OST Ostschweizer Fachhochschule

Expansion of open-source drone software to include wind analysis

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Abstract

This project aims to develop a cost-effective and portable system for measuring wind and turbulence using a small unmanned aerial vehicle (UAV). Traditional methods of measuring wind and turbulence (e.g. weather stations or anemometers) are often expensive and not portable, which limits their usefulness for activities such as paragliding. Paragliding pilots are highly dependent on accurate wind and turbulence data for safety reasons, as strong winds and turbulence can create dangerous flying conditions. However, such data is often inaccurate due to the nearest weather station being far away, not up-to-date or not available at all in remote areas.

The proposed solution involves equipping a small, lightweight UAV with various sensors to collect data on wind speed, direction, and turbulence intensity and transmit it in real-time to a connected device. The UAV is required to be portable, allowing it to be easily transported to different locations. Due to these specific requirements, the UAV needs to be custom-built.
Current similar solutions rely on heavier UAVs or weather balloons. These are able to carry more advanced and heavier sensors, but require special permissions to operate and are less portable.
The UAV's transmitted data then must be received and processed in real-time by a connected software system. This system must be designed to also process reference data from traditional measurement devices. The data from both the UAV and the reference sources then is to be analyzed to find correlations and develop models for accurate estimations.
Several methods were evaluated to estimate the wind and level of turbulence using the received data from the UAV. Due to time constraints the evaluation of these methods remained a theoretical approach. The most promising methods and algorithms were selected based on previous research in the field and the capabilities of the constructed UAV in terms of the available sensors and data that can be extracted.

The project successfully proved the technical feasibility of using a small UAV for wind and turbulence measurements. With the prototype UAV built and equipped with an accurate IMU (Inertial Measurement Unit) and GNSS (Global Navigation Satellite System) module the required measurements can be made to enable accurate wind and turbulence estimation. The data is transmitted in real-time via WiFi to the connected software system that was implemented in this project.
The implemented software system is capable of processing and analyzing the data from the UAV together with reference data gathered through traditional measuring equipment.
Methods based on the UAV's acceleration and attitude data were identified as viable approaches for wind and turbulence estimation, laying the groundwork for future implementation and validation in subsequent projects. The prototype built in this project serves as a solid foundation for further development of the software system and conclusive field testing.

Lay Summary

This lay summary provides a brief overview of the project and its key outcomes.

Problem Statement

The overall goal of this project is to develop a cost-effective and portable system for measuring wind and turbulence using a small unmanned aerial vehicle (UAV) to provide accurate wind and turbulence data for paragliding pilots in remote areas.

Importance of Wind and Turbulence Measurements

Wind plays a major role in every aspect of aviation. It dictates decisions about the direction of takeoff and landing, flight path and cruising altitude. Strong wind conditions or thermals can also create turbulence, which can be uncomfortable or even dangerous for aircrafts of all sizes, but especially for smaller aircraft like paragliders. Knowing the current wind conditions is therefore of vital importance before making decisions about taking off or where to fly. While airports provide detailed wind measurements, paragliding sites often lack accurate information, especially if the launch site is remote and chosen spontaneously. Traditional methods of measuring wind and turbulence are often expensive and not portable in all locations, which limits their usefulness for activities such as paragliding.

Proposed Solution using UAVs

UAV technology has become ever more popular and sophisticated. Modern UAVs are equipped with a variety of sensors, such as GNSS, accelerometers, gyroscopes and barometers which allow them to fly autonomously and maintain stable flight even in challenging conditions. This requires the UAVs to be able to react precisely to changes in wind direction or strength and gusts. The data produced by the sensors should therefore in reverse also be usable to measure wind and turbulence.

There have been previous projects, which used UAVs to measure wind and turbulence, but they involved relatively large and heavy UAVs. This project in turn aims to develop a small, light and portable solution that can be carried by paragliding pilots even to remote launch sites to retrieve accurate information about the wind and level of turbulence in real-time.

Approach / Technology

To proof the feasibility using a small UAV to measure wind and turbulence, the project is divided into three areas:

Constructing a UAV capable of carrying the required Sensors

The requirements towards the UAV's capabilities are very specific, as it needs to support various sensors and be able to transmit the measured data in real-time. This necessitates the construction of a custom-built UAV that is optimized to this use case and is light and portable enough to be carried by paragliding pilots to their flight locations.

Developing a connected software system

A software system is necessary, which is connected to the UAV and receives and processes its data in real-time. In addition to the UAV's data, the system also needs to be able to process reference data from e.g. nearby weather stations or mobile measuring equipment in order to develop and verify wind and turbulence estimation methods.

Researching wind and turbulence estimation methods

Several methods were evaluated to estimate the wind and level of turbulence using the received data from the UAV. Due to time constraints this remained a theoretical approach and methods were selected and evaluated based on previous research in the field and the capabilities of the constructed UAV.

Result

The project successfully proved the feasibility of using a small UAV for wind and turbulence measurements. A prototype UAV was built and equipped with the necessary sensors, and a software system was developed to receive the UAV's measurements in real-time. The implemented software system is capable of processing and analyzing the data from the UAV together with reference data gathered through nearby weather stations and other traditional measuring equipment.

From the methods researched for wind and turbulence estimation, two approaches were identified as the most promising and feasible for further development and testing in future work. These are:

- Estimate turbulence based on the UAV's **accelerations** while hovering
- Estimate wind speed based on the UAV's **attitude** required to compensate for wind drift

All three areas of the project were implemented or investigated, but their combination into one functioning portable solution needs further development, research and testing. Still, the project can be viewed as successful in proving the concept and the intended approach as feasible.

Future Work

To fully develop a functioning system, further work is needed in two areas:
First, the UAV must be further tested and a number of measurements need to be performed in different conditions to gather sufficient data for analysis. This data will then have to be compared to reference measurements to develop and validate the wind and turbulence estimation algorithms. Second, the remote software system needs to be further developed to visualize the collected data in real-time and provide useful insights to the users, ideally also allowing the user to control the UAV.

Conclusion

The project demonstrated the potential of using a small UAV for wind and turbulence measurements. While further work is needed to fully develop a functioning system, the results of this project provide a solid foundation for future research and development in this area.

Figure 1: Image of the UAV in flight

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Glossary

Abbreviations

EDR	Eddy Dissipation Rate — A measure of the rate at which turbulent kinetic energy is converted into thermal internal energy.
ESC	Electronic speed controller — Electronic component that controls and regulates the speed of an electric motor.
FC	Flight controller — control unit of a UAV
GNSS	Global Navigation Satellite System — the general term for satellite navigation systems, including GPS, GLONASS, and Galileo.
GS	Ground Speed — Speed of an aircraft relative to the ground.
IAS	Indicated Airspeed — Airspeed as measured by an airspeed sensor, not corrected for instrument or position error.
IMU	Inertial Measurement Unit — An electronic device that measures and reports a body's specific force, angular rate, and sometimes the magnetic field surrounding the body, using a combination of accelerometers, gyroscopes, and magnetometers.
MTOW	Maximum Takeoff Weight
TI	Turbulence Intensity — A measure of the intensity of turbulence.
UAV	Unmanned aerial vehicle — drone
VS	Vertical Speed — Rate of climb or descent of an aircraft, usually measured in feet per minute (fpm) or meters per second (m/s).

Chapter 1

Initial Situation and Problem Statement

This project aims to develop a portable solution using a small unmanned aerial vehicle (UAV) that supports pilots in assessing wind conditions at remote locations. The following sections analyse the current situation, problems and challenges that need to be addressed.

1.1 Current Situation

The two main areas, on which this project is based, are meteorology in the context of aviation and UAV technology, wherefore both areas are briefly described below.

1.1.1 Aviation and Wind

Wind plays a major role in every aspect of aviation. It dictates decisions about the direction of takeoff and landing, flight path and cruising altitude. Strong wind conditions or thermals can also create turbulence, which can be uncomfortable or even dangerous for aircrafts of all sizes [9], but especially for smaller aircraft, including paragliders.
Accurate measurements and forecasts are therefore of essential importance. While major airports and even smaller airfields provide accurate data to local pilots, hanggliding and paragliding sites often lack precise data, or sometimes any data at all [10]. This is especially true when the launch site is chosen spontaneously.

1.1.2 UAV Technology

As UAVs have become ever more popular and affordable, their technology has become more advanced. Modern UAVs are equipped with a variety of sensors which allow them to fly autonomously and maintain stable flight even in challenging conditions. The data produced by the sensors should therefore in reverse also be usable to measure wind and turbulence.

1.1.3 Previous Studies

A number of comparable studies have been conducted. An overview of those can be found in Chapter 7. Although these studies have focused on larger UAVs and weather balloons, their results provide a good foundation for further research in this area.

1.2 Problems and Challenges

The most common solution of measuring wind conditions at ground level is using weather stations, which are generally expensive and need to be installed at a fixed location. But even if a weather station is present, its data might only be updated infrequently and becomes rapidly invalid.

The use of larger UAVs, as used in previous studies, is not practical for smaller scale use cases as for example an ad-hoc paragliding site. Their cost, size and weight, which impose legal restrictions, limit their use in many places. Using smaller UAVs, such as quadcopters, would reduce these issues, but as they are lighter, their payload capacity is limited, limiting the sensors that can be used. This might reduce the accuracy of the measurements, posing a significant challenge to the project.

1.3 Type of Project

This project is a research project, as the main focus lies on researching the possibilities and limitations of using small UAVs to measure wind and turbulence. The project aims to build a prototype system that can be used as a proof of concept and as a basis for further development in this area.

Chapter 2

Task Description

Here, an overview of the aim of the project and its intended results is given. The original task description can be found in the appendix.

2.1 Vision

The aim of the project is to research a small and cost efficient solution to measure wind and turbulence at low altitudes using a UAV (in this case a small quadcopter). The UAV should be able to send data in real-time to a ground station, where it can be processed and visualized. The system should be easy to use and portable, so that it can be used at different locations, in particular by paragliding pilots.

2.2 Technologies

A cost efficient consumer UAV should be used, with an MTOW (Maximum Takeoff Weight) of less than 250g. This will reduce legal restrictions (see Section 4.4) and increase portability. The software used needs to be open source to reduce cost and maximize flexibility. During development a UML model of the system architecture should be created using Enterprise Architect.

2.3 Method and Expected Result

As this project focuses on research, its expected results are a prototype system and an evaluation on the feasibility of using small UAVs to measure wind and turbulence. The main goals are:

- Building a **prototype UAV system** that is capable of collecting relevant data.
- Developing a **basic software solution** that can receive and display the data in real-time.
- **Researching and evaluating different methods** for measuring wind and turbulence using the collected data.

To achieve these goals, the project consists of three main areas:

1. **Construction of the UAV system**, including the selection of appropriate sensors and hardware components. The details of this process are described in Chapter 10.
2. **Development of the software solution** that receives and processes the data from the UAV in real-time. Details about the software architecture, design and implementation can be found in Chapter 9.
3. **Research and analysis** of different methods to measure wind and turbulence using the data collected by the UAV. This includes a review of existing methods, which are listed in Chapter 7, as well as the development, testing and validation of new hypotheses that are specific to our use case. The research methods are described in Chapter 8.

Achieving the projects goals should lay the ground work to develop a portable solution for measuring wind conditions at remote locations using a small UAV and displaying the estimated wind and turbulence conditions in a user friendly way for paragliding pilots on location.

Chapter 3

Framework Conditions

OST, the Eastern Switzerland University of Applied Sciences, provides the framework conditions for this semester thesis as follows:

3.1 Purpose and Scope

This project is a semester thesis, required for the completion of the Bachelor's degree in Computer Science at OST. The primary purpose of this project is to prepare the participants for their Bachelor's thesis. The project is to be carried out independently by the participants, under the guidance of a supervisor from OST.

3.2 Time Budget and Resources

The total time budget for this project is 240 hours per participant. This results in a total of 720 hours for all three participants.

OST directly or indirectly provides the necessary resources, in particular access to a fixed workplace at the campus in Rapperswil, as well as access to the university's library and online resources. This also includes the financial resources for the hardware necessary to build the UAV.

A more detailed view on the project resources is given in the project plan.

Following are the dates given by OST for the completion of this project:

- **15.09.2025:** Start of the project
- **15.12.2025:** Submission of the Brochure abstract
- **18.12.2025:** Release of the Brochure Abstract by the supervisor
- **19.12.2025:** Submission of the complete documentation
- **09.02.2026:** Submission of the grade by the supervisor

3.3 ECTS

The project is worth 8 ECTS credits (30 hours per credit).

Chapter 4

Context and Domain Analysis

In order to set the project into context, this chapter provides an analysis of the meteorological context and system context, starting with an analysis of the main target group of the project: Paragliding pilots.

4.1 Paragliding

Paragliding is a widespread recreational and competitive adventure sport, where pilots launch themselves from elevated terrain using a fabric wing [11]. Flight is generally unpowered and pilots rely on thermals and ridge lift to stay airborne for extended periods of time [12].

Figure 2: Paraglider Takeoff [4]

Because of their relience on natural lift sources and their light weight, paragliders are heavily influenced by the wind and turbulence conditions [13]. Strong winds can make takeoffs and landings difficult or even dangerous, while flying into turbulence or a strong downdraft can lead to a loss of altitude and potentially a crash.
It is therefore of vital importance for paragliding pilots to have access to current and accurate weather information. Oftentimes, however, weather stations are located too far away from the launch sites or update their measurements too infrequently, rendering pilots having to rely on visual observations of the environment and personal experience to assess the current conditions [10].

Hike and fly paragliding, where pilots hike to remote locations and launch from there [14], has become increasingly popular, with regular competitions being held [15]. This type of paragliding often takes place in areas without established weather stations which exacerbates the lack of accurate information about the current weather conditions. Therefore hike and fly pilots are a key target group for the system developed in this project.

4.2 Wind

Wind is the horizontal or vertical movement of air from areas of high pressure to areas of low pressure. It is heavily influenced by the topography, especially in the alps, where a lot of paragliding activity takes place [16].

4.2.1 Measurement of Wind

A basic understanding of traditional wind measurement methods is necessary, as this projects aim is to measure wind and turbulence.

Wind Parameters

Since meteorology focuses mainly on horizontal wind, usually only the following two parameters are measured [16]:

- **Wind Speed** (usually in m/s, km/h, knots or Beaufort)
- **Wind Direction** (usually in degrees from North)

By convention the average windspeed is calculated over a period of 10 minutes, with gusts being the highest windspeed measured over a shorter period of 1 second within that 10 minute window [16].

Anemometers

Wind is commonly measured using various kinds of anemometers, the most common of which are cup anemometers and ultrasonic anemometers, both of which are for example in use by Meteo Swiss [5], who provides official weather data for Switzerland and in turn to paragliding pilots.

Cup Anemometers measure the wind speed by counting the rotations of cups mounted on a vertical axis. The rotation speed is proportianal to the wind speed. Wind direction is determined using a wind vane, which aligns itself with the wind direction [5].
They are relatively simple and robust, but are subject to inertia and therefore can't provide instentanious wind speed measurements.

Figure 3: Cup Anemometer L14512 from Lambrecht [5]

Ultrasonic Anemometers measure the wind speed and direction by sending ultrasonic signals between pairs of sensors. The time it takes for the signals to travel between the sensors is affected by the wind speed and direction. By measuring the time it takes for the signals to travel in different directions, the wind speed and direction can be calculated [5].
Ultrasonic anemometers are available in 2D and 3D variations which determines the dimensions in which the wind direction can be measured. This method is very accurate and can provide instentanious wind speed measurements and is therefore also useful for measuring turbulence.

Figure 4: Ultrasonic Anemometer 2D from Thies [5]

4.3 Turbulence

While wind in general is a laminar airflow, disturbances and irregularities in the airflow are considered to be turbulence. The smoother and steadier the airflow, the less turbulence there is. Disturbances in the airflow can be caused by various factors, as detailed below.

Although there are several theoretical models to describe turbulence, such as the Kolmogorov theory of turbulence [17] or the Taylor microscales [18], in practice these models only have limited applicability in aviation, as the influence of turbulence on an aircraft and the pilots is highly dependent on the the type of aircraft, its speed and the current flight conditions. Additionally, the perception of turbulence is highly subjective and varies from person to person [9].

4.3.1 Eddies

Turbulence is often described as being made up of eddies, which are swirling motions of air that can vary in size from very small (a few millimeters) to very large (several kilometers). These eddies can be thought of as "whirlpools" in the air, where the air is moving in a circular motion. The size and strength of the eddies can vary depending on the cause of the turbulence and the current weather conditions.
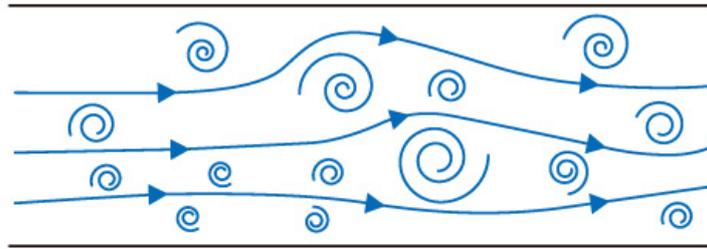
Figure 5: Eddies of different sizes in turbulent airflow [6, Fig. 5.23]

4.3.2 Causes and Types of Turbulence

Turbulence can be caused by a variety of factors. At lower levels, on which this project focuses, the most common causes of turbulence are mechanical turbulence, thermal turbulence, mountain wave turbulence [9, Ch. 12].

Mechanical turbulence is caused by physical obstructions in the airflow, such as buildings, trees, or terrain. When wind flows over or around these obstructions, it can create eddies and vortices that result in turbulence. Similarly, **mountain wave turbulence** occurs when stable air flows over a mountain range, creating a series of eddies on the leeward side of the mountains.

Thermal turbulence is especially prevalent during spring and summer, when the sun heats the ground, causing warm air to rise and cooler air to sink. This creates vertical air movements that can lead to turbulence.

These are the types of turbulence that paraglider pilots will most commonly encounter and which are therefore most relevant for this project.

4.3.3 Turbulence Measurement

There are multiple ways of assessing turbulence, both quantitatively and qualitatively. Scientifically, turbulence is often described using statistical measures, such as the eddy covariance [19] the eddy dissipation rate (EDR) [20] or the turbulence intensity (TI) [21].

As EDR is quite complex to calculate and usually only used at higher altitudes, where commercial aircraft fly, this project focuses on TI as the main quantitative measure of turbulence.

There are also qualitative measures of turbulence, such as pilot reports (PIREPs) [22], which are widely used in aviation or general assumptions based on more commonly available data, such as the average windspeed.

Turbulence Intensity

TI is the simplest quantitative measure of turbulence, which is based on the wind speed fluctuations. It is defined by the ratio of the standard deviation of the measured windspeeds over a given amount of time to the absolute mean wind speed over the same period of time. By convention this period of time is usually 10 minutes, with a sample rate of at least 1 Hz. [23]

It can be calculated as follows:

$$\text{TI} = \frac{\sigma_u}{U}$$

Where σ_u is the standard deviation of the wind speed fluctuations and U is the absolute mean wind speed.

The standard deviation σ_u can be calculated using the following formula:

$$\sigma_u = \sqrt{\frac{1}{N-1} \sum_{k=1}^{N} (u_k - U)^2}$$

Where N is the number of measurements taken over a certain period of time and u_k is the wind speed at a certain time.

TI is a measurement that can be calculated relatively easily, provided that high-frequency wind speed measurements are available. This makes it a suitable measure to calculate reference values for the measurements taken in this project.

It must be noted that there exists a second formula to calculate TI, which is based on a three-dimensional wind vector [21]. However, since this requires specific measuring equipment which is not available at every test location, this formula is not used in this project.

Pilot Reports

Upon encountering turbulence, pilots can submit a pilot report (PIREP) to inform other pilots and air traffic control about the current weather conditions [24]. PIREPs are usually submitted via radio or through an electronic system, such as the Aircraft Communications Addressing and Reporting System (ACARS).

The sensation of turbulence is highly subjective and depends on the size and type of aircraft. Data gathered through PIREPs is not accurate enough to be used as reference data for this project. Still, having subjective reports from paraglider pilots about the turbulence they encountered during their flights can provide valuable insights on how to interpret the calculated TI.

4.4 Regulatory Context

The Bundesamt für Zivilluftfahrt (BAZL) is the Swiss authority responsible for civil aviation. It regulates and oversees all aspects of civil aviation in Switzerland, including the operation of UAVs. The BAZL has established regulations and guidelines for the safe operation of UAVs, which are published on their website [25].

Skyguide is the Swiss air navigation service and air traffic control provider. It is responsible for managing and controlling air traffic in Swiss airspace, including the operation of UAVs. As such Skyguide has published additional guidelines regarding airspace usage and restrictions for UAVs [26].

4.4.1 Category

Figure 6: BAZL UAV Categories [7]

The UAV used in this project falls under the "offen" (open) category, as it is lighter than 250g. This means that it can be flown without a permit, as long as it is flown within visual line of sight (VLOS) of the operator and not higher than 120m above ground [7]. Additionally, the UAV must not be flown over crowds, and must not be flown in restricted airspace, near airports or military installations.
In this category, a Remote ID is not required. This means that the UAV does not need to broadcast its location and identification information to other airspace users.

4.4.2 Registration

UAVs that weigh more than 250g or are equipped with sensors which allow for identification of people (camera, microphone, etc.) must be registered with the BAZL. The UAV used in this project weighs less than 250g and is not equipped with such sensors or cameras and therefore does not need to be registered [27].

4.4.3 Airspace Restrictions

Current airspace restrictions can be found in the NOTAM (Notice to Airmen) and DABS (Daily Airspace Bulleting Switzerland) published by Skyguide [28].
Additionally, the BAZL provides an online map with information about airspace restrictions for UAVs [28].

These restrictions include:

- 5km radius around airports and airfields
- control zones (CTR)
- SIL-perimeter around civil airfields
- SPM-perimeter around military airfields
- correctional facilities
- certain nature reserves
- surroundings of nuclear power plants
- military zones
- infrastructure of energy or gas supply
- cantonal restricted areas

4.4.4 Insurance

UAVs that weigh below 250g are covered under the operators liability insurance [29].

4.5 System Context

This section describes the system context, including the stakeholders and users, the system environment and a domain model.

4.5.1 Users

Wind and turbulence measurement in a compact and flexible form is of interest for a wide variety of users in general aviation. However, in order to keep the scope of this project manageable, the focus lies on **paragliding pilots**, as they are particularly affected by wind and turbulence conditions due to their low speeds and weight. They often fly in mountainous terrain and from remote locations, where traditional weather stations may not be accessible.
This focus allows us to concentrate on a specific group of requirements and a specific turbulence scale with the goal of providing a tailored solution for these users. However, the system researched in this project could potentially be adapted for use by other stakeholders in the future, such as glider pilots, private pilots, or even meteorologists.

4.5.2 Stakeholders

The main stakeholders of this project are the project team and the supervisor.

4.5.3 System Environment

The system developed in this project consists of:

- A **UAV (quadcopter)** equipped with sensors to measure different flight parameters.
- A **UAV App** as a connected software system to receive, process and display the data from the UAV in real-time.
- **Calibration Notebooks** used to test and calibrate the system.

4.6 Domain

The domain of the final system includes the paraglider pilots, the UAV, the UAV App and the environment in which the system is used. During the development the domain also includes reference weather stations and measurement equipment used to gather reference data for calibration and validation of the system.

4.6.1 Domain Model

The domain model below illustrates the main entities and their relationships within the domain of the system as it is required during the development phase of the project. The project aims to develop a prototype of this system and is therefore oriented closely around this domain model.
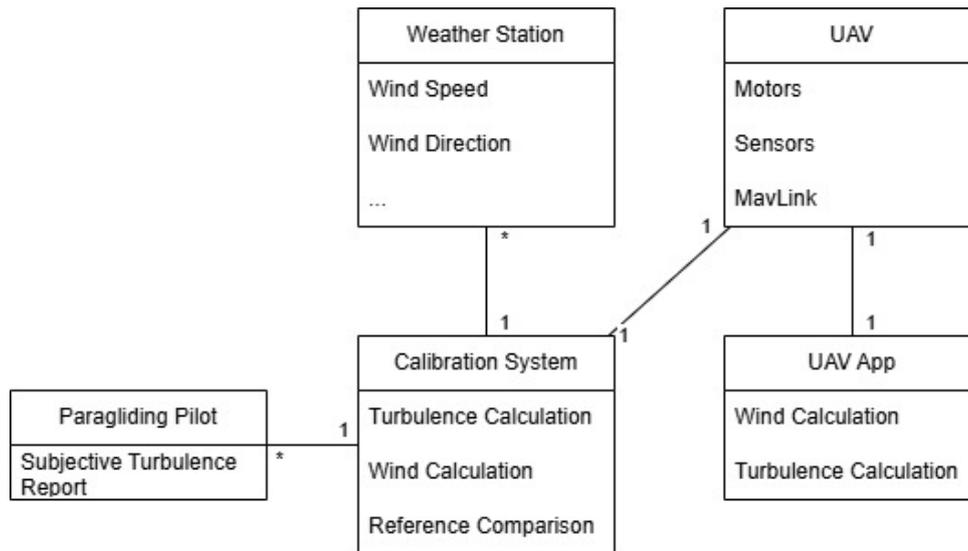
Figure 7: Domain Model

The **Weather Station** entity represents the reference weather stations and the portable measurement equipment used to gather reference data. Their data combined with subjective feedback from **Paragliding Pilots** is used to validate and calibrate the measurements taken by the **UAV**. This comparison and calibration process takes part in the **Calibration System**.
The findings from the **Calibration System** are then used to develop the **UAV App**, which provides the pilots with real-time access to the processed data and insights derived from the measurements.

Chapter 5

Requirements

The functional and non-functional requirements of the system are based on the original task description, as well as the system context described in Chapter 4.

5.1 Functional Requirements

The functional requirements concentrate on the UAV hardware and the software used to receive, process and display the data.

Actors

The sole actor in the finished system is the **paragliding pilot**, who uses the system to measure wind and turbulence at their flying location.

Requirements

FR1	Wind Measurement
Type	Output
Workitem	Story 21: Evaluate Wind Direction and Speed
Description	As a pilot I want to see an estimate of the wind speed and direction at my flying location, so that I can make an informed decision about whether or not to fly.
Acceptance Criteria	• A real-time estimate of the wind speed and direction is calculated and displayed in the application. • The minimum, maximum and average wind speed over a period of 2 minutes can be displayed.

FR2	Turbulence Measurement
Type	Output
Workitem	Story 71: Evaluate Turbulence
Description	As a pilot I want to see an estimate of the turbulence at my flying location, so that I can make an informed decision about whether to fly or not.
Acceptance Criteria	• A real-time estimate of the turbulence is calculated and displayed in the application. • The level of turbulence is displayed on a scale which can be interpreted by hanggliding and paragliding pilots.

FR3	Wireless Data Transmission
Type	Implementation
Workitem	Story 17: Stream Data via MavLink
Description	As a pilot I want the UAV to send the data in real-time to the UAV App, so that I can see the measurements live.
Acceptance Criteria	• The UAV streams the data to the UAV App in real-time. • The data can be received and processed by the UAV App.

5.2 Non-Functional Requirements

The non-functional requirements describe the quality attributes of the system, such as usability, reliability and performance.

NFR1	UAV Size and Category
Requirement	The UAV shall have a maximum takeoff weight (MTOW) of less than 250g, so that it can be flown in category A1 in Switzerland [30].
Workitem	Story 9: Build UAV
Verification	The weight of the UAV is regularly measured during the development process to ensure it remains below 250g.
Time of Verification	During Development and Final Testing.
Acceptance Criteria	• The UAV is lighter than 250g. • The UAV can be legally flown in category A1 in Switzerland. • The UAV is small and portable enough to be easily transported by the pilot.

NFR2	Open Source
Requirement	The UAV control system should be implemented by extending an existing open source solution.
Workitem	Story 9: Build UAV
Verification	Checking the source code for used software and frameworks.
Time of Verification	During Development and Final Testing.
Acceptance Criteria	• All software and frameworks that are used are either open source or a custom implementation.

NFR3	Enterprise Architect
Requirement	Enterprise Architect should be used to create a UML diagram of the implemented code.
Workitem	Story 5: Documentation
Verification	The source code of the UAV and the remote software is documented using Enterprise Architect.
Time of Verification	During Final Testing
Acceptance Criteria	• A UML diagram representing the source code has been generated.

NFR4	Logging
Requirement	An intensive logging system with 2-dimensional runtime configuration is required: • Category (e.g. Package, Layer, etc.) • Log-Level In dense logging situations (e.g. loops) unnecessary logs must be prevented.
Workitem	Story 72: Logging
Verification	During testing of the software the logs are usable to improve debugging.
Time of Verification	During Development.
Acceptance Criteria	• The log-level can be selected at runtime. • The desired log categories can be selected at runtime. • There are no unessessary logs in dense code execution such as loops.

Chapter 6

Market Analysis

This chapter analyses the target audience, current solutions and competitive landscape.

6.1 Target Audience

The primary target audience for this project are paragliding pilots who require accurate and up-to-date wind and turbulence data to make safe decisions about their departure place and flight path. Especially hike and fly pilots, as discussed in Chapter 4. In order for them to be able to transport measurement equipment to these locations, portability and ease of use are crucial factors.

6.2 Current Solutions

Several solutions currently exist for measuring wind conditions, but they often fall short in terms of portability, cost, or accuracy for the specific needs of paragliding pilots.

6.2.1 Nearby Weather Stations

Many paragliding sites rely on data from nearby weather stations. However, these stations are often located far from the actual flying sites, rendering their reports less accurate for local conditions. Some sites provide an installed weather station which offers more accurate data [31], but the information provided to the pilots might be updated infrequently, making it less useful for real-time decision-making.

6.2.2 Observation and Experience

Many pilots rely on their own observations of the terrain, vegetation, and cloud formations, as well as their personal experience to estimate wind conditions [10]. While this method can be effective for experienced pilots, it is inherently subjective and can lead to misjudgments, especially for less experienced pilots or in rapidly changing weather conditions.

6.2.3 Portable Anemometers

Portable anemometers are available for measuring wind speed at specific locations. They can be more precise than a remote weather station, but they only show wind speed and provide no information over the wind direction or level of turbulence.

6.2.4 Larger UAVs with Advanced Sensors

Larger UAVs equipped with advanced sensors can provide high-quality wind and turbulence data, as discussed in Chapter 7. However, they are often expensive, require a high level of expertise to operate, and their weight limits their portability and ease of use in remote locations.

6.3 Competitive Analysis

The competitive landscape for wind and turbulence measurement solutions is relatively sparse, with no direct competitors specifically targeting paragliding pilots, especially in remote locations. The offered solutions are either too inaccurate, too expensive, or not portable enough to meet the specific needs of this niche market.

The proposed UAV-based solution aims to fill this gap by providing a portable and accurate method for measuring wind and turbulence conditions at remote flying sites or at sites with limited access to traditional weather data.

Chapter 7

Previous Studies

There have already been several attempts at measuring the level of turbulence using various kinds of unmanned aerial vehicles, although they mainly focused on larger UAVs, which are able to carry heavier and more advanced sensors.

7.1 High-resolution wind speed measurements with quadcopter uncrewed aerial systems: calibration and verification in a wind tunnel with an active grid [1]

The study by Johannes Kistner et al. used a UAV with a weight of 0.645 kg. The wind direction was measured using their autopilot's weather vane mode, which aligns the UAV to the wind direction, while the wind speed was measured by observing the tilt angle of the UAV during hovering. Turbulence intensity (TI, see Section 4.3.3.1) was calculated by measuring the wind speed fluctuations. To verify the results a wind tunnel was used.
The results showed a good correlation between the UAV measurements and the wind tunnel measurements, with an error of between 0.3 m/s and 0.8 m/s.

This study confirms that it is possible to achieve accurate wind and turbulence measurements using a UAV. However, the UAV used is too heavy and large for the intended use case of our project and real-time data transmission was also not implemented, which is crucial for our project.

7.2 SAMURAI-S: Sonic Anemometer on a MUlti-Rotor drone for Atmospheric turbulence Investigation in a Sling load configuration [2]

The study by Ghirardelli et al. used a larger UAV with a weight of roughly 4 kg, which was equipped with a 3D sonic anemometer. They developed this system as an alternative to tower weather stations, which they used to calibrate their UAV mesaurements. As a sonic anemometer is able to measure wind speed and direction directly, their main obstacle was the placement of the anemometer on the UAV, to avoid rotor wash effects. They solved this by carrying the payload as sling load 18 m below the UAV.

Although this study was able to achieve accurate results, the size of the UAV and the methods used are not suitable for our project, as it is not portable and requires a lot of space for takeoff and landing.

7.3 A balloon-borne accelerometer technique for measuring atmospheric turbulence [3]

Another attempt has been made using weather balloons by Graeme J. Marlton et al., which are able to reach higher altitudes and are not influenced by the rotors disturbances of the air around the sensors as would be generated by the rotors of a UAV. In this study, an accelerometer was suspended 4 m below a weather balloon, and the turbulence intensity was calculated based on the accelerations encountered by the sensor.
The study proofed the possibility of measuring turbulence using an accelerometer, but a lot more comparisons to in situ measurements are needed to calibrate the findings.

While incomplete and using the wrong type of aerial vehicle for our use case, this study shows that using an accelerometer for turbulence measurements is a viable approach.

Chapter 8

Methods

Several methods for estimating wind speed, direction and turbulence using the UAV's sensors are discussed and evaluated. This chapter contains hypotheses formulated for the different methods, as well as the planned approach for verifying them through testing and data collection. This analysis is important to determine the requirements for the UAV and its sensors, as well as to identify potential challenges and limitations of the proposed methods.

8.1 Hypotheses and Approach

Since the size and weight of the UAV is a limiting factor in regards to the available sensors, it is impractical to measure turbulence the traditional way using an anemometer. Instead, the methods have to rely on data from different, built-in sensors to estimate the level of turbulence.

In order to verify that this approach is feasible, the following hypotheses are researched. The hypotheses are evaluated through analysis of the capabilities of the UAV, as well as by comparing them to previous studies already performed in this field, as can be found in Chapter 7. If they are found to be viable, they will be accepted and can be tested through future flight tests.

8.1.1 Hypothesis 1: Turbulence can be estimated using the accelerometer data of the UAV.

The accelerometer measures the acceleration of the UAV in all three dimensions. The idea is that in turbulent conditions the accelerations measured by the accelerometer will be higher and more erratic than in calm conditions.

Assumption	The magnitude of the accelerations correlate with the level of turbulence.
Approach	The accelerometer data will be recorded during the test flights and compared to reference data gathered from traditional measurement method.
Difficulties	The accelerometer data is influenced by many factors that are not directly related to turbulence. For example the pilots inputs or the corrections made by the flight controller to stabilize the UAV. These factors will have to be filtered out in order to get a clear signal that can be correlated with turbulence.
Status	Accepted

Discussion

The National Oceanic and Atmospheric Administration (NOAA) provides global turbulence guidance (GTG-G) as EDR values, which among other factors is calculated using the vertical acceleration of aircraft flying in the area (so called "In-Situ Flight EDR") [20]. Similarly, the study by Marlton et al. [3] uses accelerometer data from a weather balloon to estimate turbulence levels.

Seeing that this method is already being used in similar contexts, it is considered a viable approach and has been accepted as a valid hypothesis. The UAV will therefore need to be equipped with a high-quality accelerometer in order to achieve accurate results.

8.1.2 Hypothesis 2: Turbulence can be estimated using the commanded rotor speeds.

The flight controller of the UAV constantly adjusts the rotor speeds in order to keep the UAV stable. In turbulent conditions, the flight controller will have to make more frequent and larger adjustments to the rotor speeds in order to counteract the disturbances caused by the turbulence.

Assumption	The magnitude and frequency of the adjustments to the rotor speeds correlate with the level of turbulence.
Approach	The rotor speed data will be recorded during the test flights and compared to reference data gathered from traditional measurement method.
Difficulties	The rotor speed data is influenced by many factors that are not directly related to turbulence. For example corrections made by the flight controller to stabilize the UAV, as well as up- or downdrafts, air pressure and temperature. These factors will have to be filtered out in order to get a clear signal that can be correlated with turbulence.
Status	Rejected

Discussion

It is not possible to read the commanded rotor speeds directly from the flight controller with sufficient accuracy, as they are not exposed through the telemetry data. The rotor speeds are also heavily influenced by too many external factors, making it impractical to isolate the effects of turbulence. This hypothesis has therefore been rejected.

8.1.3 Hypothesis 3: Wind speed and direction can be estimated using the attitude data of the UAV.

The attitude of the UAV (pitch, roll, yaw) is influenced by the wind speed and direction. When the UAV is commanded to hover at a certain place, the flight controller will adjust the attitude of the UAV to face into the wind, correcting any potential drift. By analyzing how much the UAV tilts into the wind, it may be possible to estimate the wind speed.

Assumption	If the wind is laminar, the attitude that the flight controller commands while hovering to hold its position will be relatively constant and therefore allows for the estimation of wind speed and direction.
Approach	The attitude data will be recorded during the test flights and compared to reference wind data gathered from traditional measurement method.
Difficulties	This method of measuring wind speed and direction is highly dependent on the UAV being able to hold its position accurately. It will also only work in laminar wind conditions, as turbulence will cause the attitude to vary more erratically.
Status	Accepted

Discussion

This hypothesis is considered a viable approach, as there are also previous studies performed using this method [1]. ArduPilot (the UAV autopilot software used in this project, see Chapter 10) implement a similar wind estimation algorithm to estimate wind speed and direction. This function is based on the attitude of the UAV and two additional parameters (body drag coefficient and propeller drag coefficient), that need to be calculated based on the specific UAV [32]. Using this function allows the implementation of this method with minimal effort.

The UAV will therefore need to be equipped with a high-quality IMU (Inertial Measurement Unit) in order to achieve accurate results. Additionally, the UAV needs to be able to hold its position accurately while hovering, which requires a good GNSS reception and a well-tuned flight controller.

8.1.4 Hypothesis 4: Up- and downdrafts can be estimated using the rotor speeds of the UAV.

Up- and downdrafts are vertical movements of air that can be caused by various factors, such as thermal activity or terrain. When the UAV encounters an up- or downdraft, the flight controller will have to adjust the rotor speeds in order to maintain altitude.

Assumption	With no wind and no up- or downdrafts, the rotor speeds will be relatively constant while hovering. When encountering an updraft, the rotor speeds will decrease, as the UAV is being lifted by the upward moving air. Conversely, when encountering a downdraft, the rotor speeds will increase, as the flight controller has to work harder to maintain altitude.
Approach	The rotor speed data will be recorded during the test flights and compared to reference data gathered from traditional measurement method.
Difficulties	The rotor speeds can also be influenced by turbulent air, that is not directly related to up- or downdrafts, the air pressure and temperature. These factors will have to be filtered out in order to get a clear signal that can be correlated with up- and downdrafts.
Status	Rejected

Discussion

As the rotor speeds are influenced by too many external factors and cannot be read from the flight controller accurately enough, this hypothesis has been rejected (related to Hypothesis 2).

8.1.5 Hypothesis 5: Turbulence can be estimated using the vertical speed measurement of the UAV.

The vertical speed (VS) of the UAV is influenced by up- and downdrafts, as well as turbulence. In turbulent conditions, the vertical speed of the UAV will be more erratic than in calm conditions.

Assumption	The VS measurement is sensitive enough to detect changes in vertical speed caused by turbulence. By analyzing the fluctuations in vertical speed, it may be possible to estimate the strength of the turbulent eddies affecting the UAV.
Approach	The vertical speed data will be recorded during the test flights and compared to reference data gathered from traditional measurement method.
Difficulties	Barometric-based or GNSS-based VS measurements may not be accurate enough to detect the small changes in vertical speed caused by turbulence. They also introduce latency, as the calculation is not instantaneous. Therefore this approach is only viable if the UAV measures the VS using accelerometers and gyroscopes.
Status	Open

Discussion

This hypothesis is considered a viable approach, as it is possible, that the vertical speed measurement is sensitive enough to detect turbulence. However, it is uncertain if the available sensors on the UAV can provide accurate enough vertical speed measurements. This will have to be verified through testing and can therefore not be definitively answered in this project.

8.1.6 Hypothesis 6: Wind speed can be estimated by comparing the GNSS-based ground speed with the airspeed of the UAV.

Wind speed and direction can be estimated by comparing the ground speed (GS) of the UAV, which should be zero in a hover, with the indicated airspeed (IAS) of the UAV, as measured by an onboard airspeed sensor. The difference between the two speeds can be used to calculate the wind speed.

Assumption	The airspeed sensor is accurate enough to provide a reliable measurement of the UAV's airspeed.
Approach	The GNSS-based ground speed and airspeed data will be recorded during the test flights and compared to reference wind data gathered from traditional measurement method.
Difficulties	The airspeed sensor might be influenced by the UAV's own propeller wash, especially at low speeds and during hover.
Status	Accepted

Discussion

Calculating the wind speed by comparing GS and IAS is a common method used in aviation [33]. Implementing it relies on the UAV being equipped with a reliable airspeed sensor, which is an additional challenge when building the UAV. However, if the UAV can be equipped with such a sensor, this method would be one of the most direct and reliable ways to measure wind speed. Therefore, this hypothesis has been accepted.

8.1.7 Hypothesis 7: Wind can be estimated by measuring the wind drift while hovering.

When the UAV is commanded to hover at a certain position, it will drift with the wind. In position hold mode this effect is cancelled out automatically by comparing the initial position with the current GNSS-based position.

Assumption	The GNSS-based correction can be disabled, whereafter the UAV will drift with the wind while maintaining its altitude and attitude. By measuring the drift using GNSS data, it may be possible to estimate wind speed and direction.
Approach	The GNSS-based position data will be recorded during the test flights, while the UAV is allowed to drift with the wind and compared to reference wind data gathered from traditional measurement method. For safety and practicality reasons, the drift will have to be limited both in distance as well as in time.
Difficulties	The GNSS-based position data might not be accurate enough to provide a reliable measurement of the UAV's drift, especially in areas with poor GNSS reception or in low wind conditions. Additionally, the UAV might not be able to maintain its altitude and attitude perfectly while drifting, which could introduce additional errors in the measurements.
Status	Rejected

Discussion

This hypothesis is the most challenging one on a techincal level, as it requires multiple steps and saftey measures to provide results without endangering the UAV or surrounding people and property. It also relies heavily on the GNSS accuarcy. Because of its complexity, this hypothesis has been rejected, even though it would be technically feasible.

8.1.8 Hypothesis 8: Wind direction can be estimated using ArduPilot's built-in weather vaning mode.

When the weather vaning mode is enabled, the UAV will automatically yaw to face into the wind while hovering. By recording the heading of the UAV, it may be possible to estimate the wind direction. This method is inspired by a study by Kistner et al. [1].

Assumption	The weather vaning mode is accurate enough to align the UAV with the wind direction.
Approach	The heading data will be recorded during the test flights with weather vaning mode enabled and compared to reference wind direction data gathered from traditional measurement methods.
Difficulties	The effectiveness of the weather vaning mode may vary depending on the UAV's design and the specific flight controller settings. Additionally, the UAV may not be able to maintain a perfect alignment with the wind direction, especially in turbulent conditions.
Status	Abandoned

Discussion

This approach could be implemented with minimal effort and also has been demonstrated in previous studies [1]. However, since Section 8.1.3 already provides a two-in-one solution for both wind speed and direction, this hypothesis has been abandoned in favor of the simplicity of having fewer methods to implement and test.

8.2 Selected Hypotheses

Based on the discussions above, the following hypotheses have been selected for further testing and validation through future flight tests:

- Hypothesis 1: Turbulence can be estimated using the accelerometer data of the UAV.
- Hypothesis 3: Wind speed and direction can be estimated using the attitude data of the UAV.

These two hypotheses show the most potential in terms of accuracy and feasibility. Both use cases of the project (wind and turbulence estimation) are addressed by relying on well researched methods. The UAV will therefore need to be equipped with high-quality IMU and accelerometer sensors in order to achieve accurate results.

8.3 Reference Data Collection

In order to verify the hypotheses and validate the measurements taken by the UAV, reference data needs to be collected using traditional measurement methods. This reference data then needs to be compared to the data collected by the UAV in order to calibrate the UAV's measurements, improve their accuracy and ultimately prove or disprove the hypotheses.

This project builds the theoretical basis for future test flights, where the actual data collection will take place. The following sections outline the planned methods for collecting reference data.

8.3.1 Wind Tunnel Testing

A wind tunnel provides a controlled environment where wind speed and turbulence can be precisely regulated. By flying the UAV in a wind tunnel, it is possible to expose it to known levels of turbulence and wind speeds, allowing for a direct comparison between the UAV's measurements and the known conditions.

For initial testing and calibration of the UAV's sensors, a wind tunnel test is planned at the OST Techpark in Rapperswil, which has a small wind tunnel and a Windshaper available for such purposes.

Figure 8: Windshaper at OST Techpark Rapperswil

The Windshaper consists of a 6x6 grid of small fans that can be controlled individually to create different wind patterns and turbulence levels. This allows for a wide range of testing scenarios, from laminar flow to highly turbulent conditions.

Possible Tests

Tests, that can be conducted using the Windshaper include:
- H1: Simulating different levels of turbulence and measuring the accelerometer data of the UAV.
- H3: Simulating different laminar wind speeds and measuring the attitude of the UAV.
- H6: Measuring the influence of the rotor wash on the airspeed sensor.
- H8: Observing the UAV's heading while weather vaning mode is enabled.

8.3.2 Weather Station

A weather station equipped with anemometers and other meteorological instruments can provide accurate measurements of wind speed, direction, and turbulence at a fixed location. By flying next to an existing weather station, it is possible to compare the UAV's measurements with known to be accurate reference data.

This method is preferred for field testing, as it is more representative of real life conditions and can be done at various locations.

Weather stations, that are available for this project include:
- At the OST campus in Rapperswil (SPF Institute)
- Holfuy station in Alp Scheidegg (nearby Paragliding site)

This method of collecting data is heavily reliant on the weather conditions at the time of the test flights, as well as the proximity of the weather station to the UAV's flight path. Therefore multiple test flights at different locations and under different weather conditions are necessary in order to gather a diverse dataset.

8.3.3 Field Measurements

In order to gather more diverse data and not being bound to specific locations, field measurements need to be conducted at various locations and under different weather conditions. During these flights, the reference data can be gathered by mobile equipment such as a portable anemometer.

Possible Tests

Possible tests during field measurements include:
- H1: Flying in different turbulence conditions and measuring the accelerometer data of the UAV.
- H3: Flying in different wind conditions and measuring the attitude of the UAV.
- H6: Flying in different wind conditions and recording the GNSS-based ground speed and airspeed of the UAV.
- H8: Flying in different wind conditions and observing the UAV's heading while weather vaning mode is enabled.

Planned Locations

Locations considered for field measurements include:
- Schänis (nearby Paragliding site)
- Amden (nearby Paragliding site)
- Turren (open fields, forests, complex terrain)
- Mägisalp (open terrain, nearby mountainsides with potential for strong turbulence)
- Planplatten (mountaintop with lee and luv sides and nearby weather station)
- Guttannen (narrow valley with potential for strong winds)
- Brünig Pass (mountain pass, nearby forests and a sharp cliff with potential for strong winds)

Reference Data Collection

To measure the reference wind speed at these locations a handheld anemometer (testo 410i) is mounted on a tripod at a height of approximately two meters. The anemometer logs wind speed data throughout the UAV flight, while the wind direction is noted manually at regular intervals.

Conducting measurements independently from fixed weather stations allows for greater flexibility in choosing locations with varying terrain and wind conditions and also enables more spontaneous measurements based on weather forecasts.

Executed Field Tests

Due to delays in the UAV construction, field tests could only be conducted towards the end of the project. They focused mainly on the flying characteristics of the UAV and the process of reference data collection. The following field tests were executed:
- 22.11.2025: Meiringen (light wind)
- 23.11.2025: Meiringen (light wind)
- 23.11.2025: Gadmen (light wind)

The test results are documented in the Operational Notes.

8.4 Data Analysis

In order to validate the hypotheses, calibration notebooks are developed using Juypter Notebooks and Python. They combine the data from the UAV and the reference data to analyze correlations and find estimation algorithms. The notebooks can also be used to test and validate the implementation of the hypotheses formulated above.

Their integration into the system can be found in Chapter 9, and the notebook for Hypothesis 1 containing sample data can be found in the appendix.

Chapter 9

Design and Architecture

The architecture focuses mainly on the software components developed in this project. The design and implementation of the hardware components can be found in Chapter 10.
The architectural documentation is based on the arc42 template.

9.1 Introduction and Goals

The goal of the project is ultimately to design an application which can calculate the wind and turbulence intensity based on the UAV's telemetry data. In order to find the correlations between the measured telemetry data and the wind, a secondary architecture is required to determine the calculations and algorithms needed to process the data.

The architecture is therefore divided into three phases. During this project the focus lies on the first phase and some preparations for the following phases.

1. Analysis and Calibration phase
2. Validation phase
3. Operation phase

9.1.1 Architectural Goals

Each phase depends on different components, whence the architecture shifts slightly throughout the project. The goals and focus of each phase are:

In the **analysis and calibration phase**, the architectural focus lies on flexibility, as different weather stations and sensors need to be integrated and evaluated and different algorithms need to be tested. In order to compare the measured data effectively, the data needs to be in a common format. This is achieved by creating an adapter layer for the weather stations to create a unified output. Additionally a script has to be written that can connect to the UAV via WiFi, get the required telemetry data and store it in a file.
Lastly calibration notebooks need to be created to analyze the recorded data and find correlations between the UAV data and the reference data from different weather stations.

In the **validation phase**, the framework for the UAV App needs to be in place, so that the output of the final algorithms can be validated against testing data.

The **operation phase** removes the guard rails of the previous phases and focuses on a stable and reliable operation of the UAV and the UAV App.

9.1.2 Quality Goals

The focus of the project lies in the research, which is reflected in the quality goals:

Table 1: Quality Goals of the Architecture

Category	Quality	Description
Maintainability	**Reference Source Flexibility**	Input from different weather stations can easily be integrated to calculate reference values.
Maintainability	**UAV Sensors Flexibility**	Additional sensors could be added to the UAV and used in the calculations.
Performance	**Real-time Data**	The required parameters should be calculated in an interval of roughly 1 Hz.

9.2 Constraints

The time and budgetary constraints of the project can be found in the project management section. The technological constraints are described in Section 2.2.

9.3 Context and Scope

The architectural scope primarily covers two components: the software for analyzing data from the UAV and weather stations (which outputs various JSON-based formats) and computing wind and turbulence parameters, and the UAV hardware and software responsible for data collection and transmission.

The weather stations and sensors used to provide reference data are considered external systems that are being integrated into the architecture but are not part of the architecture itself.

9.3.1 Business Context

The business context is centered around the needs of paragliding pilots, who can give helpful input during the analysis and calibration phase, as well as being the potential users of the final system.

During the **analysis and calibration phase**, the business context involves collaboration with paragliding pilots to gather feedback on the perceived wind and turbulence conditions to fulfill the functional requirements FR1 and FR2. This feedback is crucial for calibrating the algorithms used in the UAV App. Weather stations are used to provide objective reference data for comparison.
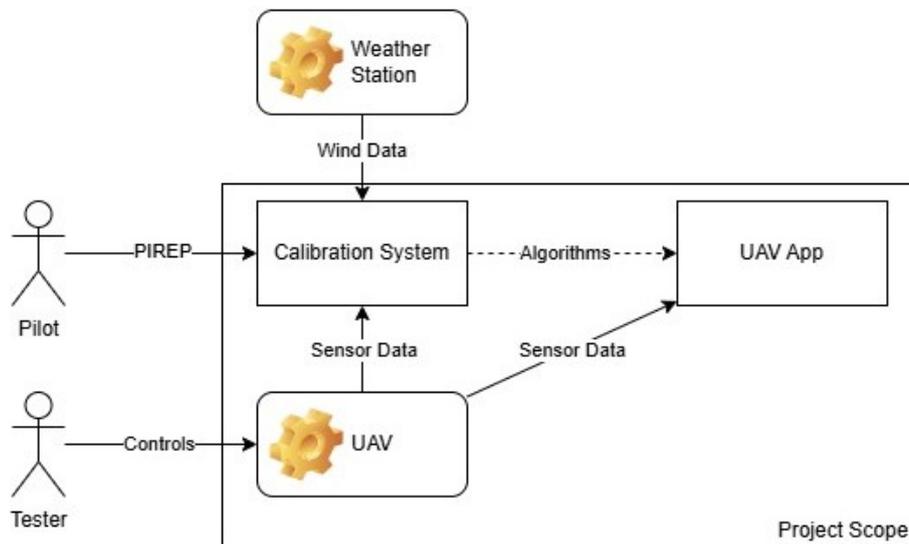

Figure 9: Business Context of the Analysis and Calibration Phase

In the **operation phase**, the business context shifts to the end-users, primarily paragliding pilots who will utilize the UAV App. The UAV is the sole data source for the application, reporting its findings back to the pilots in real-time (FR3).
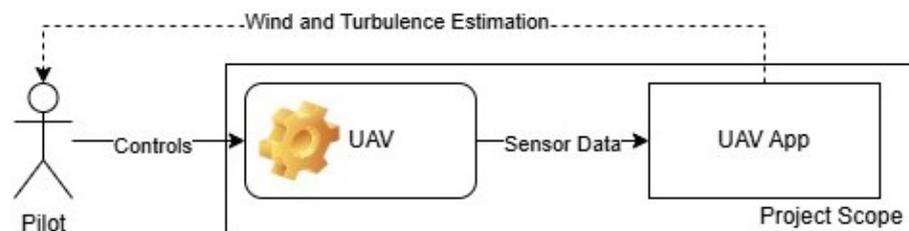

Figure 10: Business Context of the Operation phase

9.3.2 Technical Context

The technical context focuses primarily on the UAV, the UAV App, the calibration notebook used during the analysis and calibration phase, and technical links between these components and external systems such as weather stations.

The components and layers of the architecture evolve throughout the different phases of the project, as shown in the following sections.

Analysis and Calibration Phase

In the **analysis and calibration phase**, data is gathered from the UAV as well as from various weather stations. The data from the weather stations is expected to be exported in a file format, which the Weather Station Adapter then maps into a common format for further processing. The first logic layer calculates the turbulence intensity from the reference data, which is then used in the calibration notebook along with the UAV data to analyze and calibrate the algorithms.

On the UAV side, the sensor data is transmitted via the WiFi receiver to a remote device, where the data is collected and processed by the UAV Data Adapter into a common format. This data is will also be fed into the calibration notebook for analysis.
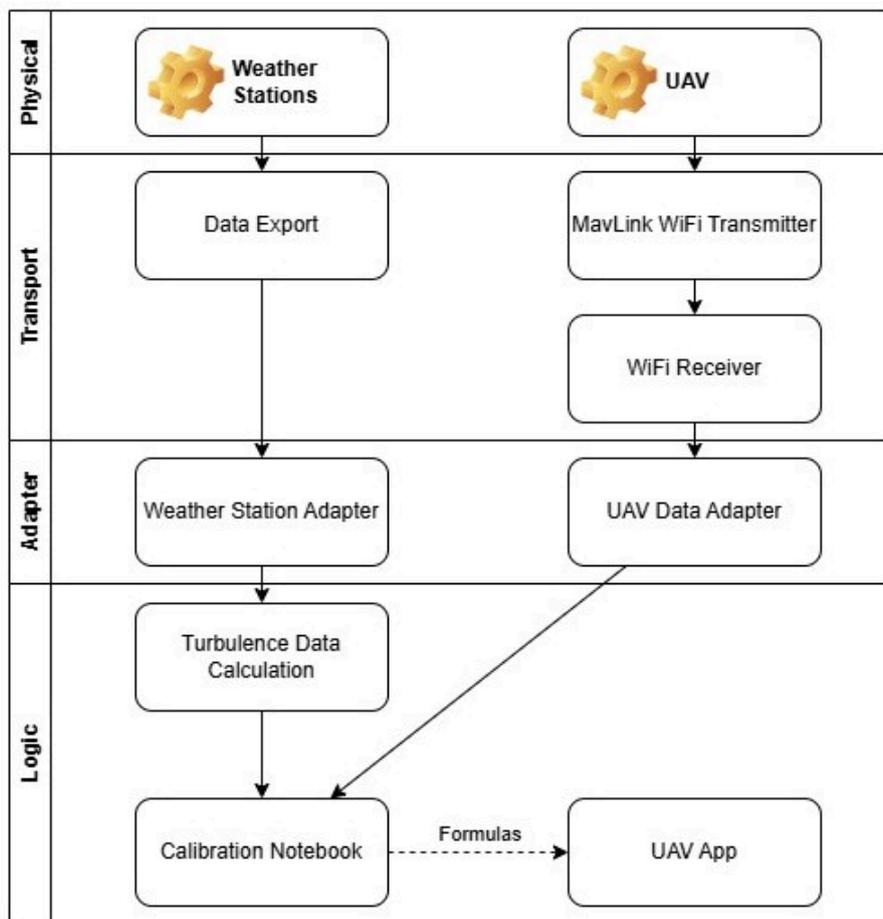
Figure 11: Layers of the Analysis and Calibration Phase

Validation Phase

In the **validation phase**, the focus shifts to validating the algorithms and their outputs. The weather station data is still used as a reference, but now the algorithms and calculations are integrated into the UAV App. The UAV App receives real-time data from the UAV and applies the algorithms to calculate wind and turbulence.

The data from both the UAV and the weather stations is then compared in the validation script to validate the accuracy of the algorithms.

Figure 12: Layers of the Validation phase

Operation Phase

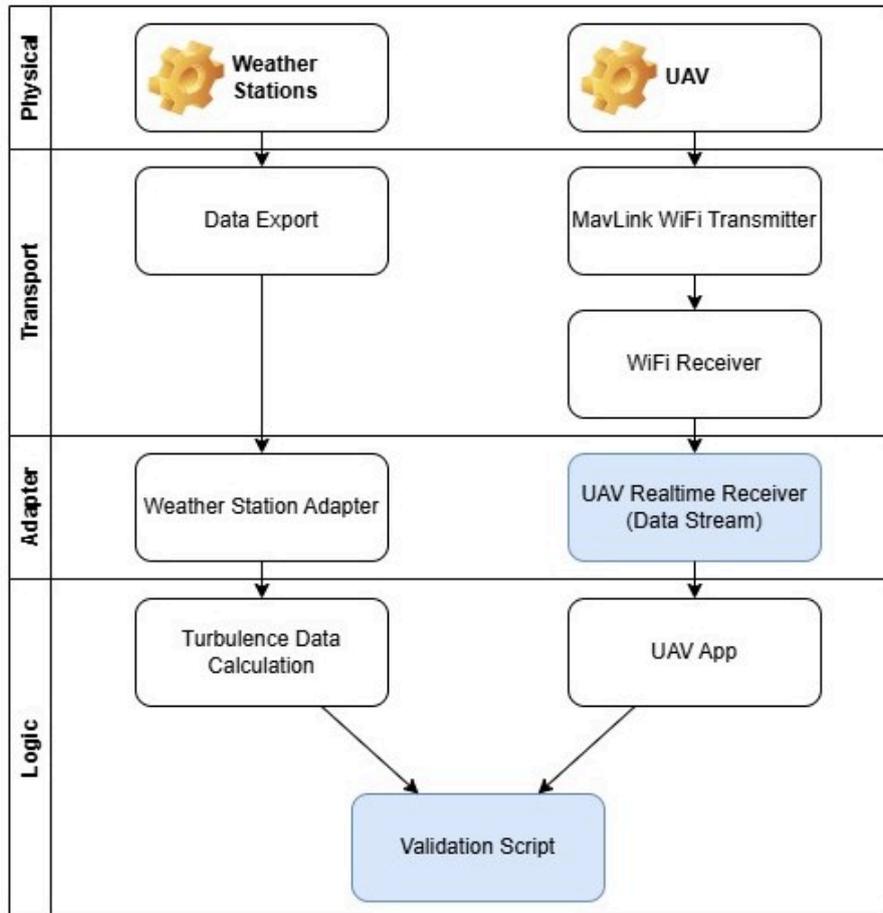In the **operation phase**, the UAV App is fully deployed and operational. The components relating to the weather stations and validation scripts are removed, as the focus is now solely on the UAV and the UAV App.
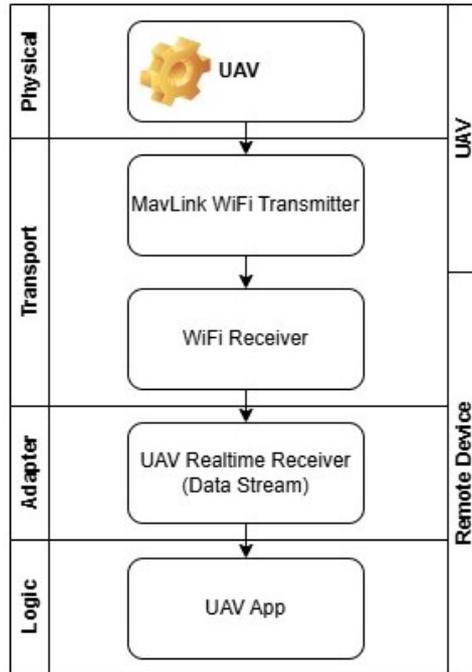

Figure 13: Layers of the Operation Phase

9.4 Solution Strategy

This layered architecture was chosen to address the quality goals outlined in Table 1. The following table summarizes how the architectural approaches contribute to achieving these goals.

Table 2: Solution Strategy

Quality Goal	Architectural Approach	Details
Reference Source Flexibility	Weather Station Adapter	An adapter layer is placed between the different weather stations' output and the Calibration notebook, so that the research and calculations can be conducted based on a homogenized data pool.
UAV Sensors Flexibility	UAV Data Adapter	To convert the stream of data received from the UAV, an adapter layer is set between the WiFi Receiver and the Calibration notebook, so that there is a reusable and comprehensible dataset to perform the research.
Real-time Data	MAVLink WiFi Transmitter	Although MAVLink provides a USB interface, the final product will need to run in real-time and remotely, wherefore the development starts using the WiFi interface already for data collection in the analysis and calibration phase. This makes further development of the UAV App easier and more comparable to the Calibration notebook.

9.5 Building Block View

The components found on level 1 of the building block view are already described in Section 9.3.2. The following sections describe the components on level 2.

9.5.1 Level 2: Calibration System

To make the diagram more readable, first the components of the calibration system are described.
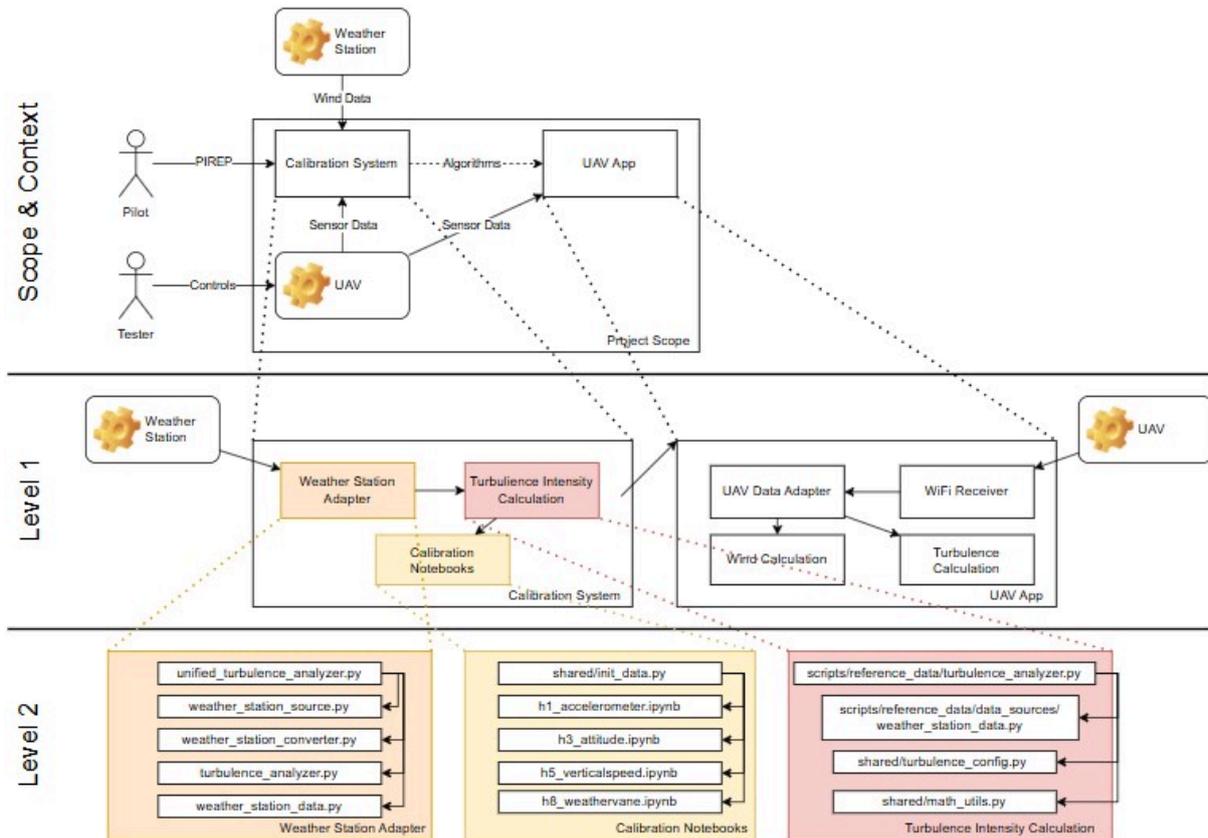
Figure 14: Building Block View of the Calibration System

Weather Station Adapter

Location: `scripts/reference_data`

The weather station adapter is responsible for collecting data from the weather stations and providing it in a unified format for further processing. The adapter is implemented as a Python class **UnifiedTurbulenceAnalyzer**, which can be easily extended to support additional weather stations by creating a new config file in `scripts/reference_data/data_sources/mapping_configs/`. The adapter also supports a sliding window configuration where the window and the step size for the output can be configured.

Figure 15: Class Diagram of the Weather Station Adapter

Turbulence Intensity Calculations
Location: `scripts/reference_data/turbulence_analyzer.py`
This part of the software is responsible to calculate the turbulence intensity from weather station reference data. The calculations support a sliding window in order to calculate the turbulence intensity in a configurable time window. The actual mathematical formula (TI = σ/U) is implemented in `shared/math_utils.py`.
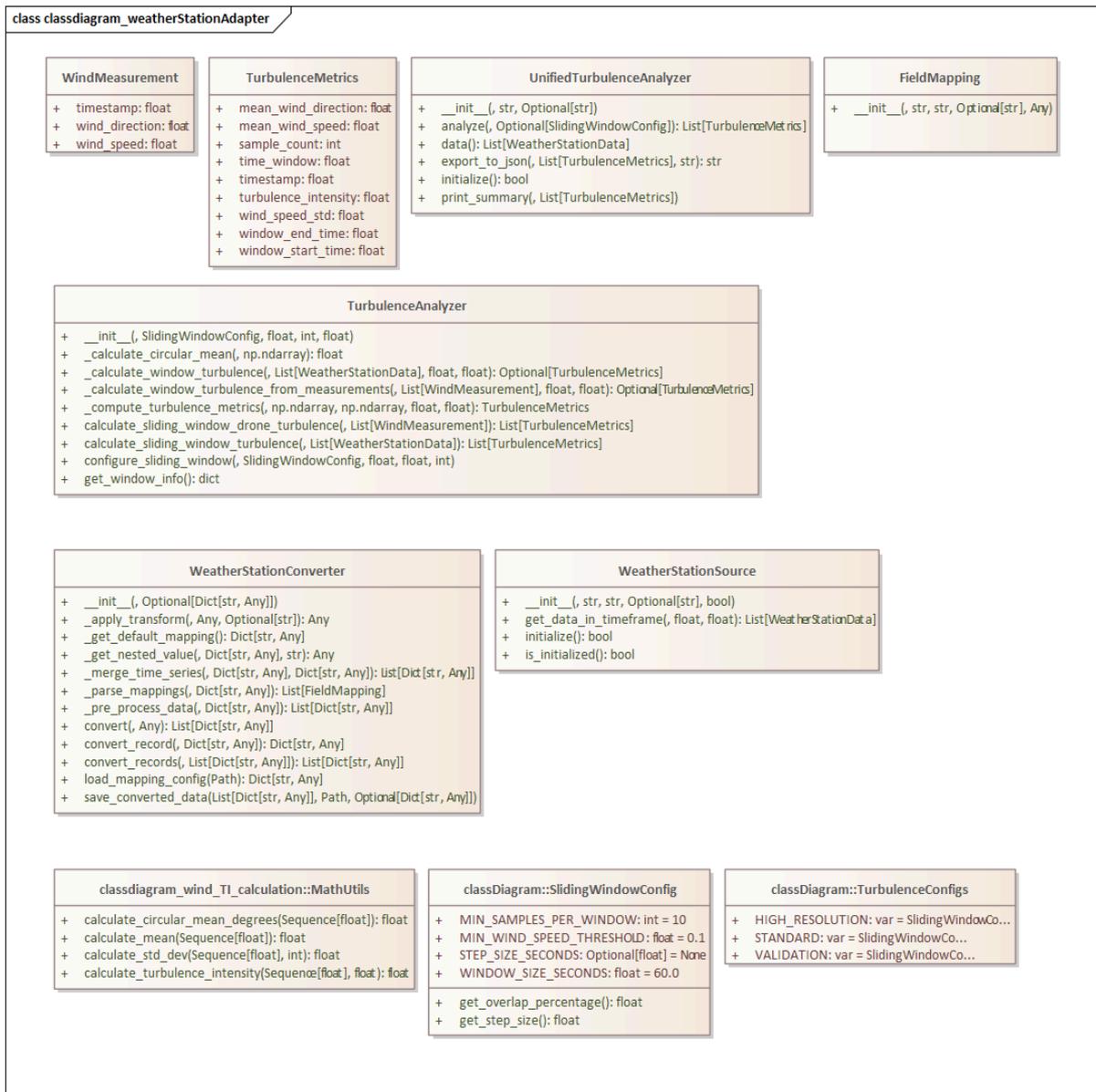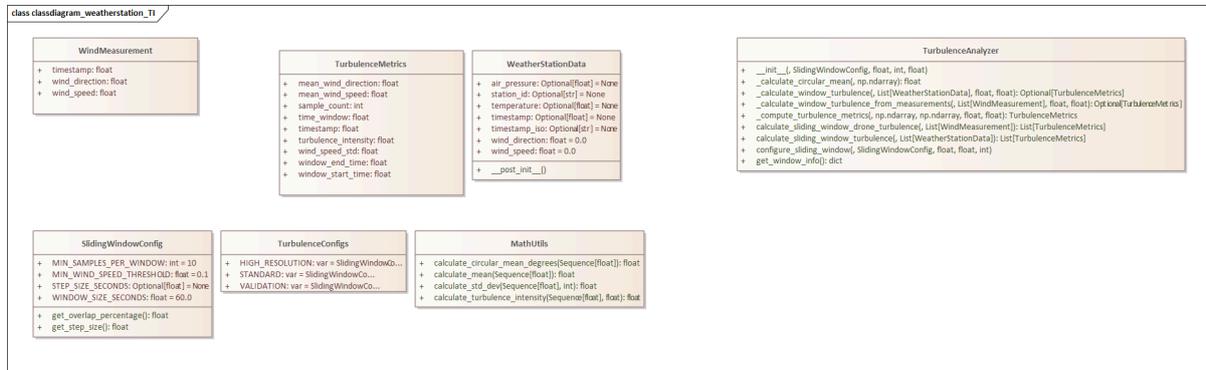

Figure 16: Class Diagram of the Turbulence Intensity Calculation

Calibration Notebooks
Location: `scripts/`
The calibration notebooks are prepared to analyze the data received from the UAV and the weather stations. They contain logic to read the measured data, process it, and visualize it for further analysis.

Notebooks were created for those hypotheses from Chapter 8, that were feasible to test with the available hardware and time:

Hypothesis	Notebook
H1: Turbulence can be estimated using the accelerometer data of the UAV.	`h1_accelerometer.ipynb`
H3: Wind speed can be estimated using the attitude data of the UAV.	`h3_attitude.ipynb`
H5: Turbulence can be estimated using the vertical speed measurement of the UAV.	`h5_verticalspeed.ipynb`
H8: Wind direction can be estimated using ArduPilot's built-in weather vaning mode.	`h8_weathervane.ipynb`

Each notebook makes use of the helper script `shared/init_data.py`, which collects all the data from the Weather Station Adapter and the UAV Data Adapter and combines them into a merged dataset based on the timestamp. The notebooks then narrow down the datasets to the relevant parameters, whereby the timeframe can be dynamically adjusted to focus on specific flight sessions.
The notebooks then contain individual logic and diagrams to analyze the hypotheses and find correlations between the UAV data and the reference data from the weather stations.

As an example, the notebook for hypothesis 1 (`h1_accelerometer.ipynb`) containing sample data is provided in the appendix.

9.5.2 Level 2: UAV System

The components of the UAV App are described in the following diagram.
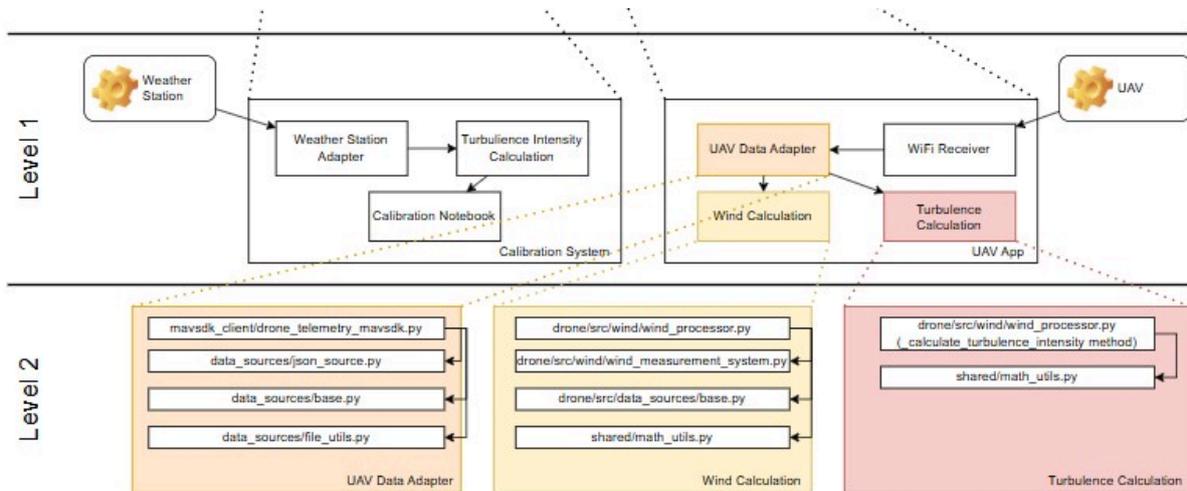
Figure 17: Building Block View of the UAV App

UAV Data Adapter

Location: `drone/src/mavsdk_client/drone_telemetry_mavsdk.py`

The UAV data adapter is responsible for collecting data from the UAV and providing it in a unified JSON format for further processing. This adapter is implemented as a Python script using MAVSDK, a Python library for controlling and receiving telemetry from MAVLink-enabled UAVs. It retrieves raw telemetry streams from the UAV which are then processed and stored in a file.
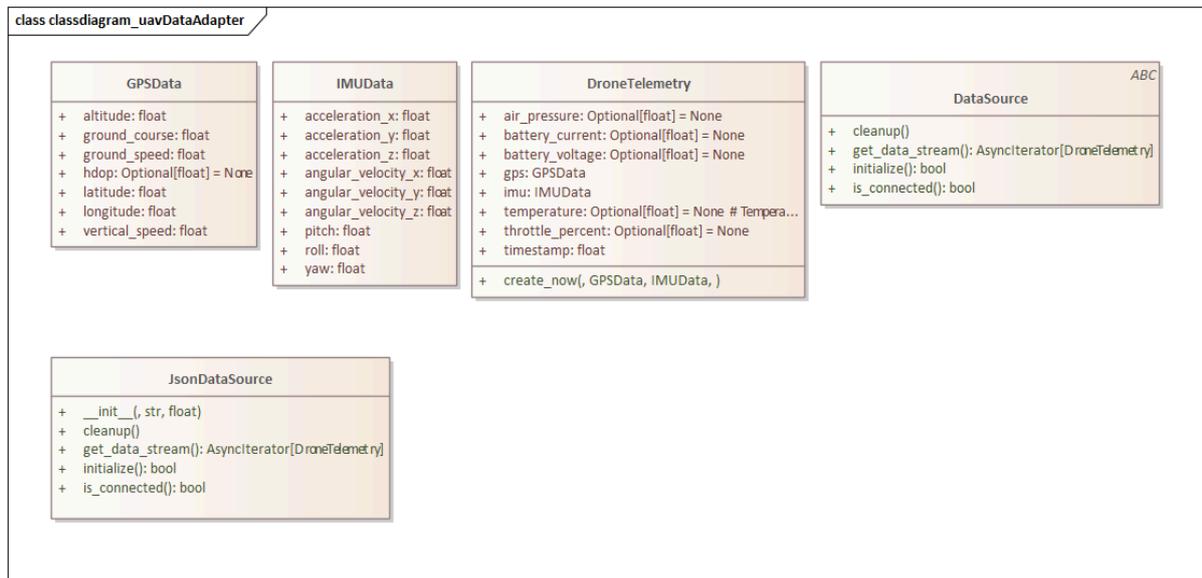
Figure 18: Class Diagram of the UAV Data Adapter

Wind Calculation

Location: `drone/src/wind/wind_processor.py`

The wind calculation is responsible for calculating the wind speed and if needed direction based on the recorded telemetry data. The calculations are implemented as separate functions in the Python class `ParaglidingWindProcessor`. Currently it contains placeholder algorithms, which need to be replaced with the final algorithms based on the results of the calibration notebooks.

These methods will finally be called with real-time data in the operation phase.
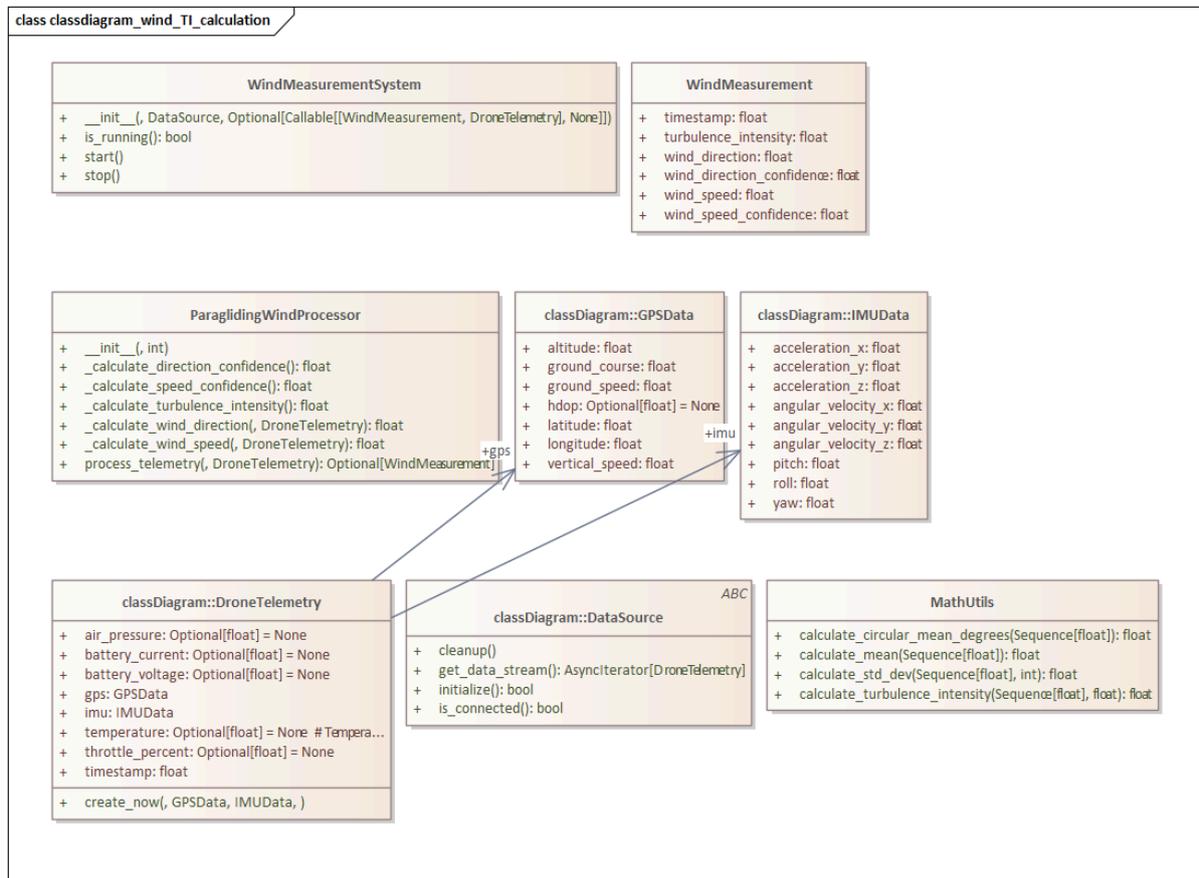
Figure 19: Class Diagram of Wind and TurbulenceCalculation

Turbulence Calculation

Location: `drone/src/wind/wind_processor.py`

The turbulence calculation is responsible for calculating the turbulence intensity from the UAV data. The calculation is implemented as a separate function in the Python class `ParaglidingWindProcessor`. Therefore it is also a part of the wind calculation and the class diagram from the wind calculation is reused.

9.6 Architectural Decisions

The following section covers the most important architectural decisions made during the project.

9.6.1 ADR 01: UAV Software

Table 3: ADR01: UAV Software

Title	**UAV Software**
Context	The UAV software is responsible for controlling the UAV and processing the data collected by its sensors. It must be able to communicate with the ground station and other components of the system. In the context of this project, an open source solution is required in accordance with requirement NFR2. The options considered were: • PX4 Autopilot • ArduPilot
Decision	We decided to use **ArduPilot** as the UAV software, because it is widely used in the UAV community, has a large support base, and offers extensive documentation. Additionally, the team already has previous experience with ArduPilot.
Status	Accepted
Consequences	The hardware and sensors used in the project must be compatible with ArduPilot.

9.6.2 ADR 02: Programming Language

Table 4: ADR02: Programming Language

Title	**Programming Language**
Context	It is possible to use different programming languages to program the UAV as well as the UAV App and the Calibration System. Whereas the programming of the external systems can be done in almost any language, the chosen UAV system (ArduPilot) restricts the available languages (e.g. Python or C#).
Decision	We decided to use **Python** for every component of the project, because it is the best supported language by ArduPilot and has by far the biggest community. Additionally, it allows the whole project to be written in the same programming language.
Status	Accepted
Consequences	The code base is homogenized and functions can be used across the Calibration system and the UAV App if needed. However, all team members must get familiar with Python again.

9.6.3 ADR 03: Adapter Layer

Table 5: ADR03: Adapter Layer

Title	**Adapter Layer**
Context	Because the reference data is collected from different sources, mainly different weather stations, and a hand anemometer, there is a need to have an adapter layer that can convert the data from the different sources into a common format.
Decision	In order to make this adapter easily extendable and configurable, we decided to implement it as a set of Python classes, that can be easily extended to support additional weather stations by only creating a new config file. These config files contain straightforward mappings of properties from the source to the target properties and additionally support optional data pre-processing steps, which can be defined using lambda functions. Additionally it directly calculates the turbulence intensity from the reference data while applying the same sliding window approach as used for the UAV data while formatting the output.
Status	Accepted
Consequences	The adapter layer adds additional complexity to the code base. However, the flexibility and ease of extension outweigh these drawbacks.

9.6.4 ADR 04: Real-time Data Transmission

Table 6: ADR04: Real-time Data Transmission

Title	**Real-time Data Transmission**
Context	The UAV needs to transmit telemetry data to a ground station for real-time wind and turbulence calculations. ArduPilot supports both USB and WiFi interfaces for MAVLink communication. The choice of communication method impacts the system's portability, operational range, and ease of deployment in remote locations where paragliding pilots operate.
Decision	We decided to use WiFi-based real-time data transmission via MAVLink over UDP from the beginning of the project. The system uses the MAVSDK library to establish wireless connections and stream telemetry data at approximately 10 Hz, enabling real-time processing with a target calculation interval of 1 Hz as specified in the quality goals (Table 1).
Status	Accepted
Consequences	WiFi communication requires additional hardware (ESP WiFi bridge) and may be less reliable than USB in terms of connection stability. The wireless approach enables remote operation and portability, which are essential for the final product's use case in paragliding environments.

9.7 Technical Debt

During the development of the architecture, several compromises had to be made due to time constraints and limited resources. The following technical debts have been identified:

Table 7: Technical Debt

Area	Debt	Mitigation Strategy
Wind Calculations	The calculations for wind speed and direction are currently only placeholder algorithms and need to be replaced with real methods based on the results of the calibration notebooks.	Since the calibration notebooks are still under development, no mitigation strategy is currently applicable but when the results are finalized, the algorithms can be implemented.
Turbulence Calculations	Currently the turbulence intensity calculations only use the wind speed and do not take other factors into account.	These calculations will also be refined based on the results of the calibration notebooks.
Calibration System Accuracy	The calibration algorithms may not be fully accurate, leading to potential errors in wind and turbulence calculations.	Continuously refine and validate the calibration algorithms using the reference data.
Adapter Layer input format	The adapter layer for the weather stations might not cover all possible output formats of the weather stations and might need to be extended. Currently it supports all JSON formats.	If additional formats are encountered, the adapter layer can be extended fairly easily.
Configurability and cleanness	Because the project is still under development, the codebase is not yet as configurable and clean as it should be for a production ready system. The current state of the code is a mix of the different project phases and does not yet reflect the final architecture.	Because the first phase of the project is not finished yet and parts of the second and third phase already had to be prepared, it was not possible to implement a fully clean codebase that reflects only one phase at a time. This will be addressed in the future.

Chapter 10

Implementation

This chapter describes how the UAV was built to satisfy the defined requirements. The often conflicting requirements described in Chapter 5 constrained the range of feasible UAV designs.

10.1 Decision Metrics

To systematically compare different designs and components, decision matrices were used based on the following equally weighted metrics:

10.1.1 Prevalence

How well-established is a technique or build approach? Is it common to combine these UAV components, or is the design unusual? Unconventional combinations are often riskier, as little guidance or support is available online. Although the 3D-printed 2S frame achieved a slight point advantage in the decision matrix, we ultimately decided to use a 3D-printed 4S frame. This decision was driven primarily by system compatibility considerations: the Matek H405 flight controller is a conventional 4S platform and is not designed to operate reliably in 2S builds. Choosing a 4S architecture therefore reduced electrical and integration risks, while still allowing us to benefit from the flexibility of a custom 3D-printed frame. The ability to rapidly adapt and reprint the frame ensured that this approach remained compatible with the experimental nature of the project.

Prior experience with certain parts therefore reduces risk significantly.

10.1.2 Versatility

If a chosen component or design path turns out to be unsuitable, how flexible is the system? A versatile design provides alternative options for integration and operation, making it easier to replace parts, expand functionality, or adjust to unforeseen problems during development and testing.

10.1.3 Simplicity

How simple is the design to build, modify, repair, and understand? Simplicity reduces development time and lowers the likelihood of errors.

10.1.4 Previous Experience

Is the team familiar with the selected components or the chosen architecture? Prior knowledge accelerates integration and reduces uncertainty.

10.1.5 Weight / Size

What impact does this design choice have on the overall weight and size of the UAV? This metric is the direct result of the requirement NFR1.

10.1.6 Additional Metrics

Certain decisions required specific and specialized metrics which go beyond the general criteria defined earlier and were tailored to the unique technical or project-related challenges of the project.

10.2 Design Decisions

The following sections detail the decisions made during the UAVs design and construction, along with the rationale behind each choice.

10.2.1 Flight Controller Decision: Matek H405 vs. Tiny 2S FC

Choosing the right flight controller affects not just sensor integration and telemetry, but also extensibility, firmware compatibility, and power delivery.

A specialized tiny 2S controller offers a very lightweight, compact design with integrated motor ESCs, which removes the need for external ESC wiring. This saves both weight and assembly time. However, these small units often require custom firmware and typically do not support ArduPilot.

The Matek H405 is much heavier, but features integrated MAVLink telemetry over Wi-Fi.

Table 8: Decision Matrix — Flight Controller Options (No Weights)

Criterion	Matek H405	Tiny 2S FC	Rationale
Prevalence	9	4	Matek is widely supported; tiny FCs are more niche and firmware-limited.
Versatility	10	3	Matek supports a wide range of sensors, outputs, and MAVLink over Wi-Fi.
Simplicity	6	9	Tiny FC is simpler due to integrated ESC and compact design.
Previous Experience	9	4	The team has prior integration experience with the Matek H405.
Weight / Size	4	10	The Matek flight controller is 14g heavier than average 2s FCs.
Firmware Compatibility	10	2	Tiny FCs often require custom firmware and lack ArduPilot support.
Total	48	32	A clear win for the Matek H405.

Conclusion: The Matek H405′s versatility is outstanding. With everything that could go wrong, this flight controller is the last component that needs to be replaced, as it supports every backup solution that could be anticipated. This choice significantly reduces risks.

Despite this, the selected Matek H405 unit experienced a technical defect that destroyed two ESCs. To continue development, the unit was replaced with a readily available SpeedyBee F405. However, this substitution led to the loss of MAVLink telemetry functionality. This incident confirmed that the original choice of flight controller was technically sound. The failure was due to a defective unit rather than a design decision.

10.2.2 Frame Decision: 3D-Printed 2S/4S vs. Off-the-Shelf 4S

Choosing the right frame size and construction is crucial for the entire UAV project. A larger frame makes it easier to assemble components, add peripherals, and improvise fixes during testing. However, larger frames conflict with the requirement of transportability and often result in heavier builds.

In the UAV industry, the number of battery cells connected in series (denoted as **S**) is commonly used as a standard to classify different UAV designs. The S-rating directly corresponds to the battery voltage and influences the overall power level of the system. A higher S-rating typically implies a larger and more powerful platform. Consequently, the choice of S-rating affects nearly all design decisions and represents a fundamental constraint when defining the overall UAV architecture.
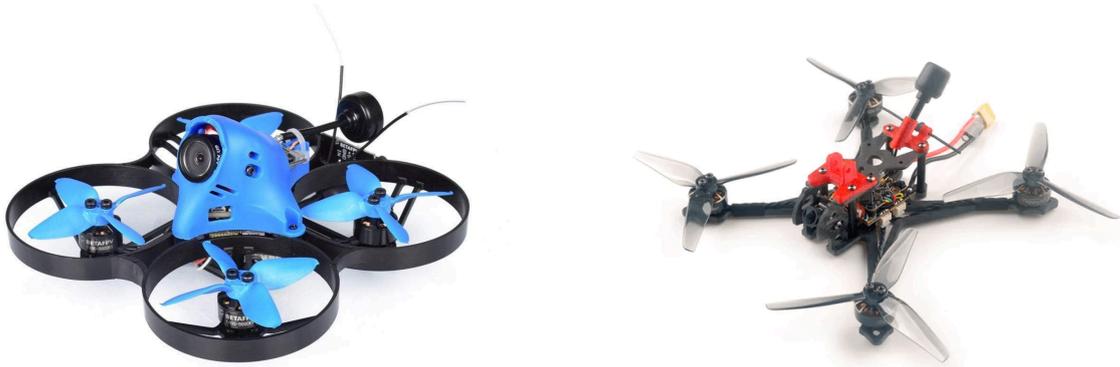
Figure 20: Design comparison between a 2S (left) and a 4S (right) UAV. [8]

Buying an off-the-shelf 4S frame is the more common approach. It is well-documented, supported by the community, and integrates smoothly with standard flight controllers. On the other hand, 3D-printing a smaller custom frame is less common and riskier, but it allows us to adapt the frame if unexpected challenges occur.

To systematically evaluate these options, following decision matrix was created:

Table 9: Decision Matrix — Frame Options (No Weights)

Criterion	3D-printed 2S	3D-printed 4S	Off-the-Shelf 2S	Off-the-Shelf 4S	Rationale
Prevalence	5	3	9	10	It is difficult and thus uncommon to ensure stability with 3D-printed 4S frames.
Versatility	9	10	4	5	3D-printed builds offer maximum flexibility.
Simplicity	7	6	5	10	Robust 3D-printed frames are a challenge on their own. 4S is easier to build in many ways.
Previous Experience	9	9	5	5	We have strong 3D printing experience.
Weight / Size	9	7	8	5	3D-printed reduces weight. 4S is bulkier.
Total	39	35	31	35	Close win for the 3D-printed 2S.

Conclusion: Although the 3D-printed 2S frame achieved a slight point advantage in the decision matrix, this led to the decision to use a 3D-printed 4S frame. This decision was driven primarily by system compatibility considerations: the Matek H405 flight controller is a conventional 4S platform and is not designed to operate reliably in 2S builds. Choosing a 4S architecture therefore reduced

electrical and integration risks, while still allowing us to benefit from the flexibility of a custom 3D-printed frame. The ability to rapidly adapt and reprint the frame ensured that this approach remained compatible with the experimental nature of the project.

10.3 Minor Decisions

This section summarizes the less important decisions that were made during the construction of the UAV.

Motors and Rotors: Flight performance is not a primary objective of this project, as achieving meaningful improvements would require extensive aerodynamics knowledge and typically results in only marginal gains in flight time. Based on the guidance provided by Oscar Liang [34], suitable motors were selected, which determined the rotor size, after which rotors optimized for slow and efficient flight were chosen.

Sensors: Sensors were selected directly from Mateksys. These sensors are lightweight, provide sufficient accuracy for the mission requirements, and integrate seamlessly with the Matek flight controller. To minimize compatibility issues and simplify wiring, both the GNSS and the airspeed sensor were chosen from Mateksys' product line.

Telemetry Link: After the replacement of the original flight controller with a less optimal alternative, the ability to transmit MAVLink telemetry over WiFi was no longer available. As a result, an external telemetry module was required. Following ArduPilot recommendations, an ESP32-based WiFi telemetry module was selected.

Chapter 11

Results

11.1 UAV Hardware

The prototype UAV constructed for this project is a custom-built quadcopter capable of carrying and utilizing a wide range of sensors necessary for wind and turbulence estimation. The 3D-printed frame is easily customizable and the PA6 filament it is printed with makes the frame robust. A WiFi module ensures real-time data transmission to the connected software system during flight, fulfilling FR3.

The UAV weighs less than 250g, allowing it to be flown in category A1 in Switzerland, in accordance with NFR1. The compact design of the UAV makes it easily portable for pilots to carry to their flying locations.

Several tests have proven the UAV's stability and controllability in different environments, making it a reliable platform for wind and turbulence measurements. However, these tests have shown, that care must be taken when flying in cold environments, as the flight controller tends to short circuit when it condensates moisture.

The UAV's firmware is based on the open-source software ArduPilot, which provides a robust and flexible platform for autonomous flight. This ensures the fulfillment of NFR2. Custom modifications were made to the firmware to accommodate the integration of the required sensors and data transmission capabilities.

Detailed logs of the UAV's performance and sensor data are recorded during each flight, allowing for thorough analysis of relevant parameters after each flight. The logging system is configurable at runtime, enabling the selection of log levels and categories as specified in NFR4.

11.2 Software Components

The software architecture is divided into three phases, of which the first one was the focus of this project:

1. Analysis and Calibration Phase
2. Validation Phase
3. Operation Phase

Within the Analysis and Calibration Phase, the development focused on receiving the transmitted data from the UAV in real-time (FR3), collecting the reference values from traditional measurement devices, as well as processing and preparing the data for analysis.

Data transmission via a reliable WiFi connection was successfully established, allowing for future real-time calculations of wind and turbulence metrics during flight. The data is being logged for analysis, evaluation and validation purposes.

Data collection from traditional measurement devices was implemented to gather reference data for calibration and validation of the UAV measurements. This data serves as a benchmark for evaluating the accuracy of the UAV-based measurements.

Data processing and analysis involved formatting the received data from each source into a common structure suitable for further analysis. This included synchronizing the data by timestamp and pre-calculating the turbulence intensity over a moving window.

To fulfill NFR3, UML diagrams were generated to represent the software architecture and data flow, providing a clear overview of the system's design and functionality.

11.3 Wind and Turbulence Estimation

The core functionality of the system revolves around the estimation of wind speed, wind direction (FR1), and turbulence levels (FR2) using the data collected from the UAV's sensors. Due to time constraints and technical challenges only a theoretical basis could be established, while practical implementation and validation remain future work. Still, several methods of wind and turbulence estimation were researched and evaluated for their suitability in the context of UAV-based measurements. Two methods were identified as the most promising and feasible, covering all the required measurements.

11.3.1 Hypothesis 1: Turbulence estimation using the accelerometer data of the UAV

The accelerometer measures the linear acceleration of the UAV in three axes. By analyzing the amplitudes and deviations in the accelerometer data, it is possible to estimate the level of turbulence experienced by the UAV during flight. This method is backed up by existing practices of in-situ turbulence measurements conducted today by commercial airliners [20] and weather balloons [3]. It is therefore considered a viable approach for turbulence estimation.

11.3.2 Hypothesis 3: Wind speed estimation using the attitude of the UAV

The UAVs Inertial Measurement Unit (IMU) provides data on the UAV's orientation in space, including pitch, roll, and yaw angles. By analyzing the UAVs pitch angle required to maintain position against the wind, it is possible to estimate the wind speed. This hypothesis has been proven in previous studies [1]. Additionally, ArduPilot includes a function which implements this exact method and returns wind speed and direction [32], which can be leveraged for this project.

11.4 Summary

In conclusion, a prototype for a UAV-based wind and turbulence measurement system has been successfully developed, focusing on the Analysis and Calibration Phase. The UAV hardware has been constructed to meet the necessary requirements, and the software components have been implemented to facilitate real-time data transmission, collection, and processing. Several promising methods for wind and turbulence estimation have been identified, albeit without practical implementation within the scope of this project.

Nevertheless, this project laid the groundwork for future development, validation, and operational deployment of the system and can be considered a success in proving the feasibility of the intended approach.

Figure 21: UAV in flight

Chapter 12

Conclusions and Outlook

12.1 Goal Achievement

The primary goal of this project was to find a solution for measuring wind and turbulence using a small unmanned aerial vehicle (UAV) that is portable and cost-effective. The project faced several challenges, including defective parts that required multiple rebuilds of the UAV and damage sustained during a test flight in cold weather. Due to these setbacks, at each point in the project only a part of the overall system was functional, meaning that either data extraction or stable flight worked at any given time, but never both simultaneously. This limited the ability to perform meaningful tests and gather enough data to fully validate the proposed methods for wind and turbulence estimation.

Despite this, the project was able to find a viable solution that enables wind and turbulence measurement using a small UAV. In that sense, even if no conclusive test and calibration flights could be performed, the overall project goal was achieved.

12.2 Reflection

Throughout these challenges the project team proved to be well organized and demonstrated strong teamwork, with each member contributing their strengths and giving their best. The team reacted flexibly to the obstacles encountered, adapting their approach as needed to continue working towards the intended goal.

The communication strategy within the team was effective, sharing information and updates regularly. Still, some knowledge silos remained, especially regarding the construction of the UAV, introducing a risk in case of team member absence.

Another issue was the the development process of the UAV. With many unknowns and uncertainties at the beginning, many of the utilized components were later found to be unsuitable, leading to multiple rebuilds. The ways to mitigate this risk would have been to invest more time in research at the start of the project and choosing a backup solution early on.

12.3 Future Work

To fully validate the proposed methods for wind and turbulence estimation using a small UAV, further work is needed. This includes performing comprehensive test flights in various weather conditions to gather sufficient data for analysis. This data should be used to calibrate and validate the intended estimation methods.

Additionally, the UAV Application should be further developed to allow for real-time data processing and visualization during flight. This would enhance the usability of the system and provide immediate feedback on wind and turbulence measurements. One possibility is the development of a mobile application that additionally allows for easy mission planning and UAV control.

In conclusion, the future work should focus on connecting the different components of the system, performing extensive testing, refining the data processing and adding user-friendly visualizations to achieve a fully functional solution for wind and turbulence measurement using a small UAV.

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Operational Notes

This chapter provides additional operational information about the project, including tools used, test logs, and practical guidance on building a similar UAV system.

Tools

The following table lists the various tools that were utilized throughout the project for different purposes.

Table 10: Tools used in the Project

Area	Tools
Literature Research	Google, Google Scholar, Swisscovery, ChatGPT, Zotero
Location Scouting	burnair Map, Google Earth, Google Maps, Windy, MeteoSwiss, map.geo.admin.ch
Data Analysis and Visualization	Jupyter Notebook, Copilot, ChatGPT
Diagrams and Modeling	Enterprise Architect, draw.io, Desmos
Translation	DeepL
Coding	Visual Studio Code, Augment Code, Copilot
Text creation, text optimization, spelling and grammar checking	Typst, Copilot
Collaboration and Projectmanagement	Teams, Azure DevOps, Youtrack, 7Pace Timetracker

Test-Logs

Throughout the development of the UAV system, various tests were conducted to ensure the functionality and reliability of the implemented components. The results of these tests are documented below.

The testing strategy is further detailed in the project management section.

Hardware Integration Tests

Date	Test Case	Location	Result	Findings
19.11.2025	UAV is able to fly.	Rapperswil	Success	UAV is able to fly. However, only with large oscillations and very unstable.
22.11.2025	Flight is stable and position hold using GNSS works.	Meiringen	Partial Success	The oscillations are smoothed out, but in position hold mode the UAV drifts both laterally and vertically.
23.11.2025	Position hold using GNSS works.	Meiringen	Partial Success	The position hold mode works well laterally, but the UAV descends slowly.
23.11.2025	Position hold is accurate enough to fly next to the reference weather station for a prolonged amount of time.	Gadmen	Success	The flight was stable enough to enable future measurements.

System Tests

Due to the experimental nature of this project, system tests could not be performed as initially intended. The focus had to be shifted to hardware integration tests in order to get the UAV flying first.

Building the UAV

This chapter is a collection of the knowledge gained during the construction of a quadcopter. Its purpose is to accelerate future UAV development by documenting key insights, design decisions, proven solutions, and common challenges. This allows upcoming projects to build directly on established experience and reduce redundant work.

Flight Controllers (FC)

At the time this was written, advanced chip exports to China were being boycotted which made advanced FCs with 2MB flash memory unavailable. FCs are essentially a single main chip on a small PCB, while the remaining area is mostly pads that route signals to sensors, ESCs, and peripherals. The chip itself acts as the central control unit of the UAV and determines which features the FC can support. Many common chips, such as the STM32F405 series, provide only around 1 MB of RAM/ flash, which is sufficient for lightweight firmware like Betaflight. However, this memory limit is too restrictive for more advanced systems such as ArduCopter or INAV, which include features like wind estimation, automatic navigation, precision landing, and other high-level autonomy functions. As a result, these firmwares often need to be trimmed down to fit into 1 MB, losing important capabilities in the process. ArduPilot offers the option to build a custom firmware configuration, allowing you to include only the features you need so the firmware fits the hardware constraints while still providing the required functionality.

Electronic Speed Controllers (ESC)

In most quadcopter builds, ESCs come as 4-in-1 modules that connect directly to a serial interface on the flight controller. This is the standard approach because it reduces wiring, simplifies installation, and ensures clean signal routing. It is also possible to drive ESCs via servo outputs of a FC. The most reliable setup is to use a 4-in-1 ESC from the same manufacturer as the flight controller, ideally as a matched stack. This improves compatibility and avoids unnecessary troubleshooting. Before using the ESC, it is important to verify which firmware it is running. To check or flash the firmware, connect the ESC to the flight controller and enable

SERVO_BLH_AUTO in arducopter firmware. This param forwards ESC telemetry/data through the FC. Without it, the ESC will not be detected, and ESC-Configurator will tell you that another device is using the bus. Once forwarding is active, you can use esc-configurator.com to read and flash the ESC firmware. Bluejay is recommended, as it has become the standard for modern builds. BLHeli_30 or BLHeli_60 are also options for compatibility, but in most cases the choice has no significant impact on performance or compatibility. The FC is the most crucial part of the UAV and as the requirements of this project are very specific, we recommend following attributes:
- Must have a DA-CL bus
- Must have at least 3 accessible serial ports
- Should have a compatible ESC from the same manufacturer
- Should have 2 MB flash memory to load all ArduCopter firmware features

Frame Design and Vibration Prevention

Frame design requires careful placement of components and attention to vibration sources. The GNSS module should be mounted as far away from any high-current wiring as possible, with at least 6 cm of separation. ArduPilot provides an ESC–GNSS interference test that helps determine the ideal GNSS location for minimal noise. The frame itself must stay lightweight while still offering good rigidity; PA6-CF carbon-fiber filament proved to be a strong and reliable choice. Vibrations must be kept under control. Identify which motor introduces the strongest vibration by checking logs or running simple motor tests. Ensure all screws on motors and propellers are properly tightened and that there is no mechanical play. If a motor is imbalanced, it should be replaced immediately. Check

for weird noises of the motor. A dangerous but effective test is to hold the UAV down and let the rotors spin. The vibrating motors arm should visibly vibrate. For software-side damping, ArduPilot offers several filtering parameters. A simple and effective option is adjusting the INS_GYRO_FILTER, which reduces high-frequency noise from the gyro. In our case, tuning this filter was enough to bring vibrations into an acceptable range. Additional options such as INS_ACCEL_FILTER or harmonic-notch filters exist, but starting with the gyro filter usually provides quick results.

Sensors and Serial Configuration

Sensor and serial wiring requires attention to signal direction, bus behavior, and power availability. For UART-based peripherals, RX and TX must always be crossed between the flight controller and the device. For I2C devices (DA/CL), the bus allows multiple sensors on the same two pins, but identical sensors with the same address cannot share the bus, otherwise address conflicts occur. Most peripherals support a wide input-voltage range, but it is essential to confirm this in their specifications. Many ports on flight controllers only supply power when a battery is connected. During USB-only debugging these pads may remain unpowered, and this behavior is often not documented by the FC manufacturer. Camera-UART ports typically provide weak or unstable voltage and should be avoided for powering sensors. You can still use their RX/TX lines, but power and ground should be taken from more reliable pads elsewhere on the board. The baud rate defines the speed at which data is transmitted over a serial connection. When selecting the correct protocol and baud rate for a sensor or peripheral, the protocol must match what the device expects, while the baud rate is usually auto-detected by ArduPilot. However, certain components, especially radio receivers, require an exact baud rate specified by the manufacturer and will not function otherwise. It is also important to verify the mapping between logical serial ports and physical UARTs, since the numbering on the board does not always correspond to the SERIALx entries in the configuration. Always double-check the serial port configuration tab to ensure each device is assigned to the correct logical port with the correct protocol and baud settings.

Flight Modes

This section describes the most relevant flight modes for a basic quadcopter setup. **Stabilize** This is the manual baseline mode. The flight controller automatically levels roll and pitch, and maintains heading (yaw), but leaves throttle and horizontal position fully under pilot control. No GNSS or other position sensor is required — only a working IMU.

Alt Hold

This mode automatically maintains altitude (using a barometer or another altitude sensor), while horizontal position remains under pilot control. Roll, pitch, and yaw are self-levelled as in stabilize. Alt hold does not require GNSS but does require a functioning altitude sensor.

Position Hold

When the sticks are centred, the UAV holds latitude, longitude, altitude, and heading automatically. Moving the sticks commands motion; releasing them returns the UAV to hover. This mode requires a valid position fix (GNSS or another position sensor) and typically a compass (magnetometer) for orientation.

Flight Mode Configuration

- Open your ground station software (e.g. Mission Planner) and navigate to the **flight modes** configuration screen.
- Select the AUX/RX input that will act as the flight-mode channel. This is configured via the parameter `FLTMODE_CH`.
- Assign each switch position on the transmitter to one of the available flight modes (e.g. stabilize, alt hold, position hold / Loiter, RTL, etc.).

- Ensure that at least one switch position remains assigned to **stabilize**, providing a safe fallback in case of GNSS signal loss.
- Save the configuration. Flipping the corresponding switch on the transmitter will now command the flight controller to change to the selected mode.

Motors, Rotors, Battery Size

Use Oscar Liang's website (oscarliang.com) to understand how to select motors, propellers, ESCs, and battery sizes, and purchase components that match the required performance class. External tools such as ChatGPT can provide helpful explanations, but should be used with caution — always verify recommendations with manufacturer data or established sources.

Our final Components Choice

We chose the Matek F405-WTE flight controller because it includes an integrated Wi-Fi telemetry module, saving both energy and weight. This specific FC is deprecated and no directly comparable alternative could be found. By the time you read this, we recommend selecting a flight controller that includes an ESP32 chip and provides at least 2 MB of flash memory — which, admittedly, is difficult to find.
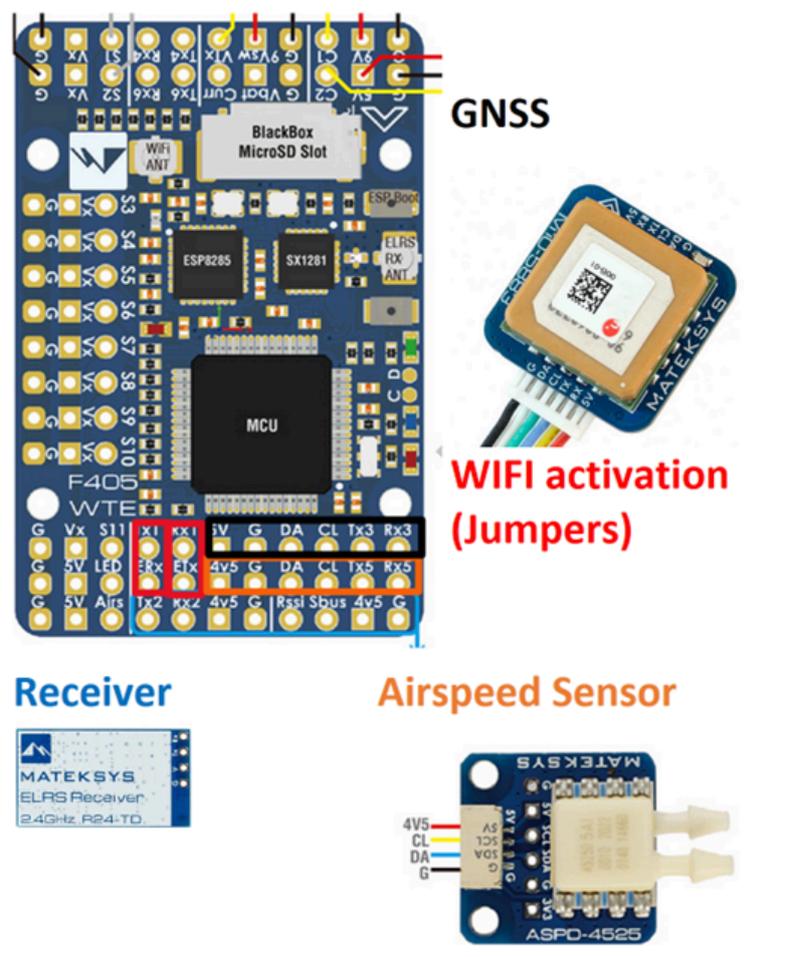

Figure 22: Wiring overview of the selected flight controller and peripherals

The Wi-Fi activation jumpers on this board are unique to the Matek F405-WTE. They instruct the controller to repurpose the internal receiver traces as a Wi-Fi antenna rather than as a radio-receiver input, enabling the integrated telemetry module.

3D-Printed UAV frame

Because this project was highly experimental, we did not know in advance which exact components or sensors we would ultimately integrate into the UAV. A 3D-printed frame offered the flexibility needed to adapt the design as requirements evolved. Mounting points, clearances, and structural elements could be modified quickly, making it far easier to accommodate different sensors and layout changes throughout development.

UAV frames must withstand high tensile loads and remain extremely stiff; insufficient rigidity leads to motor-induced vibrations that can make the UAV difficult or even impossible to control. For this reason, we selected PA6-CF as the frame material. Although it is challenging to print, it provides excellent stiffness and long-term tensile strength retention. We chose PA6 over PA12 specifically because PA6 maintains its mechanical properties better over time.

To ensure a successful print, several measures were necessary. PA6 tends to warp and detach from the build surface, so we applied glue stick to the print bed to improve adhesion. After printing, the frame was annealed in an oven at 120 °C for 18 hours. This post-processing step improves the crystalline structure of the material and reduces moisture absorption, which is important because absorbed water can significantly reduce the tensile strength of PA6.
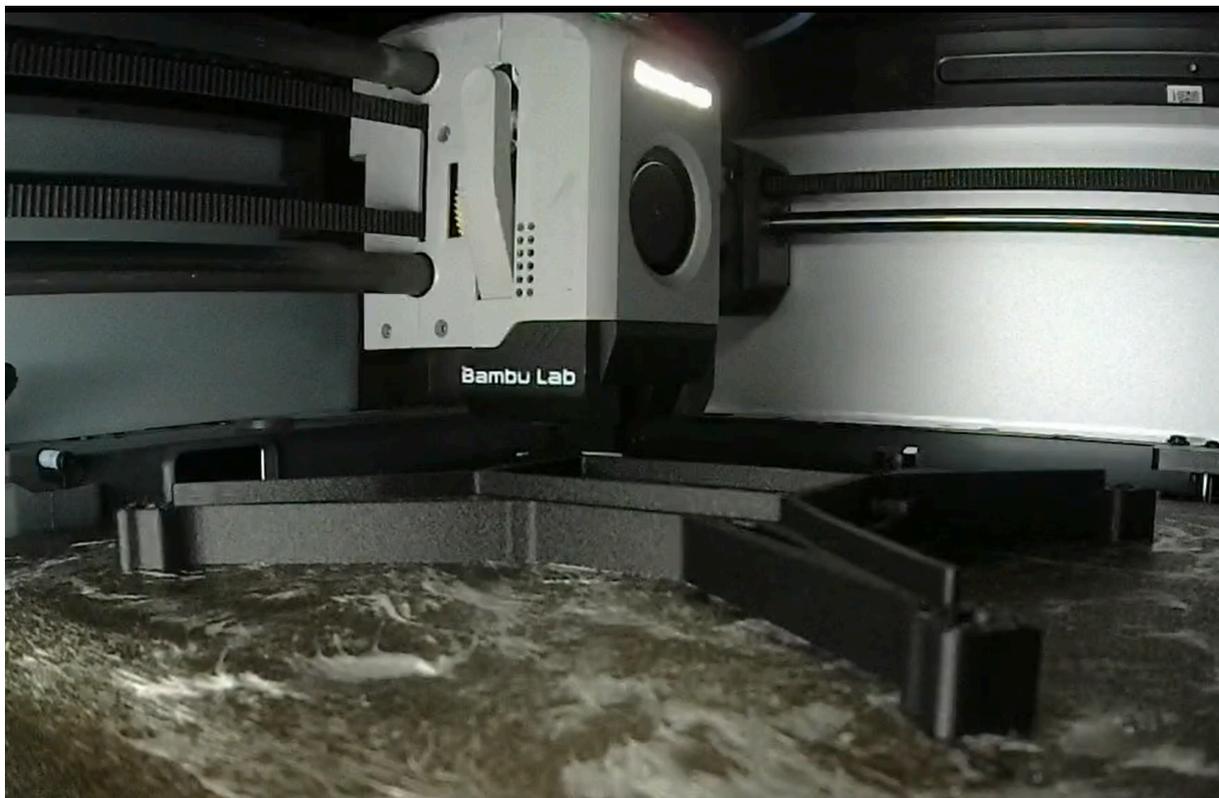

Figure 23: View of the frame being printed from the inside of the printer.