

where $\boldsymbol{R}^{\text{WGS84}}$ is tanget plane rotation matrix 2.3.

ECEF to WGS84

Following iterative convergence algorithm defines conversion from ECEF frame to WGS84 frame as a function $f : \boldsymbol{p}^{\text{ECEF}} \rightarrow \boldsymbol{p}^{\text{WGS84}}$ defined in 2.4 and 2.1 that is:

Algorithm 1: ECEF to WGS84 algorithm

input : x,y,z
output : lat, lon, alt
$a = 6378137.0;$
$f = 1.0/298.257223563;$
$b = a * (1 - f);$
$e2 = 2 * (1 - f);$
$p = \sqrt{x^2 + y^2};$
$theta = \text{atan2}(z * a, p * b);$
$lat := \text{atan2}(z + e2 * b * \sin(theta)^3, p - e2 * a * \cos(theta)^3;$
$alt := 0;$
$n = \frac{a}{\sqrt{1-(f(2-f)-\sin(lat)^2}};$
$epsilon = 1e - 10;$
$maxiter = 100;$
$i = 0$ **while** $i < maxiter$ **do**
  $lat_n = \text{atan2}(z + e2 * n * \sin(lat), p);$
  $alt_n = \frac{p}{\cos(lat)} - n;$
  if $|lat - lat_n| \leq epsilon \ and \ |alt - alt_n| \leq epsilon$ **then**
    break
  end
  $lat = lat_n;$
  $alt = alt_n;$
  $n = \frac{a}{\sqrt{1-(f(2-f)-\sin(lat)^2}};$
end
$lon = \text{atan2}(y, x)$

2.6.2 Altitude

Measuring altitude can be a complex task, as it involves different reference frames and measures. Barometric altitude estimates height based on atmospheric pressure, but it's prone to inaccuracies due to weather changes and pressure variations. AMSL altitude is calculated based on a specific average sea level, providing a standardized reference point for elevation calculations, which is essential for aviation and geography. Geoid altitude refers to height relative to Earth's geoid, a model approximating global mean sea level, and is commonly used in geodetic surveys. GPS altitude determines elevation above Earth's ellipsoid using satellite signals, offering precise measurements, but it can be affected by satellite geometry and signal interference.

However, determining and comparing altitudes across diverse reference frames can be challenging due to several factors. These factors include accuracy and variability in data collection, atmospheric pressure fluctuations or signal interference in measurement devices, Earth's irregular surface, variations in gravitational forces and geodetic complexities, discrepancies between reference frames, environmental conditions such as temperature, humidity, and terrain irregularities, instrument calibration precision, and interdisciplinary intricacies across geodesy, meteorology, and sensor technology.

2.6.3 Heading, Bearing, Track

In aviation navigation, there are several directional aspects that are crucial to consider, such as heading, bearing, and track. An aircraft's heading is the direction in which its nose points, typically in relation to magnetic or true north. Bearing, on the other hand, measures the angle between the aircraft's position and a particular point of interest, helping to determine the direction from the plane to that point. Finally, track displays the actual path over the ground that the aircraft travels, indicating its true direction of movement, regardless of its orientation to the Earth's magnetic or true north. These three fundamental components are essential for planning routes and ensuring precise direction during flight. While heading aligns with the aircraft's nose, bearing focuses on directional angles, and track denotes the true path of the aircraft's movement.

2.7 Visual computing

This section introduces to visual computation later used in various parts of the system.

2.7.1 Camera to World transformation

To obtain real-world coordinates from image points captured by a UAV camera, a complex process must be followed. The first step involves considering the camera's intrinsic parameters and orientation to correct for lens distortion and move image points to the camera's reference frame. This requires an understanding of the camera's focal length, field of view, and distortion coefficients.

The next step is to apply the transformation from camera coordinates to UAV body coordinates, which involves accounting for the UAV's orientation and position relative to the camera, including the camera's mounting angle and any offsets between the camera and UAV body.

Finally, the UAV's attitude angles (roll, pitch, and yaw) are incorporated to convert coordinates from body frame to the world frame. This results in the determination of the real-world position of the object of interest, while considering the relative angles between the UAV and the object.

It's essential to note that either the distance to the object or the altitude above ground level and terrain elevation of the surrounding area must be known to calculate the real-world coordinates. The comprehensive transformation process ensures accurate mapping of image points to their corresponding positions in the real world, taking into account the intricate interplay of camera angles, body transformations, and UAV attitude.

2.7.2 Object tracking

The task of video object tracking is a vital aspect of computer vision. It involves the ability to locate and follow specific objects across a sequence of frames in a video. Its primary objective is to identify and trace the movement of objects of interest as they move within a video stream. This capability has proven highly beneficial in a variety of fields, including surveillance, autonomous vehicles, and augmented reality. Through the implementation of various algorithms and techniques, video object tracking enables machines to comprehend object movements, predict trajectories, and retain consistent identification. Such capabilities make it possible to achieve accurate and continuous object monitoring in diverse real-world scenarios.

CSRT Tracker

The Channel and Spatial Reliability Tracker (CSRT) is a highly advanced algorithm used to track objects in video sequences. Known for its robustness and accuracy, it can effectively track objects in challenging scenarios such as occlusion, scale variation, and motion blur. CSRT works by separating an object's appearance and motion information, using a correlation filter to track objects across frames. By integrating spatial and color information, CSRT can precisely track objects, even in situations where traditional trackers fail.

Its flexibility in handling diverse tracking challenges and maintaining accurate object localization make CSRT a widely respected option for video object tracking.

2.7.3 Feature extraction

In video analysis, feature detection involves pinpointing unique points or regions within frames that exhibit distinct characteristics. These points act as landmarks that represent significant information and enable further analysis and tracking. Various techniques, like corner detection, identify specific spots where intensity variations occur in multiple directions, providing crucial points for matching and tracking across frames. Other methods, such as blob detection (using difference of Gaussians), highlight regions with significant intensity variations, making them useful for identifying objects or areas of interest. These detected features have a vital role in tasks such as optical flow estimation, object tracking, or understanding dynamic scenes. They contribute to the interpretation and analysis of video content without relying solely on convolutional neural networks (CNNs).

2.7.4 Optical flow

When it comes to computer vision, optical flow is a crucial concept that helps us understand object movement in visual scenes. This is done by analyzing how pixels move between consecutive frames in a video sequence, which gives us an estimate of their velocity or movement. By assuming that neighboring pixels move similarly, one can calculate a dense representation of motion across frames and determine their displacement. Two commonly used methods for computing optical flow are differential methods (which rely on local image derivatives) and variational methods (which frame the estimation as an energy minimization problem). Optical flow has a wide range of applications in computer vision, including motion analysis, object tracking, video stabilization, and action recognition. It is an essential tool for gaining insights into scene dynamics and understanding how objects move and interact within a video sequence.

2.7.5 Custom system requirements

Based on the research in previous sections of this work, I've identified key custom UAV platform requirements:

-	requirment definition
1	remote stabilised manual control
2	autonomous operations: takeoff, flight plan following, landing
3	flight plan - creation, upload and visualisation
4	reliable encrypted real-time datalink capable of video transmission and decent range
5	ground control station capable of real-time control and monitoring with live video feed and map framework
6	onboard system monitoring and failsafe mechanisms
7	possibility to connect the system to flight simulator for algorithm verification before real deployment

Table 2.2: Platform - requirements.

Chapter 3

Practical part

3.1 Platform design

This section offers a panoramic glimpse into the intricate web of components comprising the UAV system, encompassing the aircraft, Groundstation and AntennaTracker.

3.1.1 Definition of my work

To fully comprehend the advancements in UAV systems, it's crucial to identify their specific domain and contributions. Doing so defines the scope and significance of the endeavors undertaken. It's also important to consider why certain components or proprietary aspects of the system's architecture aren't disclosed. This decision respects the boundaries dictated by the proprietary nature of certain technological aspects linked to the employer's enterprise and is based on an entrepreneurial context. It's essential to appreciate the invaluable support provided by the employer's financial investments and workforce contributions, which played a critical role in facilitating the development, realization, and operationalization of this remarkable UAV system. This acknowledgement highlights the collaborative effort between the employer's resources and the evolution of this technological innovation, emphasizing the symbiotic relationship that brought this system to fruition.

In my involvement with the complex UAV system, the aerodynamics [11] and mechanical construction weren't just a secondary concern—they were entirely outside the scope of my focus. Instead, I directed my attention entirely towards the electronic components, specifically emphasizing software development. My contribution primarily revolved around meticulously selecting and integrating electronic components spanning crucial areas like control, flight, navigation, and communication systems. Regarding software, my involvement goes beyond utilizing existing frameworks like OpenCV or libraries for tasks such as data encryption and video decoding. It's crucial to highlight that apart from leveraging these frameworks for specific functionalities, the entire software system was developed entirely from scratch by me. This bespoke software development process was integral to the project, as it ensured a tailored approach to meet the UAV system's unique requirements. The emphasis on creating software ground-up allowed for complete customization and optimization, ensuring seamless integration and robust performance within the UAV's operational framework.

3.1.2 Platform overview

The UAV system presented in this thesis embodies a sophisticated network of interconnected components designed for unmanned aerial operations. Through a series of system diagrams provided here, I aim to offer a preliminary understanding of its intricate architecture. These diagrams serve as a visual roadmap, providing a glimpse into the system's complexity and the interplay between its various elements. While this introductory section offers a high-level overview, subsequent sections delve deeper into the specifics, dissecting each component's functionalities, their integration, and the overarching role they play in the UAV's operational framework. These system diagrams act as a foundation, paving the way for a comprehensive exploration of the system's intricacies in subsequent chapters.

Air

Following figure 3.1 provides air-platform overview:

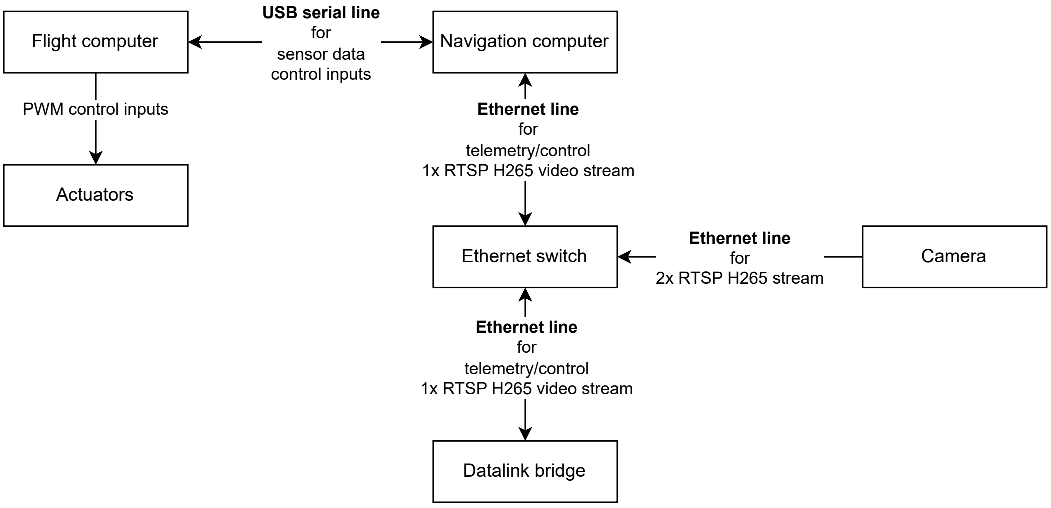

Figure 3.1: Platform design - Air.

Ground

Following figure 3.2 provides ground-platform overview:

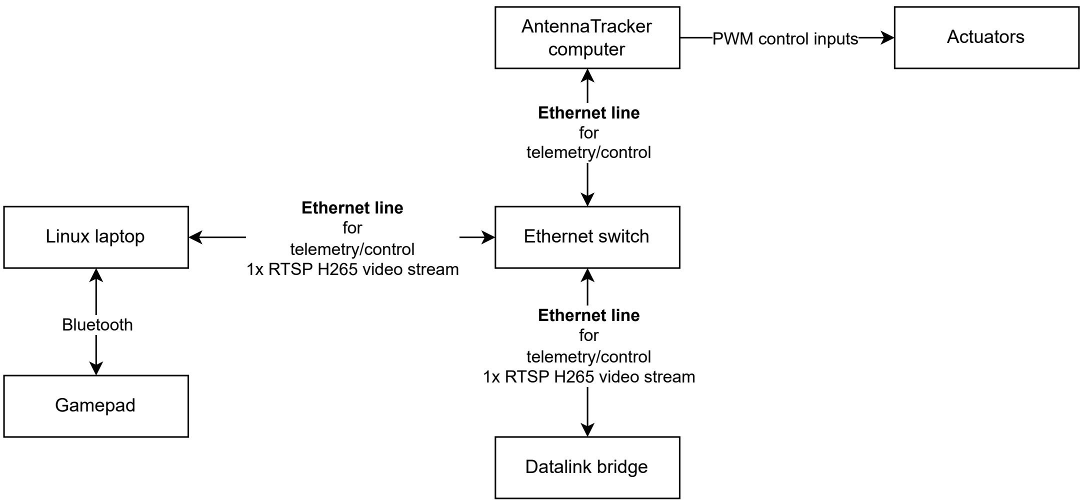

Figure 3.2: Platform design - Ground.

Flight computer

The Flight Computer is an essential component of the aerial platform, ensuring safe and seamless operation. It acts as a guardian, managing the manual control backup link and intervening as needed to maintain control and stability in unforeseen situations. The Flight Computer also regulates the UAV's mechanical components, such as steering and governing flight dynamics, using its actuators. Additionally, it serves as a skilled sensor board, working with custom navigational computer to process sensory data and create an accurate navigational framework. Ultimately, the Flight Computer is the cornerstone of stability and control, coordinating a variety of functions vital to the efficient and smooth operation of the UAV system.

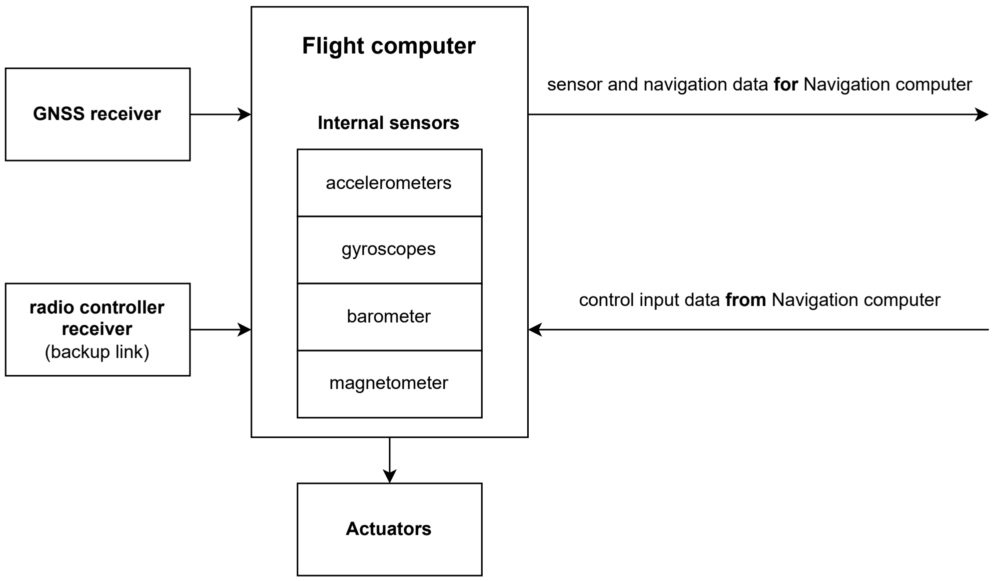

Figure 3.3: Platform design - Flight Computer.

The Flight Computer is an essential component of my UAV system, providing exceptional stability and reliability. As a commercially available microcontroller, it seamlessly integrates various subsystems and serves as the backbone of the system. Its most crucial role, however, is providing an invaluable failsafe for the navigation computer, which runs custom software. In the event of an urgent need for intervention or override, the system enables manual control takeover through a conventional radio link. This feature is a critical safety mechanism that enhances the overall operational framework of the system.

Navigation computer

At the heart of the UAV system lies the Navigation Computer running custom software, a crucial component responsible for gathering and synthesizing data from multiple sources including the Flight Computer, Datalink, and Camera. Through meticulous processing and analysis of this information, the Navigation Computer provides insights that are essential for informed decision-making. Its primary function is to compute and formulate precise guidance, navigation, and control inputs, which serve as the foundation for system's intelligence. These inputs shape the course, maneuvers, and responses to dynamic environmental cues of the UAV. The Navigation Computer relays refined instructions to the Flight Computer, which in turn orchestrates actuator control. It is the cerebral cortex of my system, driving the intricate dance of guidance and control that defines the UAV platform.

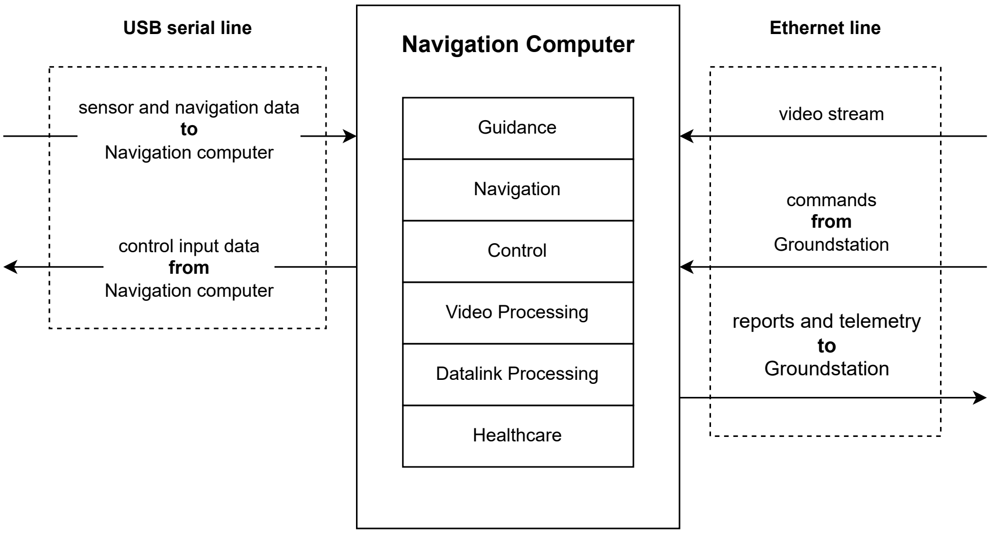

Figure 3.4: Platform design - Navigation Computer.

The UAV system boasts the most advanced computational unit available - the Navigational Computer. This cutting-edge technology is powered by the Linux platform, which provides unparalleled computational power and complexity. Unlike the Flight Computer, which is based on a microcontroller, the Navigational Computer offers a sophisticated landscape for development and networking, allowing for rapid prototyping and robust networking capabilities. Its Linux foundation provides immense computational capabilities, making it agile enough to process complex algorithms quickly and efficiently. An outstanding advantage of the Navigational Computer is its H265 hardware video decoding capability, which enables seamless integration with an advanced camera system. This innovative feature significantly reduces datalink bandwidth requirements by leveraging the camera's capabilities within an advanced compression framework. The Navigational Computer's computational prowess and H265 hardware video decoding work together symbiotically to enhance the system's efficiency, demonstrating the potential for cutting-edge technological integration within the UAV system.

Networking

The networking infrastructure within the UAV system is structured to facilitate seamless communication and data exchange between critical components, both in the air and on the ground. This network manifests as two distinct local networks, each utilizing conventional Ethernet switches to enable robust connectivity.

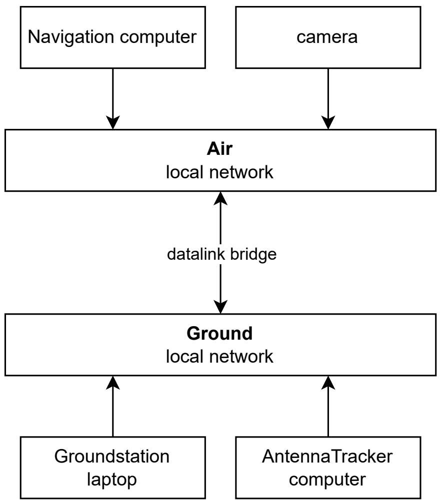

Figure 3.5: Platform design - Networking.

The UAV system consists of various components that function in unison to establish a network infrastructure for seamless data exchange and effective communication. On the ground, three primary components include the Groundstation laptop, AntennaTracker computer, and Datalink bridge. Meanwhile, in the air, the network infrastructure features the Navigational Computer, Camera, and an additional Datalink Bridge.

This network is built on a conventional TCP/IP architecture, similar to the foundation of the internet, providing the system with a sound and dependable base. By utilizing this established framework, it is ensured that standard communication protocols, enabling efficient and secure data transfer are available. The familiarity and reliability of TCP/IP allow for effortless integration and interoperability among system components, which is crucial for navigation, sensing, and system operation.

Datalink bridge

In order to ensure a reliable and strong connection between two local networks, the networking infrastructure plays a crucial role. Utilizing advanced technology, communication is made seamless through the use of a high-powered 2.4 GHz 2x2 MIMO WiFi connection, which enhances signal propagation.

Within the aerial domain, strategically placed omnidirectional antennas provide wide coverage and reception capabilities. Acting as pathways for data exchange, they facilitate effective communication between the components within the UAV.

On the ground, dish antennas are utilized and carefully calibrated to transmit and receive signals with accuracy and precision. This focused transmission helps establish a robust and stable link between the ground-based components and those in the UAV.

Operating within a 20 MHz channel width, the network configuration optimizes data transmission by allocating the appropriate bandwidth for efficient communication. To further enhance long-range capability and robustness, the system employs QPSK modulation, a reliable modulation scheme known for its ability to resist interference and facilitate long-distance communication.

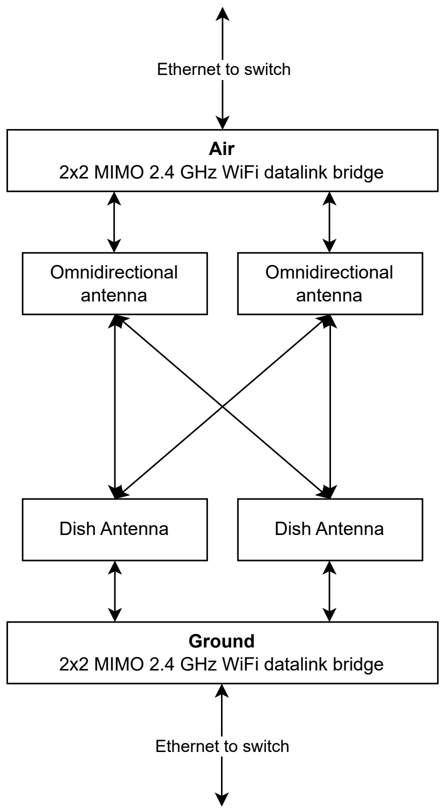

Figure 3.6: Platform design - Datalink Bridge.

The UAV system's communication link is designed for optimal performance, utilizing a sophisticated networking setup that incorporates powerful WiFi, strategically placed antennas, carefully optimized channel width, and advanced modulation techniques. This configuration ensures the dependable and long-range transmission of essential data, thereby promoting seamless operation and coordination throughout the system.

Camera

The camera integrated into the UAV system is a crucial component, functioning as "visual sentinel". With its advanced IP camera design, it offers multiple RTSP streams, enabling parallel video transmissions that can be accessed both onboard and on the ground. The camera adopts the H265 encoding, which is optimized for bandwidth efficiency, while maintaining high-quality video output. Its exceptional wide dynamic range allows it to adjust to varying lighting conditions, making it ideal for aerial environments where light contrasts can be extreme. This feature ensures that even in challenging lighting scenarios, the camera produces clear and detailed imagery, contributing significantly to the system's visual acuity and operational efficiency.

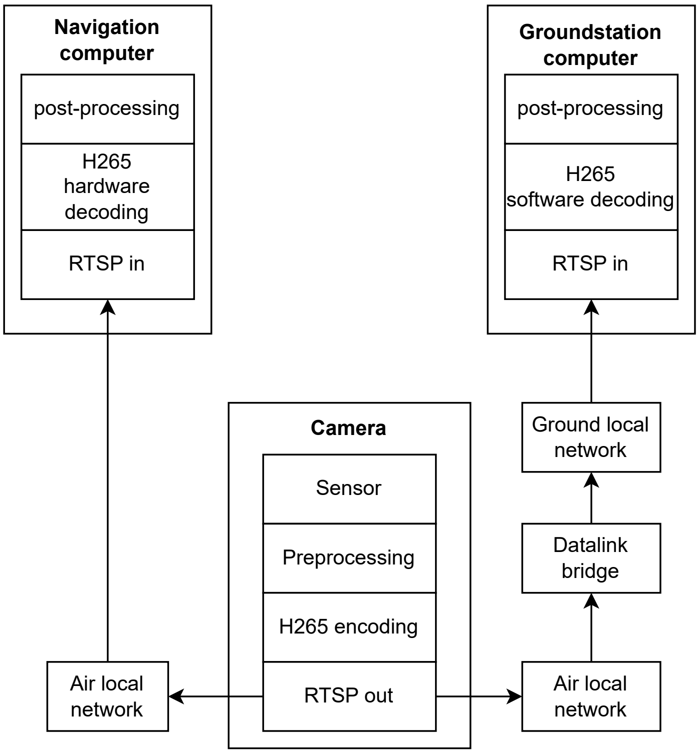

Figure 3.7: Platform design - Camera.

3.1.3 Software

This section aims to delve into the fundamental software components that are indispensable to the development of the UAV system as a whole. Through a concise yet informative overview of the key software elements utilized in its construction, I intend to highlight their critical roles and interconnections within the broader framework. My goal is to provide a clear understanding of the software infrastructure that forms the backbone of the system, encompassing the tools, platforms, and methodologies that shape its functionality and capabilities.

The intricate software that having been conceived, constructed, and refined entirely from scratch. The entire software ecosystem, which is vital to the functioning of the UAV system, is the product of my individual endeavor, meticulously developed from the ground up only utilising libraries like OpenCV for visual data processing, Go language generic encryption/decryption libraries and NVIDIA's hardware video decoding utilities. While the majority of this programming feat was accomplished during the period of this thesis assignment, it's important to note that a small portion of the foundational work was initiated during various moments in my professional career, academic pursuits, and personal projects. These fragments served as precursors that laid the initial groundwork for what has evolved into the comprehensive software infrastructure encapsulated within this thesis.

Linux

The Linux operating system is renowned for its reliability, flexibility, and adaptability in the computing world. As an open-source platform, it is robust and has become an integral part of UAV onboard and groundstation software. One of its key advantages is the stable and secure environment it provides, making it ideal for intricate UAV software systems. The open-source framework promotes collaboration and enables customization and optimization tailored to the unique requirements of unmanned aerial vehicles. With multitasking capabilities and efficient resource management, Linux empowers onboard software to execute complex algorithms and computations seamlessly. For groundstation software, Linux provides a versatile backbone, facilitating the development of intuitive and feature-rich interfaces while ensuring compatibility with a wide range of hardware configurations. In short, Linux serves as an indispensable foundation for UAV software innovation, reliability, and scalability, propelling it to new heights.

Golang

Go, also referred to as Golang, is a versatile programming language that is highly regarded for its ability to create robust and efficient software systems for both onboard and groundstation applications of UAVs. Developed by Google, the language emphasizes simplicity without compromising performance, making it an ideal choice for the intricate demands of UAV technology. Go offers exceptional benefits specifically tailored for UAV systems, including efficient memory handling, ensuring optimized resource allocation critical for lightweight onboard software. Moreover, Go's compiled nature provides inherent speed, enabling UAV software to swiftly process critical tasks and make real-time decisions in dynamic flight environments. Additionally, Go's networking capabilities facilitate seamless communication, ensuring reliable data transmission between the UAV and groundstation, while its built-in concurrency primitives support the concurrent execution of tasks, a crucial feature for managing multiple processes simultaneously in UAV operations. Go is an incredibly potent tool in the development of UAV software, providing a foundation of efficiency, speed, streamlined networking, and concurrent processing essential for the requirements of contemporary unmanned aerial systems.

Gio

Gio is an exceptional graphical user interface (GUI) toolkit that has been tailor-made for the Go programming language. This toolkit boasts of its flexibility and minimalist design, enabling developers to create impressive graphical interfaces for applications that can run seamlessly on a range of platforms, including Windows, macOS, Linux, Android, and iOS. What sets Gio apart is its efficient rendering, which utilizes modern graphics technologies to ensure smooth performance - even on low-powered devices. With Gio's declarative approach, developers can succinctly describe the UI, making it ideal for rapid prototyping and hassle-free maintenance. Gio's portability and exceptional performance make it a promising choice for building intuitive and visually-appealing applications in the Go ecosystem.

OpenCV

OpenCV is a highly versatile and robust open-source computer vision library that has revolutionized image operations in the UAV landscape. It offers a wide range of functions and algorithms that are specifically designed for image processing and analysis, making it an essential tool for both onboard systems and groundstation software. With OpenCV, UAVs can perform complex image operations with unparalleled speed and accuracy, enabling advanced vision-based applications such as real-time object detection, feature recognition, and image enhancement. Additionally, OpenCV's lightweight nature and optimization capabilities make it an ideal choice for resource-constrained environments onboard UAVs. For groundstation software, OpenCV provides a powerful backbone, allowing developers to create sophisticated image processing pipelines and analytics tools that facilitate informed decision-making based on aerial imagery. In summary, OpenCV is a critical ally that enables UAV software systems to leverage the potential of computer vision for enhanced perception, analysis, and interpretation of visual data.

GStreamer

GStreamer is an open-source multimedia framework that excels in handling a wide range of multimedia tasks, including recording, editing, streaming, and playback of various formats. It operates on a pipeline-based architecture that creates sequences of elements representing sources, processors, and sinks. These elements skillfully manage the data flow by decoding, encoding, filtering, and outputting tasks. Additionally, caps are used to describe the data format and capabilities, which guarantees compatibility between elements. GStreamer boasts a modular design and supports multiple programming languages, allowing developers to create versatile multimedia applications, such as media players, streaming servers, video editors, and conferencing systems. Its adaptability and scalability make it the perfect choice for diverse platforms and purposes.

3.1.4 Hardware

In the "big picture - hardware" subsection, I intentionally refrain from delving into proprietary entrepreneurial aspects pertaining to the mechanical and aerodynamics facets of the aircraft, such as detailed design, electric motors, regulators, and power network intricacies. While these aspects are closely aligned with my employees' entrepreneurial pursuits, they are not relevant to my academic exploration. Instead, my thesis primarily focuses on specific components that tie into my academic research, such as the flight computer, navigational computer, networking infrastructure, datalink systems, and camera technology. By doing so, I steer clear of proprietary entrepreneurial insights and concentrate solely on the technological facets that are in line with the scope of my thesis.

Flight computer - CubePilot Orange

The CubePilot Orange is a highly capable flight controller that boasts a 32-bit ARM® STM32H753 Cortex®-M7 processor (or ARM® STM32H757 for Cube Orange+), capable of running at 400 MHz. It also comes with 1 MB RAM and 2 MB Flash memory, as well as a 32-bit STM32F103 failsafe co-processor, providing an added layer of safety. Furthermore, the CubePilot Orange features three redundant IMUs, with accelerometers and gyroscopes, two barometers, and a magnetometer, connected via SPI, ensuring heightened stability and precision. The CubeOrange model is equipped with

InvenSense ICM20602 IMU, ICM20948 IMU/MAG, and an MS5611 barometer mounted on a temperature-controlled, vibration-isolated board. Meanwhile, the CubeOrange+ variant utilizes Invensense ICM42688 IMU, ICM20948 IMU/MAG, and the MS5611 barometer, also mounted on a temperature-controlled, vibration-isolated board. The CubePilot Orange is designed with redundant power supplies and automatic failover mechanisms, ensuring uninterrupted operation. It comes with a servo rail optimized for high power (7 V) and high current, with all peripheral outputs safeguarded by over-current protection. Input ports are also protected against electrostatic discharge (ESD). In terms of interfaces, the CubePilot Orange offers a wide range of connectivity options, including 14 PWM servo outputs (8 from IO, 6 from FMU), S.Bus servo output, and R/C inputs compatible with CPPM, Spektrum/DSM, and S.Bus protocols. It also includes analog/PWM RSSI inputs, 5 general-purpose serial ports (with 2 supporting full flow control), 2 I2C ports, a SPI port (recommended for short cables only), 2 CAN Bus interfaces, and 3 analog inputs (supporting 3.3V and 6.6V). With its robustness, computational capabilities, redundancy measures, sensor diversity, and extensive interface options, the CubePilot Orange is a versatile and dependable choice for a wide range of drone applications.

Figure 3.8: Hardware - Flight computer: CubePilot Orange.

The CubePilot Orange runs already introduced PX4 system.

Navigation computer - NVIDIA Jetson Nano

The NVIDIA Jetson Nano is an impressive device boasting a quad-core ARM Cortex-A57 CPU that can efficiently handle complex tasks. With a clock speed of 1.43 GHz, this device offers ample computing power for a wide range of AI and edge computing applications. The Jetson Nano also features a 128-core NVIDIA Maxwell™ GPU, which is optimized for AI-centric workloads, especially for tasks that involve neural network inference and other machine learning computations. With 4GB of LPDDR4 RAM, the Jetson Nano has enough memory to execute AI algorithms and manage data-intensive operations. Plus, it offers connectivity options like Gigabit Ethernet, HDMI, USB 3.0, USB 2.0, and a CSI camera connector, making it easy to integrate with a variety of peripherals and sensors. Additionally, the Jetson Nano supports popular AI frameworks like TensorFlow and PyTorch, making it a developer-friendly platform.

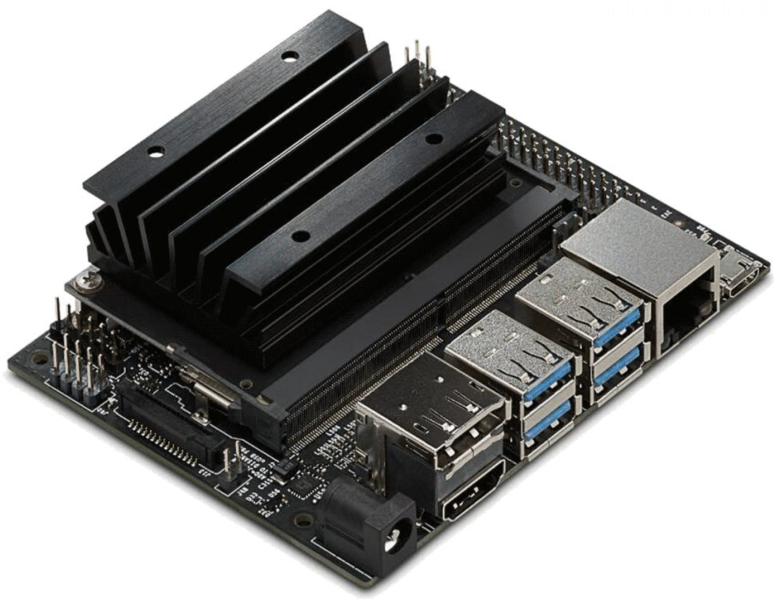

Figure 3.9: Hardware - Navigation computer: NVIDIA Jetson Nano.

The Jetson Nano is ideal for embedded and edge computing devices, thanks to its compact size and versatility in deployment scenarios. Despite its powerful performance, the device is designed with power efficiency in mind, making it an excellent choice for battery-powered or resource-constrained applications. NVIDIA provides extensive developer resources, including software development kits (SDKs) and libraries, comprehensive documentation, and community support, all of which make it easier for developers and researchers to deploy and execute AI models on the Nano platform.

The Nvidia Jetson Nano runs stock NVIDIA operating system - JetPack and on top of it my custom onboard software.

Datalink bridge - Ubiquiti Rocket M2

The Ubiquiti Rocket M2 is a remarkable WiFi Access Point that utilizes 2.4GHz / 802.11b/g/n technology. Its linear 2x2 MIMO configuration guarantees exceptional range capabilities and impressive TCP/IP speeds of over 150Mbps. The device is enclosed in sturdy plastic, making it perfect for outdoor use. Additionally, the enclosure can be removed to reduce weight and dimensions to meet your specific needs.

Figure 3.10: Hardware - Datalink Bridge: Ubiquiti Rocket M2.

The Rocket M2 boasts a handy PoE Injector that facilitates the simultaneous transmission of data and power via the Ethernet cable, ensuring an effortless and stress-free installation and setup process. Moreover, this device features the web-based airOS interface, developed by Ubiquiti Networks, which is both user-friendly and powerful. This intuitive interface allows users to easily configure and manage the Access Point, making it a highly efficient option for setting up and managing wireless networks.

Camera - HIKVision DS-2CD2D45G1/M-D/NF

The Hikvision DS-2CD2D45G1/M-D/NF is a top-of-the-line IP camera that packs a powerful 4-megapixel resolution and a 1/3" CMOS sensor into a compact frame. This camera delivers stunning Quad HD resolution at 2560 x 1440 pixels and boasts impressive sensitivity with a rating of 0.005 lux in color. Its Wide Dynamic Range (WDR) technology, which can handle up to 120 dB, ensures clear visuals even in challenging lighting scenarios.

Connecting the camera to networks is a breeze with its RJ-45 port, and its H.265 compression technology optimizes data handling while its 3D DNR noise reduction feature produces clear and sharp images. The camera also supports triple streaming with three independent streams and smart functions like line crossing, passage detection, missing object identification, abandoned luggage monitoring, and scene change detection. Additionally, it includes audio input and output options for added surveillance capabilities and convenience.

Sophisticated functions such as BLC, HLC, Privacy Mask, ROI, and defog enhance image quality, while security features like a reset button, password protection, and the ability to insert watermarks ensure data integrity and protection against unauthorized access.

The camera's basic specifications include a 1/3" CMOS sensor, Day/Night mode support, a fixed f = 2.8 mm lens that provides a 98° horizontal, 53° vertical, and 115° diagonal view. It can achieve a maximum resolution of 2560 x 1440 at 25/30 frames per second (fps). The interface includes 1x RJ-45, 1x audio input, and 1x audio output. However, it does not have a memory card slot. The power supply requirement is DC 12 V (power supply not included), with a maximum consumption of 1.5 W.

Overall, the DS-2CD2D45G1/M-D/NF IP camera is a versatile and reliable surveillance solution that can provide high-quality, detailed monitoring across various environments. Its advanced features, robust specifications, and compact build make it a top choice for security professionals.

Figure 3.11: Hardware - Camera: HIKVision DS-2CD2D45G1/M-D/NF.

3.1.5 Aircraft and other equipment

The thesis concentrates on specific aspects of designing an UAVs, without offering extensive discussions on construction, aerodynamics, or descriptive overviews. To improve its content while avoiding delving into the intricacies of development or financial investments made by my employer, incorporating an image of the aircraft can prove to be an effective strategy. This visual aid provides a snapshot of the UAV's physical appearance and serves as a reference point for readers to better contextualize discussions or analyses within the thesis. By omitting detailed descriptions or developmental backgrounds, the thesis remains focused on the specialized aspects being studied or analyzed.

Figure 3.12: Hardware - Aircraft.

The whole platform consists of aircraft, launch catapult, antenna tracker and groundstation computer.

3.2 Common Software

Efficient and precise navigation, control, and data transmission of unmanned aerial vehicles depend heavily on the software utilized in the Onboard, Groundstation, and Antenna Tracker components. In this section, I delve into the essential software components powering these vital elements. Each software suite plays a critical role in enabling seamless operation. The following subsections delve into these shared software frameworks, providing detailed insights into their functionalities, features, and the synergies they create within the presented platform.

3.2.1 Navigational Framework

In this subsection I present functions implemented in the Navigational Framework that stands as core mathematics framework across platform devices: aircraft, groundstation and antenna tracker.

Implemented functions are listed in table below:

function name	input	output
`WGS84ReferenceEllipse()`	-	WGS84 parameters
`NormalRadius()`	Latitude	normal radius
`WGS84TangentPlaneRotationMatrix()`	WGS84 point	rotation matrix
`WGS842ECEF()`	WGS84 point	ECEF point
`WGS842NED()`	WGS84 point (point of interest), WGS84 point (reference)	NED point
`ECEF2WGS84()`	ECEF point	WGS84 point
`ECEF2NED()`	ECEF point (point of interest), WGS84 point (reference point)	NED point
`NED2WGS84()`	NED point (point of interest), WGS84 point (reference)	WGS84 point
`NED2ECEF()`	NED point (point of interest), WGS84 point (reference)	ECEF point
`WGS842DDistance()`	two WGS84 points	distance
`WGS843DDistance()`	two WGS84 points	distance
`RelativeHeading()`	heading (target), heading (reference)	relative heading
`NormaliseHeading()`	heading	normalised heading
`Heading2MathAngle()`	heading	mathematical angle
`MathAngle2Heading()`	mathematical angle	heading

Table 3.1: Navigational framework functions.

The very basic functions such are:

- WGS84ReferenceEllipse()
- NormalRadius()
- WGS84TangentPlaneRotationMatrix()

they posses direct connection to formulas presented in theoretical part of the thesis: 3.1, 2.2, 2.3 respectively.

The coordinate system transformation functions:

- WGS842ECEF()
- WGS842NED()
- ECEF2WGS84()
- ECEF2NED()
- NED2WGS84()
- NED2ECEF()

are built upon four basic coordinate transformations presented in theortetical part of the thesis WGS84 to ECEF 2.6, ECEF to WGS84 1, ECEF to NED 2.7 and NED to ECEF 2.8.

The distance calculation functions:

- WGS842DDistance()
- WGS843DDistance()

are wrappers for transforming points to Cartesian coordinate systems and then computing Cartesian distances.

The heading related functions functions:

- RelativeHeading()
- NormaliseHeading()
- Heading2MathAngle()
- MathAngle2Heading()

are helper functions to keep heading values in between 0 and 360. And transforming mathematical angles used during various computations to heading and vice versa.

Mathematical angle and Heading

Following figure visually represents relation of heading and mathematical angle:

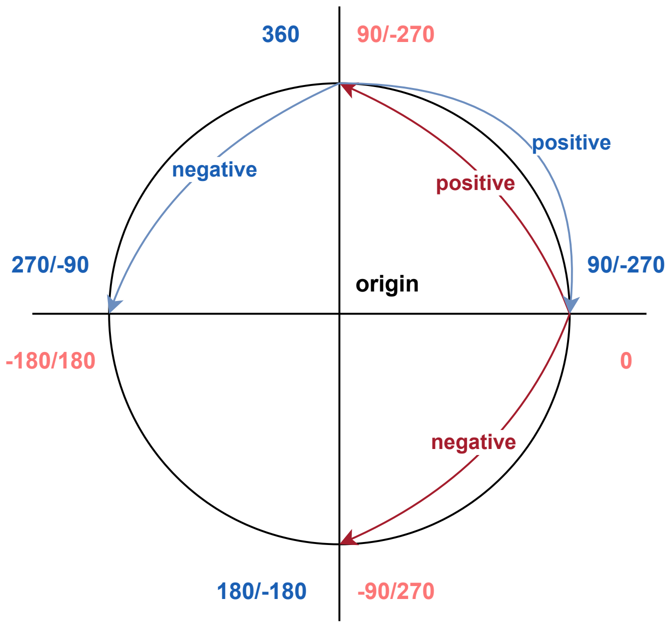

Figure 3.13: Navigation Framework - Relation of heading and mathematical angle.

These equations define it mathematically:

$$a = -h + 90 \tag{3.1}$$

$$h = 90 - a \tag{3.2}$$

where a stands for mathematical angle and h for heading.

3.2.2 Map Framework

Crafting precise and detailed maps that can be visualized on computer screens in two dimensions is a formidable undertaking. This is due to the fact that our planet is three-dimensional, and flattening this complexity into a two-dimensional surface poses a significant challenge. This involves storing massive amounts of memory-intensive map data, which is typically segmented into tiles, each housing geographic information. However, the true difficulty arises in arranging and retrieving these tiles in a way that allows for a seamless reassembly into a coherent and accurate depiction of localized maps.

Decomposing 3D world into 2D tiles

The transformation of spherical coordinates of latitude and longitude into a two-axis 2D representation involves dividing the world into a canvas that ranges between -180 to 180 for longitude and -90 to 90 for latitude. To enhance the level of detail and flexibility of this representation, the concept of zoom levels has been introduced. Zoom levels enable the planet's canvas to be divided into manageable units, resulting in varying degrees of granularity. The lowest zoom level presents the entire world on a single tile. As the zoom level increases, the planetary canvas is systematically divided along both axes- longitude and latitude- each step exponentially increasing the number of tiles and refining the precision and detail of the map. This hierarchical division approach not only creates a more nuanced representation of geographical data but also necessitates a methodical approach to tile management, retrieval, and reconstruction, which is a critical aspect of contemporary map frameworks.

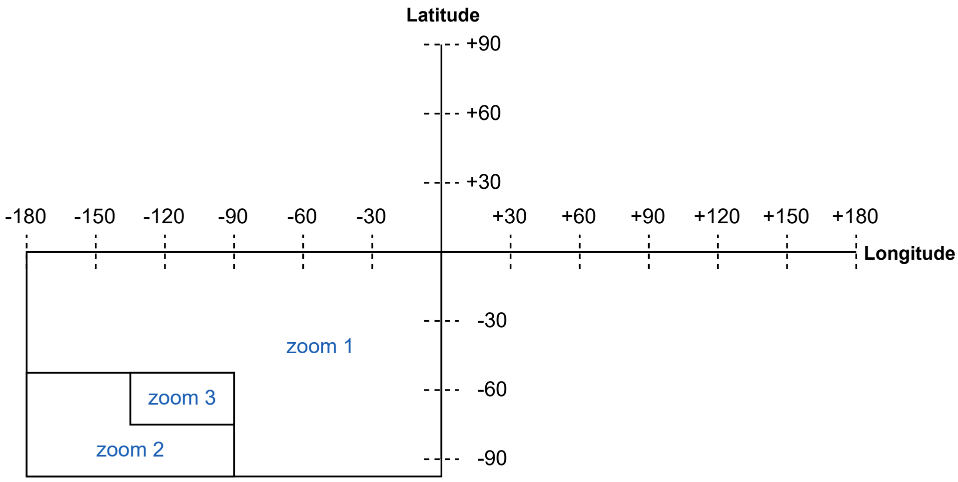

Figure 3.14: Map Framework - Tile decomposition.

Following data structure of a single tile is used within the Map Framework:

name	description	type
LatCenter	latitude of tile's center	float
LonCenter	longitude of tile's center	float
ZoomLevel	tile zoom level	uint
Parent	parent tile	*Tile
Identifier	tile identifier	string
Status	tile availability status	custom enum
Children	4 children tiles	*Tile[2][2]
LatMin	min. latitude within tile	float
LatMax	max. latitude within tile	float
LonMin	min. longitude within tile	float
LonMax	max. longitude within tile	float
Width	area width in meters	float
Height	area height in meters	float

Table 3.2: Map Tile - single tile description.

Tile diversity

The diversity of tiles in map frameworks is a complex phenomenon that is inextricably linked to the dynamic nature of our planet's topography. While the basic principles of latitude and longitude remain constant, the introduction of local area and scale brings about a significant shift in perspective. Unlike the globally fixed longitude and latitude ratios, the scale of a tile's local area undergoes a transformation as it moves across different latitudes, expressed in meters both horizontally and vertically. This transformation is a result of the Earth's spherical geometry, where the convergence of meridians towards the poles distorts spatial proportions. Consequently, the representation of an area in meters on the surface will vary depending on its distance from the equator, thereby modifying the horizontal-to-vertical ratio within a tile. This phenomenon highlights the importance of adaptive tile design and retrieval mechanisms within map frameworks as varying scales require a nuanced approach to ensure accurate and cohesive cartographic representation across different latitudes. Acknowledging and accommodating this inherent variability in tile diversity is crucial in developing an effective map framework that accurately portrays the complexities of our planet's geography.

Lat	Lon	Zoom level	Width [m]	Height [m]	Ratio
54.0	14.0	10	23073.3	19565.5	1.179
54.0	14.0	11	11536.7	9782.7	1.179
54.0	14.0	12	5768.3	4891.3	1.179
54.0	14.0	13	2882.7	2445.7	1.179
54.0	14.0	14	1440.9	1222.8	1.179
54.0	14.0	15	720.5	611.4	1.179

Table 3.3: Tile diversity - the local area width-to-height ration does not change with *zoom level*.

Lat	Lon	Zoom level	Width [m]	Height [m]	Ratio
54.0	-180.0	10	23073.3	19565.5	1.179
54.0	-135.0	10	23073.3	19565.5	1.179
54.0	-90.0	10	23073.3	19565.5	1.179
54.0	-45.0	10	23073.3	19565.5	1.179
54.0	14.0	10	23073.3	19565.5	1.179
54.0	45.0	10	23073.3	19565.5	1.179
54.0	90.0	10	23073.3	19565.5	1.179
54.0	135.0	10	23073.3	19565.5	1.179
54.0	180.0	10	23073.3	19565.5	1.179

Table 3.4: Tile diversity - the local area width-to-height ration does not change with *longitude*.

Lat	Lon	Zoom level	Width [m]	Height [m]	Ratio
60.0	14.0	10	19651.8	19584.2	1.003
54.0	14.0	10	23073.3	19565.5	1.179
40.0	14.0	10	30063.9	19517.7	1.540
20.0	14.0	10	36821.4	19459,6	1.892
0.0	14.0	10	39135.3	19436.9	2.013
-20.0	14.0	10	36821.4	19459,6	1.892
-40.0	14.0	10	30063.9	19517.7	1.540
-60.0	14.0	10	19651.8	19584.2	1.003

Table 3.5: Tile diversity - the local area width-to-height ration does change with *latitude*.

Following figures present the map tile diversity to make it visually clear for the reader. Notice the aspect ratio that makes the map reconstruction challenging task.

Figure 3.15: Map Framework - tile latitude 54 (Prague).

Figure 3.16: Map Framework - tile latitude 0 (remote land in Africa).

Tile source

Within Mapbox's [4] API framework, the latitude, longitude, and zoom level stand as pivotal inputs. These fundamental geographic parameters play a pivotal role in accessing and retrieving specific map tiles.

Map reconstruction

In the previous sections, tiles, world decomposition into the tiles and their source were presented. In this section the main task - map reconstruction is presented to the reader.

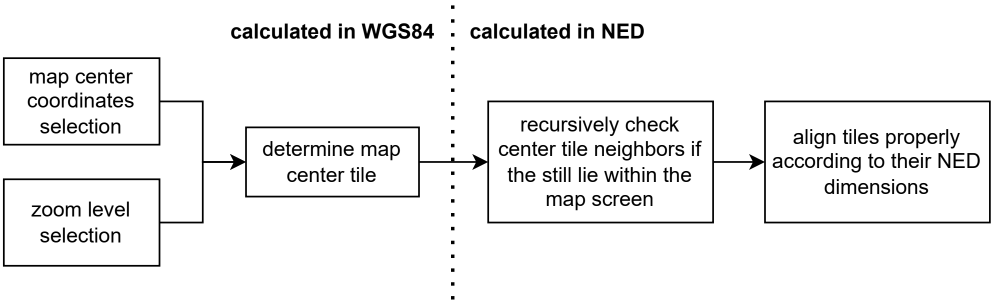

Figure 3.17: Map Framework - Using tiles to reconstruct a map.

Figure 3.18: Map Framework - Sample of map reconstructed out of six tiles covering Prague airport.

Figure 3.18 taken as a screenshot show from the custom map-framework piece of software that additionally displays map center (white cross) and map scale (left-bottom corner of the image, the number matches real world length of its white under-line). Zoom level of used tiles is 12.

Limitations

Presented approach of map reconstruction is practically usable for higher *zoom levels* than 10. For *zoom level* 10 the tile spans 23073.3 meters in horizontal dimension and 19565.5 meters in vertical dimensions that is considered enough for the UAV application.

Figure 3.19: Map Framework - Sample of map reconstructed out of four tiles covering Europe around Alps and northern Italy.

Figure 3.19 taken as a screenshot show from the custom map-framework piece of software that additionally displays map center (white cross) and map scale (left-bottom corner of the image, the number matches real world length of its white under-line). *Zoom level* of used tiles is 5. Demonstration of map reconstruction limitations - approach doesn't respect that the Earth is round while creating 2D map causing tile disalignment.

3.2.3 Datalink Framework

Following section will guide the reader throughout the datalink framework used within all parts of the UAV system: Onboard software, Groundstation software and Antenna Tracker software.

System topology

Figure 3.20 visualises the system network topology that consists of three nodes and two duplex links.

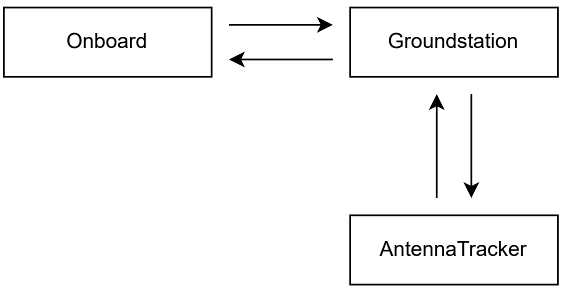

Figure 3.20: Datalink - network topology.

Generic packet

Atomic entity is so called generic packet that contains packet information necessary for the link management and the message payload. The structure of the generic packet is visualised in figure 3.21.

sender identity data — Payload

Sender ID	Sender Type	Counter	Request ACK	Type	SubType	Message
string	string	uint	bool	uint	uint	Byte[]

message counter and ACK request
(internal communication data)

Figure 3.21: Datalink - generic packet.

Messages

Implemented *message* types are listed in the table below:

name	type	sub type	class
Ping	1	1	-
ACK	2	1	-
NACK	2	2	-
Navigation Data	3	1	Report
GNSS Path	3	2	Report
Inertial Path	3	3	Report
Control Mode	4	1	Report
Set Control Mode	4	2	Set
Control Manual Input	4	3	Set
Autopilot Input	4	4	Set
Control Data	4	5	Report
Upload FlightPlan	5	1	Set
Clear FlightPlan	5	2	Command
Guidance Data	6	1	Report
Go to Next Point	6	2	Command
Go to Previous Point	6	3	Command
Set Home	7	1	Set
Set Runway for Autoland	8	1	Set
GNSS Perforamnce Data	9	1	Report
Battery Voltage	10	1	Report
Flight Computer Data	11	1	Report
Navigation Computer	12	1	Report
Onboard Systems Data	13	1	Report
Flight Model Data	14	1	Report
Increase Cruise Speed	14	1	Command
Decrease Cruise Speed	14	1	Command
OpticalFlow	15	1	Report
Initialize Tracking	16	1	Set
Tracking Data	16	2	Report
Antenna Tracker Data	17	1	Report
Antenna Tracker Control Input	17	1	Set

Table 3.6: Datalink Framework - Message types.

Dataflow

Data transmission is visualised in figure 3.22. First a *message* is encapsulated in *generic packet*, encrypted using AES256 cipher key and SHA256 32 byte checksum is appended. After these steps, data is ready to be sent.

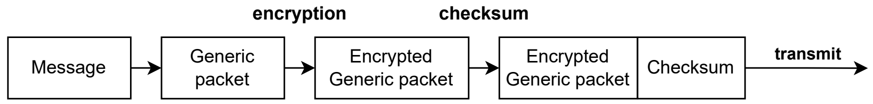

Figure 3.22: Datalink - dataflow TX.

Data reception is visualised in figure 3.23. The very first action is slicing the last 32 bytes received in order to verify SHA256 checksum. If verification succeeds then the rest of the data is decrypted using predefined AES256 cipher key. Decrypted *generic packet* containing message as payload is further processed first by internal packet handler and distributed within the software to specific message handlers.

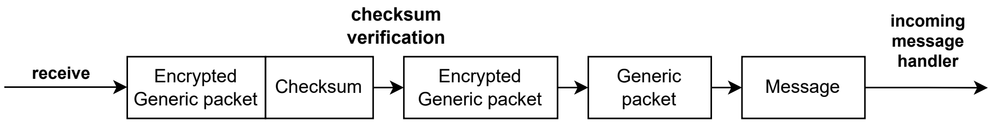

Figure 3.23: Datalink - dataflow RX.

Control mechanisms

Each node is identified using its *ID* and *Type*, *ID* as arbitrary string and Type sorts the nodes into three categories: Onboard, Groundstation and Antenna Tracker. Such selection offers readiness for operating several aircraft or groundstations as the same time within the system.

Each *generic packet* created is identified by its counter (uint64) and accompanied with ACK (Acknowledgment) / NACK (Negative Acknowledgment) serve for implementing algorithms that would handle corrupted or lost packages for increasing communication link reliability. Acknowledgment sending has been implemented and tested but remains disabled since the algorithms are yet to be implemented.

3.2.4 Visual Framework

Following section will guide the reader throughout the visual framework used within Onboard software and Groundstation software.

Camera

Implemented functions are listed in table below:

function name	input	output
`Undistort()`	distorted image	undistorted image
`ImagePoint2CameraAngles()`	image point	camera angles
`CameraAngles2BodyAngles()`	camera angles	body angles
`BodyAngles2CameraAngles()`	body angles	camera angles
`CameraAngles2ImagePoint()`	camera angles	image point

Table 3.7: Visual computing framework - camera functions.

Figure 3.24 visualises the process of calculating relative aircraft body angles out of image point.

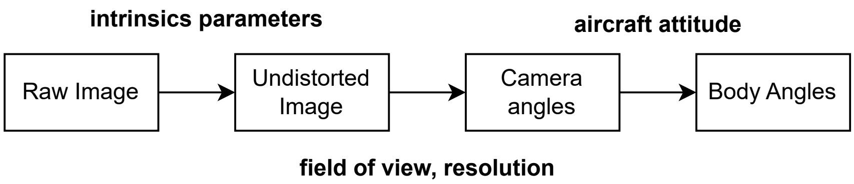

Figure 3.24: Camera - image to body angles.

Camera intrinsic and distortion parameters have been identified using MATLAB [5] chessboard calibration technique:

name	symbol	value
focal length - x dimension	fx	0.604299765
focal length - y dimension	fy	1.0814530555
principal point - x dimension	cx	0.5141959375
principal point - y dimension	cy	0.4851129166
radial distortion	k1	-0.4064
radial distortion	k2	0.2512
radial distortion	k3	-0.0851

Table 3.8: Camera intrinsic and distortion parameters.

Following images provide comparison in between raw camera image 3.25 and undistorted one 3.26.

Figure 3.25: Camera - distorted view.

Figure 3.26: Camera - undistorted view.

Object tracking

Object tracking have been implemented using OpenCV CSRT Tracker. The object tracking is controllable from the groundstation during flight and is run in real-time onboard. Stable performance on 30 frames per second video has been achieved.

Feature detection and extraction

Feature detection and extraction has been implemented using OpenCV libraries that provide various approaches. Since it is computationally demanding it has only been run post-flight and not in real-time. Performance and optimisation is object of further research.

Optical flow

Optical flow has been implemented using OpenCV libraries that provide various approaches (for instance: dense optical flow and optical flow computed from detected features). Since it is computationally demanding it has only been run post-flight and not in real-time. Performance and optimisation is object of further research.

3.3 Onboard Software

Fundamental key components of onboard software are introduced to the reader in following sections:

Guidance and control systems were designed using and inspired by [12] and my practical experience from aviation.

3.3.1 Guidance

This particular section will delve into the guidelines that are essential to ensure precise calculations when following a predefined Flight Plan. The Flight Plan itself is defined by a sequence of latitude, longitude, and altitude waypoints. In this segment, I will explore the principles, methodologies, and analytical strategies that are crucial for executing the specified Flight Plan accurately and efficiently within the context of aerial navigation.

Guidance is split into two components: *lateral* and *vertical*. These particular tasks cannot be solved independently and must be executed sequentially. Initially, the lateral guidance determines the actual position and orientation of the aircraft according to the Flight Plan active point. Once this has been determined, the vertical guidance may then be executed.

While the Control section covers basic controls such as altitude hold and track hold, this section will focus on providing the reader with advanced strategies of guidance.

Lateral guidance

Following presents modes implemented in the guidance software:

mode	description
LNAV DIRECT	captures directs track to the next waypoint
LNAV LINE	holds onto line connecting previous and next waypoints

Table 3.9: Modes of lateral guidance.

Figure 3.27 visualises *Lateral guidance mode* selection. If the subject of guidance lies within the green area then the *LNAV LINE* mode is selected. The green are spans from the previous flight plan point to 75 percent of the track to the active flight plan point (denoted by blue color) and is limited by 45 degrees of maximum line approach. Outside these boundaries it is preferred to approach the *active flight plan point* directly using *LNAV DIRECT* mode. Special case would be when the *flight plan* only consists of one point (for instance - *return home mode*).

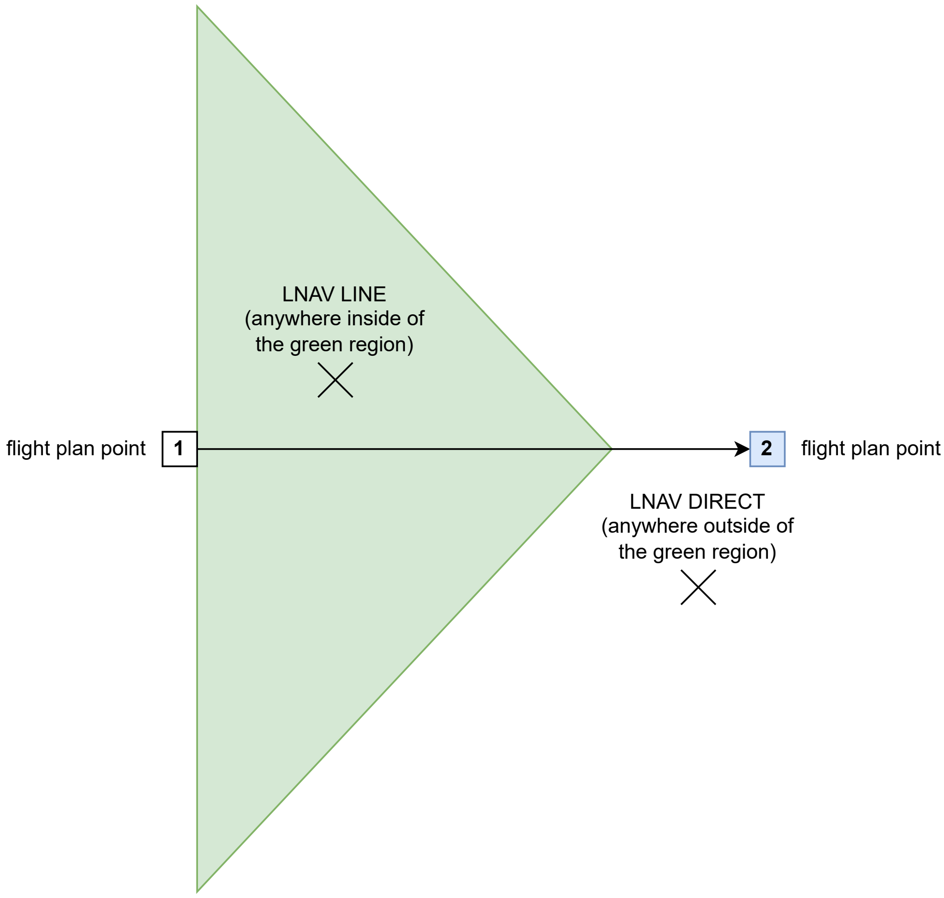

Figure 3.27: Lateral guidance.

Track hold

My system utilizes a rather simple algorithm that factors in real-time track errors as its primary input parameter. By continuously monitoring the variance between the intended trajectory and the aircraft's actual path, PI regulator dynamically adjusts the roll angle to maintain alignment with the pre-defined route. This regulator incorporates both a proportional and integral component, allowing for immediate response to deviations and addressing prolonged or cumulative errors, respectively. Ultimately, this methodical approach not only helps to mitigate deviations from the intended track but also ensures overall stability and accuracy of the flight trajectory.

Line approach and hold

To ensure accurate navigation, this process involves a continuous evaluation of the intended route. This is determined by measuring the cross-track error, which calculates the deviation from the desired path in both left and right offsets.

To calculate the desired track, two key factors are taken into account: linear and logarithmic components. The linear component aligns the path roughly, while the logarithmic component takes over for a more precise approach when the cross-track error is within a few meters. This approach was chosen after extensive testing, which revealed that the linear component, while suitable for a smooth, gradual approach from a distance, is insufficient for fine alignment. This led to roll oscillations and high cross-track error due to its low contribution.

$$t_c = \max\left(\frac{5}{v_{IAS}} * e, \frac{v_{IAS}}{100} * \log10(0.1 + e)\right) \tag{3.3}$$

where t_c denotes the track correction, v_{IAS} denotes indicated airspeed and e denotes cross track error.

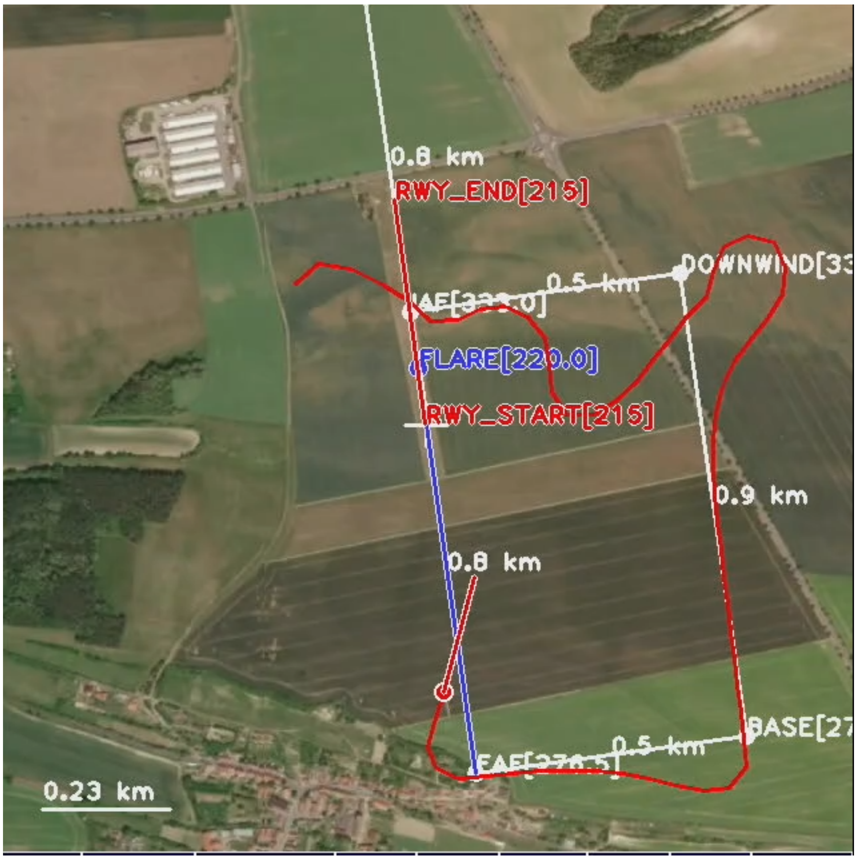

Figure 3.28: LNAV LINE - flight test.

Taken as a screen shot show from the custom map-framework piece of software that additionally displays map center (white cross) and map scale (left-bottom corner of the image, the number matches real world length of its white under- line). The red line represents flown trajectory meanwhile white (blue for active leg) visualises guidance data. Notice that after reaching desired flight plan points the aircraft (red dot with red velocity vector) gets off track but then instead of continuing directly to next the waypoint it aligns with the line again.

Vertical guidance

Following presents modes implemented in the guidance software:

mode	description
ALTHOLD	holds target altitude
VS DIRECT	holds vertical speed calculated to reach next waypoint at target altitude
VS SLOPE	holds vertical speed calculated to capture and follow slope connecting previous and next waypoints
IAS CLIMB	full power is set while airspeed is controlled by pitching
IAS DESCEND	zero power is set while airspeed is controlled by pitching

Table 3.10: Modes of vertical guidance.

VNAV ALTHOLD, VS DIRECT, IAS CLIMB/DESCEND

The guidance system of an aircraft relies on three critical modes: altitude hold, vertical speed, and IAS climb/descent. These modes serve distinct purposes in controlling the aircraft's vertical profile and speed. Altitude hold mode maintains a preset altitude by adjusting the pitch angle. This mode constantly monitors the aircraft's height above sea level and makes necessary adjustments to keep it steady. Vertical speed mode controls the rate of ascent or descent, maintaining a uniform vertical velocity despite changes in air density or wind conditions. This allows for precise and controlled climbs or descents. IAS climb/descent modes regulate the aircraft's speed by sustaining a specific indicated airspeed during ascent or descent. These modes control pitch to achieve and maintain a predetermined airspeed. Together, these modes provide pilots with versatile tools for managing altitude, vertical speed, and airspeed. This improves navigational precision and operational efficiency, making air travel safer and more reliable.

VNAV SLOPE

The mode in question will only be activated when the aircraft's *Lateral guidance* is running in *LNAV LINE* mode. Attempting to follow the vertical slope between two flight plan points without being able to follow the horizontal line is a futile effort. The aircraft will approach the slope using the *VNAV IAS CLIMB/DESCEND* modes before engaging the *VNAV SLOPE*. Tests have shown that the aircraft's current indicated airspeed is effective and practical for the proximity threshold, as it offers a one-second reaction time for mode switching.

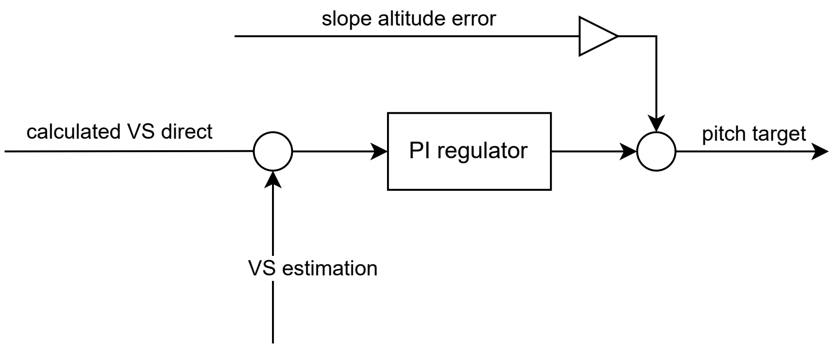

Figure 3.29: Vertical guidance - VS SLOPE mode.

Presented regulator 3.29 is a simple PI regulator having vertical speed calculated to reach the next waypoint at target altitude as its input and pitch target as its output and direct slope altitude error in feed-forward branch.

Testing proved that well working feed forward branch gain is

$$g_{FF} = \frac{10 * e_{sa}}{v_{IAS}} \tag{3.4}$$

where g_{FF} denotes the feed-forward gain, e_{sa} the slope altitude error and v_{IAS} indicated airspeed.

3.3.2 Control

The following sections describe the relationship and roles between the *flight computer* and the *navigation computer* with regards to control. Later, the software control modes (flight operation modes) are presented, followed by a description of elementary control regulators.

Flight computer and navigation computer relationship and their control roles

The flight computer assumes a critical role by operating in the specialized *offboard mode*. This mode signifies a distinct operational state wherein the flight computer seamlessly transitions to an externally directed mode. Within this configuration, the flight computer becomes reliant on external inputs and instructions, communicated through the Mavlink protocol from the Navigation computer.

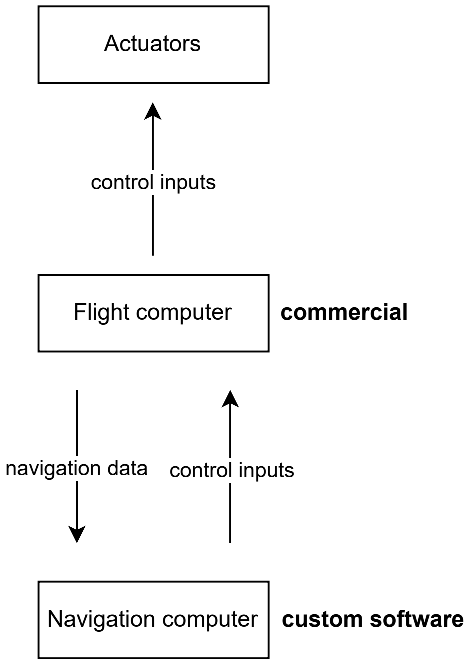

Figure 3.30: Roles of Flight and Navigation computers.

data	description
Latitude, Longitude, Altitude	absolute position
VN,VE,VD	NED velocities
IAS	indicated airspeed
HDG	current heading
TRK	current track

Table 3.11: Navigation data provided by Flight computer.

data	description
roll, pitch	attitude setpoints
P	engine power (0 to 1)

Table 3.12: Control setpoints provided by Navigation computer.

Control modes

Find control modes (flight operation modes) in the table below:

mode	description
OFF	engine is set to zero power
MANUAL DIRECT	system is controlled on groundstation using gamepad
MANUAL ATTITUDE HOLD	system holds both heading and altitude values during the mode engeage
AUTOSTART DETECT	system awaits catapult launch detection
AUTOSTART DEPARTURE	gaining both safe airspeed and altitude after start detection
FLIGHT PLAN	flight plan following
HOME	returning to home point
AUTOLAND APPROACH	approaches landing site via following calculated approach path
AUTOLAND FLARE	final stage of landing

Table 3.13: Control modes.

These are modes in which the control system is capable to operate. They closely correspond to state of the aircraft. In following paragraphs keyword *setpoints* is often used. That is how reference values that are sent from Navigation computer to Flight computer are reffered.

OFF

Roll and pitch setpoints are set to zero. Engine power also - propeller is not spinning. Overally used after start-up and as safety disable.

MANUAL CONTROLLER

Roll, pitch and power setpoints are set accordingly to actions user make on gamepad connected to groundstation. This mode requires continuous and not interrupted attention of the pilot since it is actively controlled. Control inputs are sent to aircraft at the rate of 20 Hz.

MANUAL AUTOPILOT

Heading/Track and Altitude setpoint are sent to the aircraft at the rate of 2 Hz. In case of operating in any other control mode these setpoints are being updated to current flight values onboard. Such approach offers one-click stabilisation to attitude and altitude hold. This mode requires attention of the pilot that is not neccessary continuous neither not interrupted and provides pilot time to for operating or monitoring other systems.

AUTOSTART DETECT

This mode operates automatic takeoff from catapult launching device. The propeller must not be spinning while the aircraft is still on catapult waiting to be launched. The detection logic is rather simple. After launch the aircraft starts pitching up and after positive pitch rate is detected aircraft switches to *AUTOSTART DEPARTURE* mode.

AUTOSTART DEPARTURE

The target of this this mode is to gain safe altitude and airspeed. After launch the aircraft is not in state where immediate guidance maneuvers would be safe to execute thus two conditions: climb 25 m above launch altitude and reach cruise speed must be achieved. When these conditions are met, aircraft continues to *FLIGHT PLAN* mode.

FLIGHT PLAN

Guidance system described in earlier section calculates roll, pitch and power setpoints for smooth flight plan following. When last flight plan point is reached, aircraft proceeds from the beginning all over again. Flight plan is uploaded using the groundstation.

HOME

This mode is actually simplified *FLIGHT PLAN* mode that only consists of one point which is the home point. Guidance system described in earlier section calculates roll, pitch and power setpoints for home and then circles around the point until further pilot action. Home point is automatically marked 50 m about launch location and can be later modified using the groundstation.

AUTOLAND APPROACH

When landing site is specified via groundstation - selecting runway start, end and altitude. Onboard software calculates approach track that is sent to to groundstation where it is visualised on the map. After engaging autoland, aircraft flights a standard rectangular traffic pattern around the landing site, reducing its airspeed from cruise speed to landing speed after the last turn and continues to descend along 5 degrees slope to a point 5 meters above 1/3 of the runway where it switches to *AUTOLAND FLARE* mode.

AUTOLAND FLARE

Command the aircraft to set power to idle and descend at the rate of -0.5 m per second until touchdown. Touchdown detection is not necessary since power is already set to idle.

Regulators

Other regulator apart of the ones described in *Guidance* section are implemented as PI regulators with integrator clamping and output saturation.

regulator	input	output
pitch	pitch error	pitch rate
pitch rate	pitch rate error	elevator
roll	roll error	roll rate
roll rate	roll rate error	aileron
altitude	altitude error	pitch
vertical speed	vertical speed error	pitch
airspeed (power)	airspeed error	power
airspeed (pitch)	airspeed error	pitch

Table 3.14: Control - regulators.

No advanced and approach as would for instance be a proper system identification and fine-tuning of the regulators has been applied during my work. The regulator constants have been identified by testing.

Failsafe

The system is designed and tested in such a way that in case of datalink loss, the control mode automatically switches to *Home* guiding the aircraft to return to its launch location. In case of low-battery or failure in regaining the datalink connection, system proceeds to *AUTOLAND*.

3.4 Ground Control Software

In following paragraphs the ground control software that has been fully developed from scratch is first generally introduced and later its key parts are described in more detail.

3.4.1 Introduction

The software responsible for monitoring and controlling the aircraft, known as ground control software, is a critical aspect of my work. The flight systems described in my thesis are all onboard, allowing for operation even without the ground control software. However, during launch, it is necessary to monitor the systems, upload the flight plan, and activate control. If the connection is lost or the ground control software fails while the aircraft is in the air, it is not needed as the failsafe options - either autoland or return-home - take over. When the software starts or the datalink reconnects, everything automatically goes back to a working state within seconds. The ground control software serves as a human interface to datalink control commands and data visualization, including camera view and moving map. If any of the aircraft parameters or systems display suspicious values, they turn red to alert the pilot. Figure 3.31 captures the entire flight screen.

Figure 3.31: Groundstation screen.

3.4.2 Camera view

Within figure 3.32, the camera view and data overlay are the primary focuses. A plethora of critical information is presented in an effortless visual format, such as datalink connection, GNSS performance, flight computer status, attitude, airspeed, altitude, distance and time to the next waypoint, lateral and vertical guidance error, all working in tandem to ensure a secure and smooth flying experience.

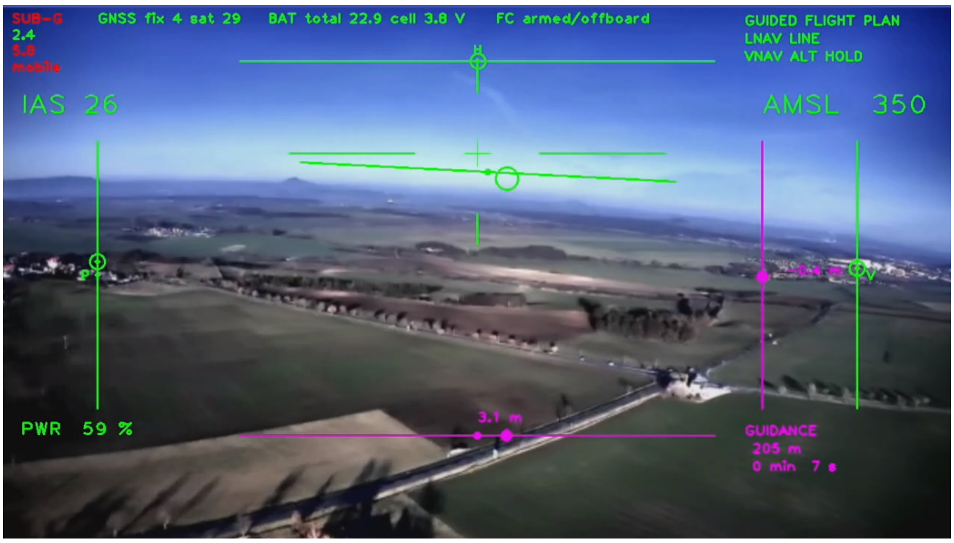

Figure 3.32: Groundstation screen - camera view with data overlay.

3.4.3 Monitoring panel

Moving on to another crucial aspect of the screen - data monitoring section. While most of the parameters are self-explanatory, I would like to draw your attention to the right-hand side of the panel, which is represented by **[OB]** and **[GS]** in figure 3.33. These sections display the status of the onboard and ground station systems respectively, and have proven to be invaluable tools during development and testing, ensuring the safe operation of flights. Additionally, the autopilot control buttons are located in this area, allowing you to easily adjust altitude and track setpoints.

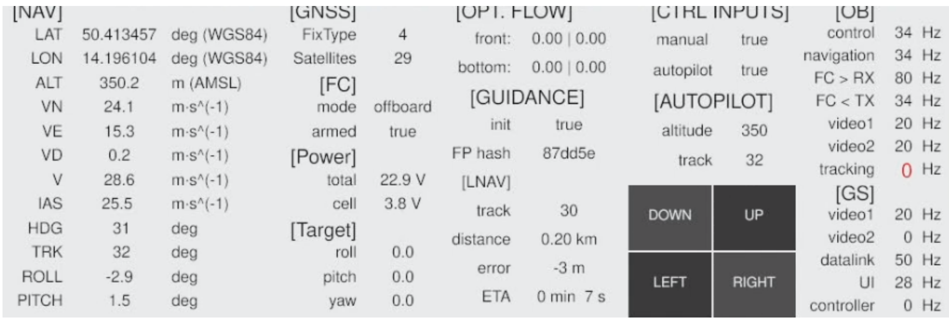

Figure 3.33: Groundstation screen - monitoring panel.

3.4.4 Flight mode control panel

The grid of buttons showed in figure 3.34] are used for flight modes switching.

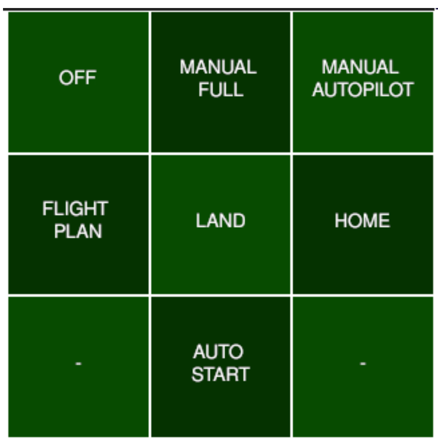

Figure 3.34: Groundstation screen - flight mode control panel.

3.4.5 Side variable panel

The adjustable side panel offers a convenient view of various areas of interest. As depicted in Figure 3.35, monitoring guidance is a breeze. The map view showcases the aircraft's location, its ten-second velocity vector, flight plan path, active leg, and trajectory flown. Detailed guidance performance data is displayed in the lower part of the panel. Additionally, two buttons located at the bottom can be utilized to instruct the aircraft to transition to the active flight plan point.

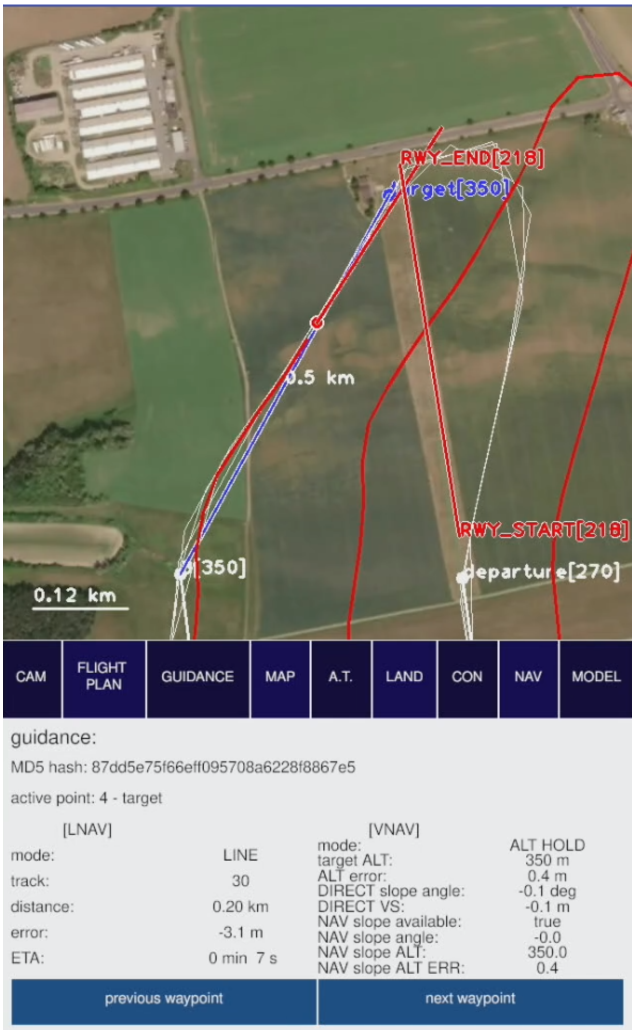

Figure 3.35: Groundstation screen - side panel with guidance data monitoring.

The visual representation presented in figure 3.36 exemplifies how the software efficiently displays and validates flight plans. These neede to be predefined in text files as a set of flight plan points on the computer disk and pilot only selects which one to display and upload to the aircraft. The groundstation software enables users to easily navigate the globe by zooming in or out and shifting the map. Additionally, real-time tile downloads are available when necessary. To enhance orientation, pertinent details such as leg length, waypoint names, and altitudes are conveniently overlaid onto the map.

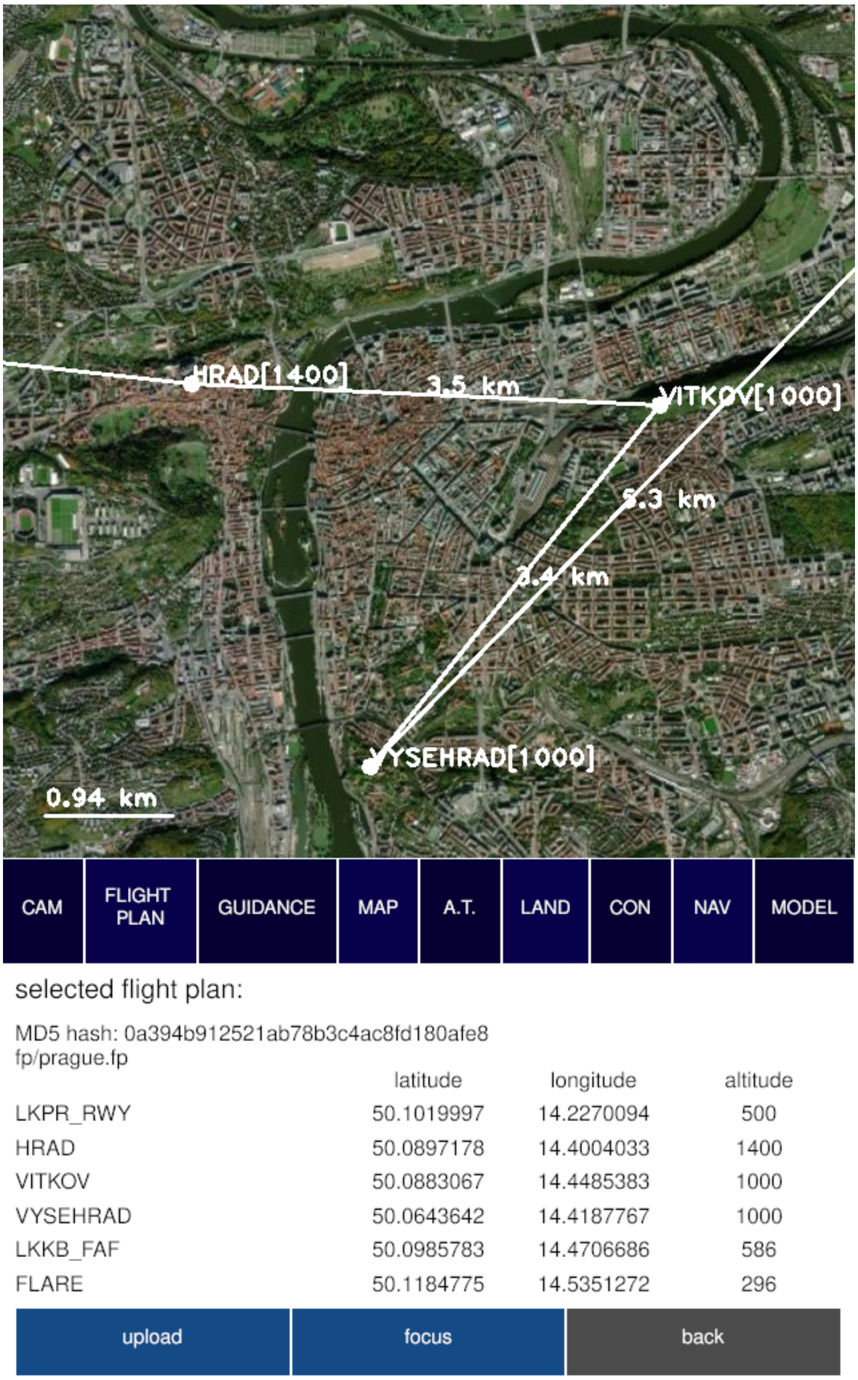

Figure 3.36: Groundstation screen - side panel with flight plan overview.

3.5 Antenna Tracker Software

Antenna tracker software allows for the adjustment of high-gain directional antennas to point towards aircrafts. This is made possible through the active reception of an aircraft's position via a datalink. Once both the positions of the aircraft and the tracker are determined, coordinates are converted to NED format, and azimuth and elevation angles are then calculated. Prior to any flight, the tracker's position and heading must be set through the ground station. It's important to note that these calculations assume zero pitch and roll angles of the tracker stand.

The software controls two stepper motors for the elevation and azimuth directions, reads end-switch state, and receives position commands from the ground station. Figure 3.37 provides a visual representation of the control.

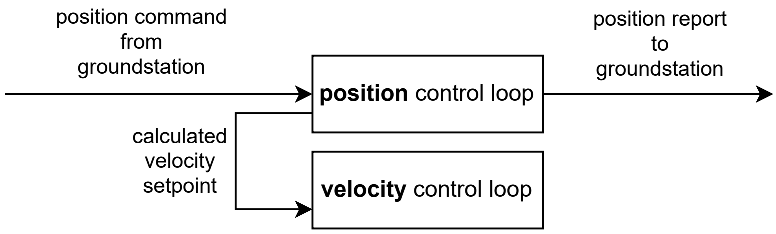

Figure 3.37: Antenna tracker software control.

3.6 Flight Simulator Connection

Linking the control system to a flight simulator is a vital stage in guaranteeing the dependability and safety of your algorithms before utilizing them in the actual world. This connection permits comprehensive testing of both onboard and ground control software, leading to thorough validation and refinement of control algorithms in a controlled environment. While it is lacking a video feed from an onboard camera, which is a crucial element in real drone operations, the capability to test and adjust control systems within a simulated flight environment significantly decreases risks, improves algorithm performance, and reinforces the general safety and effectiveness of UAV operations prior to moving to live deployments.

3.6.1 Flightgear

FlightGear is a remarkable project that caters to aviation enthusiasts, aspiring pilots, and developers, by providing an open-source flight simulator platform. It boasts a range of aircraft models, customizable features, and diverse scenery, which allows users to simulate flights under various conditions and environments. The active community that contributes to its development makes it a versatile option for flight simulation enthusiasts.

One of FlightGear's notable features is its ability to communicate using UDP for both outputting navigation data and receiving control data. Navigation data includes aircraft position, speed, altitude, and other relevant flight parameters, which can be used for various purposes such as displaying the simulated aircraft position on external mapping software, sharing information with other systems or applications, or for recording flight data for analysis.

FlightGear's control data feature enables users to receive commands or control inputs from external sources via UDP. This allows users to control the simulated aircraft from external devices or software, such as sending commands for controlling the aircraft's throttle, rudder, ailerons, elevators, or any other flight control surfaces. This feature is often used in setups where external hardware or custom-built interfaces are used to simulate the control inputs for a more immersive experience.

Figure 3.38: Flight Simulator - screenshot.

3.7 TestFlight

The following figures encapsulate the data derived from a brief yet impactful proof-of-concept demonstration flight. These visuals present a snapshot of the key findings and metrics obtained during this pivotal flight, offering insights into the experimental phase and its potential implications.

Throughout the duration of this flight, a series of stages will take place. The initial stage involves an automated takeoff, followed by a brief manual flight segment. Subsequently, five autonomous mission circuits will be completed, leading to another manual section where a human pilot takes control. Finally, two autonomous landing traffic patterns will be executed, culminating in an impressive demonstration of autonomous precision as the aircraft flawlessly lands.

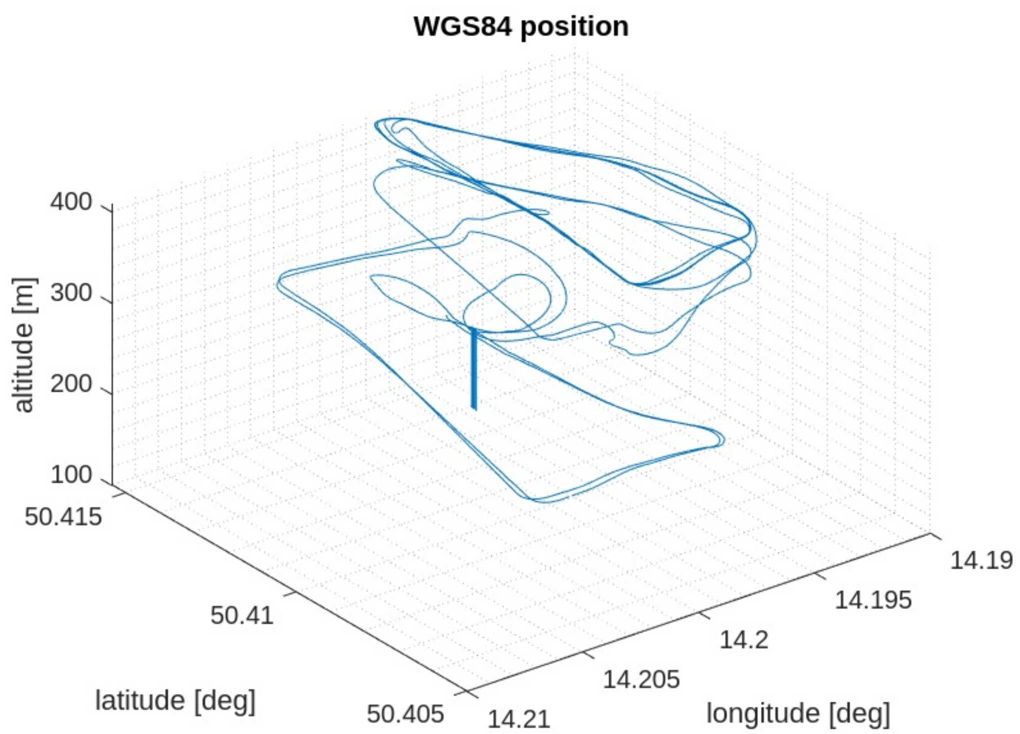

Figure 3.39: Test Flight - WGS84 position.

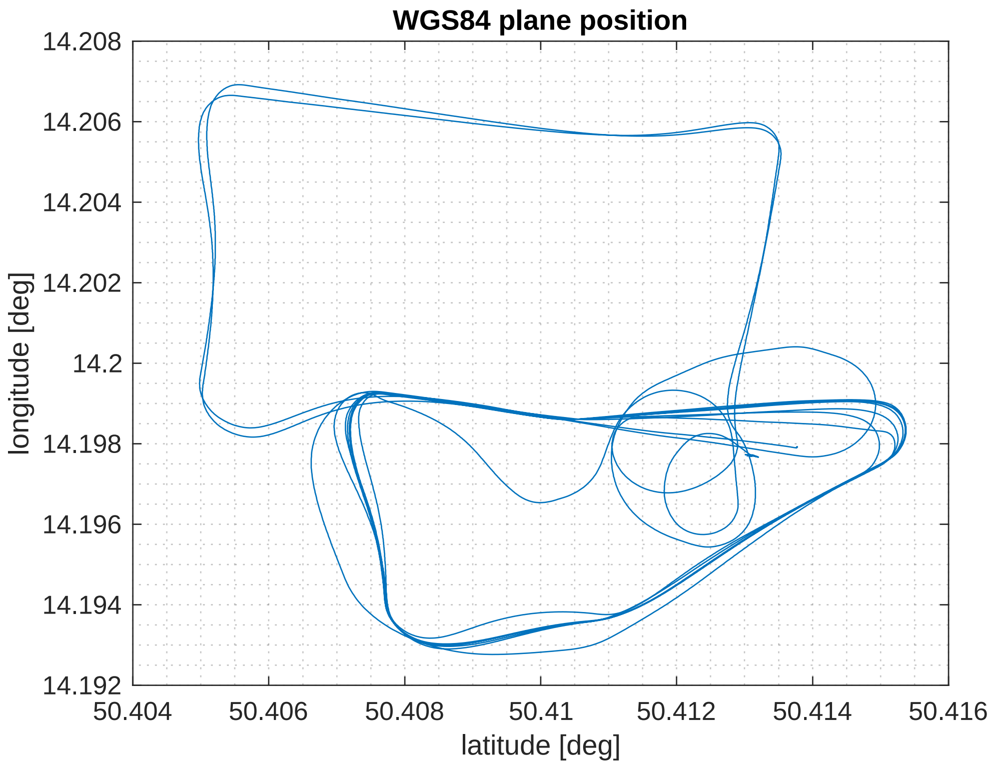

Figure 3.40: Test Flight - WGS84 plane position.

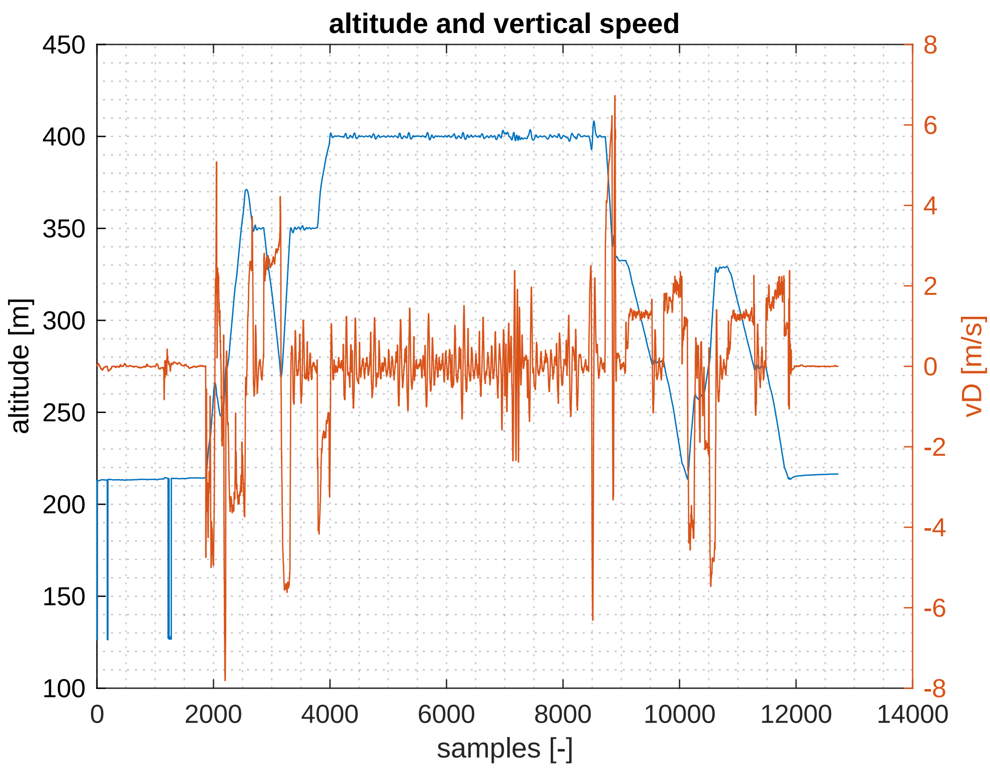

Figure 3.41: Test Flight - altitude and vertical speed.

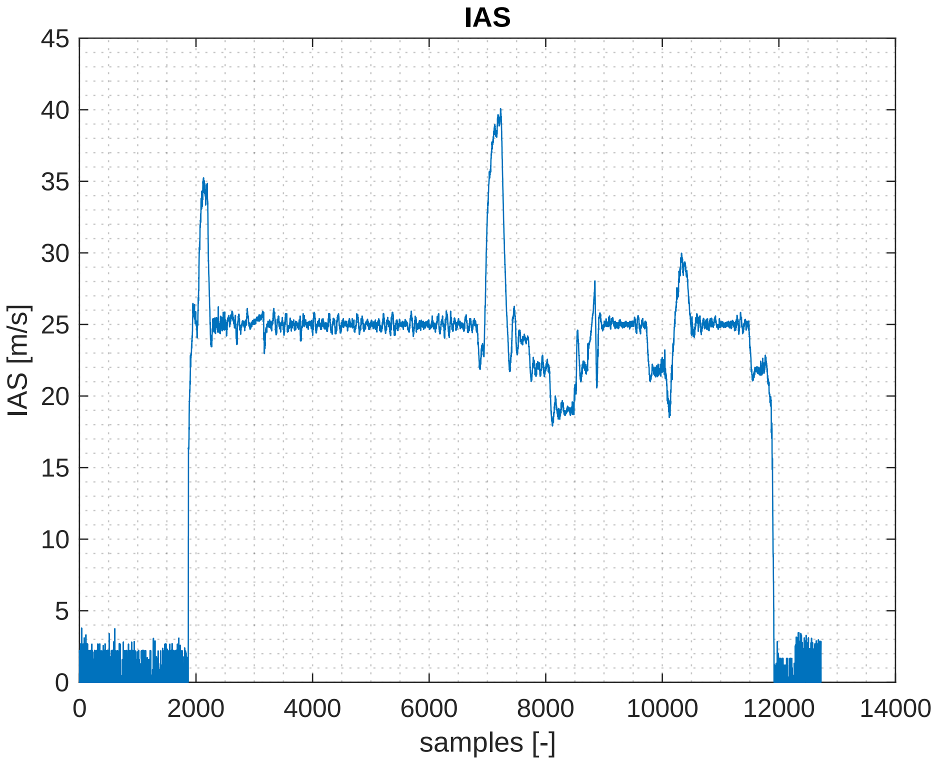

Figure 3.42: Test Flight - IAS.

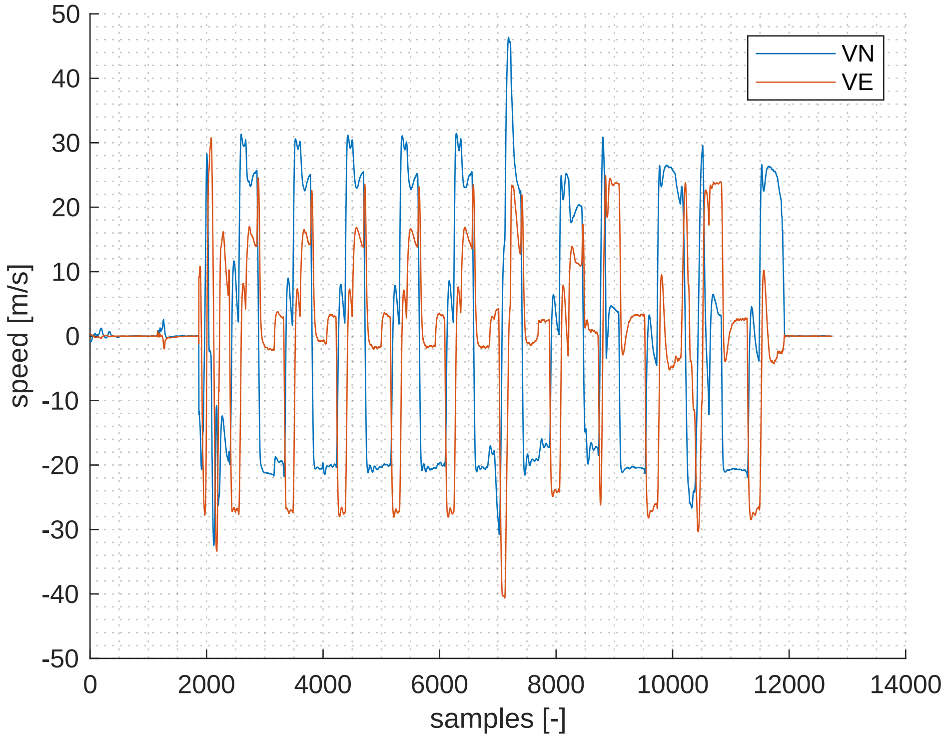

Figure 3.43: Test Flight - VN, VE.

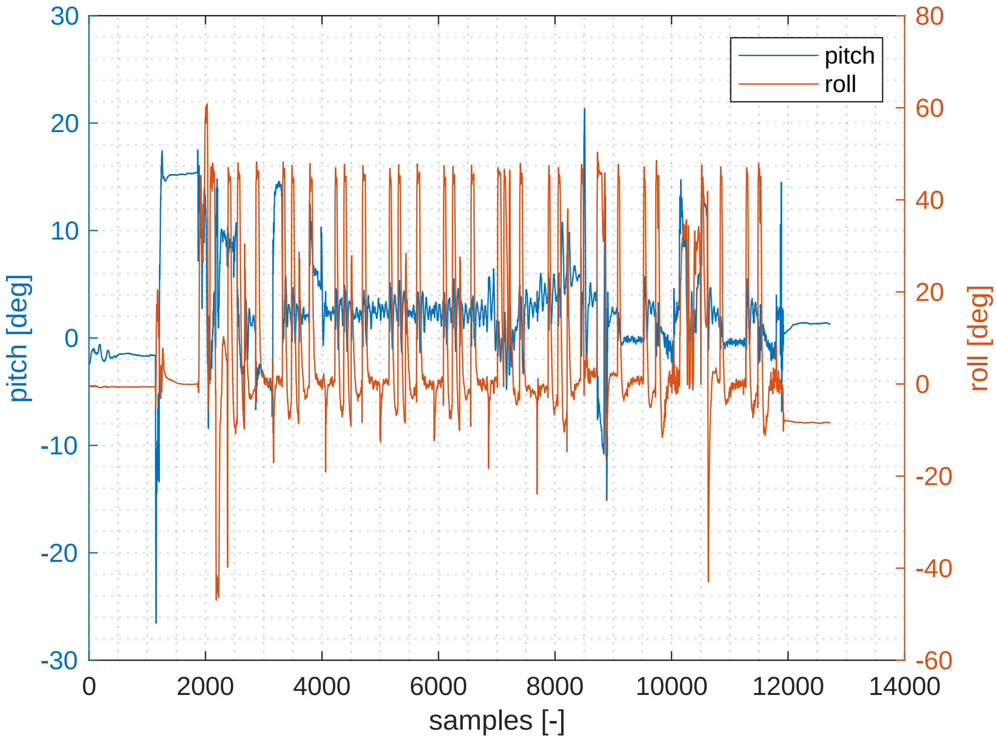

Figure 3.44: Test Flight - pitch and roll.

Presently, the guidance performance data is exclusively available in real-time during the flight. However, the aircraft demonstrates exceptional stability, maintaining an accuracy of less than one meter both horizontally and vertically along the designated track. This has been substantiated through multiple successful autonomous landings, affirming the pivotal role of this precision in the most critical phase of flight - the moment of landing.

While the stated performance showcases impressive precision during guidance, there are discrepancies in the navigation data derived from the fusion of IMU and GNSS. The accuracy of the fused data hasn't undergone comprehensive exploration or comparison against precise absolute positioning methods, such as Real-Time Kinematic (RTK) GNSS, which could offer a more meticulous assessment of the system's navigation performance. This comparison could potentially unveil further insights into the accuracy and reliability of the fused data for a more comprehensive evaluation.

The test flight was meticulously executed within the constraints of maintaining a direct line of sight, accompanied by a secondary manual control backup system. Importantly, these operations were conducted within the airspace of an uncontrolled airport, following an agreement with the airport's local radio service. This careful adherence to safety protocols and collaboration with the airport authorities ensured a controlled and monitored environment for the experimental flight, enhancing safety and regulatory compliance during the testing phase.

3.8 GNSS denied navigation

UAVs heavily depend on GPS signals for accurate navigation and positioning, making GNSS-denied navigation a critical capability. In urban areas with tall buildings, indoors, or due to intentional signal interference, relying solely on GPS can be challenging for UAVs and pose potential risks to people and property below. Therefore, GNSS-denied navigation is essential for ensuring safety. Moreover, mission continuity is crucial in scenarios such as indoor inspections or military operations where GPS signals may not reach. To enable robust navigation in GNSS-denied environments, alternative navigation systems and sensor technologies such as IMUs, LiDAR, cameras, and radar must be integrated. By reducing reliance on external signals, UAVs equipped with diversified sensors can improve operational efficiency, minimize accident risks, and safeguard expensive UAV systems. These capabilities are critical for enabling UAVs to perform autonomous missions reliably, adapt to various environments seamlessly, and ensure both safety and mission success across industries, from defense to agriculture, inspection, and emergency response.

I strongly advocate for the use of cameras in UAV navigation to ensure optimal performance. My belief in this approach has led me to develop a comprehensive visual framework that seamlessly integrates into the navigation computer. Cameras provide a plethora of visual data that, when properly utilized, can significantly improve UAV navigation, especially in areas where GNSS signals are limited. The ability to understand and interpret surroundings through visual cues enhances other sensor data and enables detailed mapping and localization. With deeply integrated visual framework, UAVs can autonomously navigate with greater precision and dependability. This approach mitigates the risks associated with GNSS signal loss and enhances UAV operations in diverse environments, ensuring safer and more successful missions. Comparison and overview on visual-aided navigation techniques is carried in [13].

Integrating advanced visual frameworks like optical flow and feature detection into custom software would enhance UAV navigation beyond what is possible with the flight computer alone. By leveraging visual data, we can achieve real-time motion understanding and identify key environmental markers for precise navigation without relying solely on GPS. This shift requires dedicated development and ongoing refinement, but promises to create robust autonomous navigation systems that can operate reliably in GNSS-denied environments. Further research is needed on utilizing visual data for navigation.

The current state-of-the GNSS-denied navigation technique that don't involve camera is for instance based on Terrain Contour Matching (TERCOM) [14] - using radar altimiter measurements matching the ground elevation with onboard preloaded database.

Chapter 4

Conclusion

The fulfillment of my thesis requirements marks a significant achievement in the field of unmanned aerial vehicles. I have designed and developed software for a comprehensive ecosystem that encompasses all aspects of fixed-wing UAV operations, from control, guidance and navigation to datalink and video systems, as well as ground equipment like the ground station and antenna tracker. This system has the capability to perform fully autonomous missions, including takeoffs and landings, while also offers data and video collection and failsafe protocols following. Additionally, the system seamlessly transitions between autonomous and manual control, all managed from custom ground control station.

In the early stages of my research, I undertook an extensive examination of critical components in UAV operations: control systems, datalink technologies, video systems, and ground station infrastructure. This involved a meticulous comparison to uncover inherent limitations and avenues for improvement. Exploring control systems led to analysis of their functionalities and adaptability, offering insights into their strengths and weaknesses and guiding pathways for refinement. Similarly, investigating datalink technologies focused on reliability and data transfer rates, highlighting constraints in communication and directing efforts toward enhancing transmission capabilities. Assessing video systems scrutinized resolution and real-time streaming, pinpointing areas for optimizing visual data integration into UAV missions. Additionally, ground station infrastructure examination shed light on monitoring and data processing limitations, steering the development of more robust ground control solution.

The revelations and limitations unearthed during these extensive explorations served as the catalyst for the next phase: the design and selection of hardware components for a bespoke UAV ecosystem. Armed with insights gleaned from scrutinizing control, datalink, video systems, and ground station infrastructure, I channeled efforts towards designing a custom UAV system. This intricate process involved leveraging the identified limitations to inform strategic decisions in hardware selection, aiming to address and overcome these constraints. The culmination of this phase resulted in the creation of a tailored UAV ecosystem meticulously crafted to mitigate known limitations and optimize performance across its various components.

My work involved creating a comprehensive suite of software for crucial aspects, including precise control mechanisms, sophisticated navigation and guidance system, encrypted and reliable datalink framework, robust mapping framework, and unique visual frameworks. Key focus was on crafting custom ground station software that allows for seamless operation, monitoring, and control of the UAV. Additionally, I have developed control software for antenna tracker computer that unlocks the usage of high-gain directional antennas. While commercially available systems may offer a broader feature set, my bespoke software provides unparalleled customizability and dynamism. This flexibility enables dynamic functionalities such as automatic takeoff, landing, guidance, and failsafe options perfectly fit for particular aircraft and its usage. Notably, the deep integration with visual information from onboard camera forms a cornerstone of the software's functionality, unclocks enriching decision-making capabilities and enhancing overall operational efficiency for future research in GNSS-denied navigation field.

Throughout the development of the UAV system, I utilized a flight simulator to conduct comprehensive safety and reliability tests enabling to conduct rigorous testing within a simulated environment. This approach was perfected over an extended development period and resulted in numerous successful fully autonomous flights. These flights serve as concrete evidence of the robustness of the system, validating its ability to operate autonomously and safely execute complex missions. The simulator played a pivotal role in this process, allowing to tune algorithms, verify functionalities, and ensure a high level of confidence in the system's performance prior to real-world deployment.

Considering the intricacy of the project at hand, I have identified several crucial areas that require further study. These include the development of comprehensive post-flight analysis software to thoroughly evaluate the data, a model identification tool to precisely fine-tune the parameters, and a dedicated flight planning tool to simplify mission preparations. Additionally, it is vital to explore GNSS-denied navigation solutions, implement parallel datalinks for robust communication, and create a custom-designed flight computer specifically for stabilization purposes. Enhancing these aspects would significantly bolster the system's resilience, operational efficiency, and adaptability in various scenarios, thereby pushing the UAV system's capabilities beyond its current limitations.

Chapter 5

Assignment requirements

requirement	**note**
research of available systems	Research and comparison of available control systems are presented throughout chapter 2.1 and 2.2, continues with datalink and video systems throughout chapters 2.3, 2.4 and 2.5, comparison against the requirements stated in the assignment is carried across the chapters.
custom system requirements	Research and comparison of available systems yielded into set of specific requirements for custom UAV system listed in Table 2.2.
realisation of custom UAV system	Realisation of custom UAV system is the object of chapter 3. Description and justification of hardware and software components is found in chapter 3.1. Navigation, Mapping, Datalink and Visual software frameworks developed are described throughout chapter 3.2 and onboard systems are with special focus covered in chapter 3.3. Ground control software and its capabilities are presented in chapter 3.4, Antenna Tracker software in chapter 3.5.
flight simulator connection	Covered in chapter 3.6 .
real world test flight	Successful fully autonomous real world test flight out the custom UAV system was conducted and results are presented in chapter 3.7 .
research GNSS-denied navigation	Possibilities of GNSS-denied navigation techniques were presented in chapter 3.8.

Table 5.1: Assignment - requirements.

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Appendix A

Acronyms

BPSK Binary phase-shift keying

CSRT Channel and Spatial Reliability Tracker

ECEF Earth-Centered Earth-Fixed

GCS Ground Control Station

HLS HTTP Live Streaming

IoT Internet of Things

LoRa Long Range

LoRaWAN Long Range Wide Area Network)

LTE Long-Term Evolution

MAVLink Micro Air Vehicle Link

MIMO Multiple Input Multiple Output

MJPEG Motion JPEG

MPEG-DASH Dynamic Adaptive Streaming over HTTP (DASH)

MU-MIMO Multi-User Multiple Input Multiple Output

OFDMA Orthogonal Frequency Division Multiple Access

QAM Quadrature amplitude modulation

QPSK Quadrature phase-shift keying

RF Radio Frequency

RTSP Real-Time Streaming Protocol

TCP Transmission Control Protocol

TERCOM Terrain Contour Matching

UAV Unmanned Aerial Vehicle

UDP User Datagram Protocol

VLAN Virtual Local Area Network

WGS84 World Geodetic System 1984

Wi-Fi Wireless Fidelity

WPA Wi-Fi Protected Access

WPS Wi-Fi Protected Setup

Appendix B

Contents of the attachment

- `thesis/` - thesis in PDF format
- `app/` - executables for groundstation, onboard and antenna tracker software
- `code/` - code needed to replicate our work
- `record/` - navigation data recorder from test flights
- `videos/` - videos from test flights