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NAROM Mikro UAS

Arve Jørgen Haugland Tokheim

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Hovedveileder: Jo Arve Alfredsen, ITK
Biveileder(e): Jøran Antonsen, Nasjonalt Senter for Romrelatert Opplæring

Norges teknisk-naturvitenskapelige universitet

NTNU
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Oppgavens tekst:
Nasjonalt Senter for Romrelatert Opplæring (NAROM) ønsker et autonomt ubemannet fly for teknologikurs og undervisningssammenheng ved Andøya Rakettskytefelt. Flyet med navigasjonssystem og bakkestasjon, herunder kalt NAROM UAS (Unmanned Aircraft System), skal blant annet benyttes til:

- Demonstrasjon av UAS operasjoner
- Generell opplæring i bruk av UAS
- Luftbasert instrumentplattform for fjernmåling og overvåking

NAROM forutsetter et lavkostnadssystem som er allsidig, robust, og enkelt i bruk. Selve flyet, referert til som UAV (Unmanned Aerial Vehicle), skal inneholde nødvendig instrumentering for autonom navigasjon, og skal kommunisere data til bakkestasjon i sanntid. Systemet er også ment å tillate størst mulig grad av ”hands-on experience” for brukerne av flyet; i første omgang universitetsstudenter på BSC og MSC nivå.

Masteroppgaven omfatter følgende punkter:
- Undersøke regelverket for UAS bruk. Søke flyvetillatelse hvis nødvendig.
- Behovsanalyse, teknologikartlegging, og utarbeidelse av kravspesifikasjon.
- Valg av hensiktsmessig instrumentnyttelast.
- Utstyrsanskaffelse for NAROM UAS, i henhold til kravspesifikasjon.
- Integrasjon og testing av fly, navigasjonssystem, og bakkestasjon, i henhold til utarbeidede testscenarier.
- Design, utvikling, og testing av instrumentnyttelast.
- Integrasjon og testing av UAS med nyttelast, i henhold til utarbeidede testscenarier.
- Vurdere valgt løsning, og utføre eventuelle modifikasjoner.
- Presentasjon og diskusjon av resultater, og valgte løsninger.
- Dokumentasjon av utført arbeid.

Abstract

This report presents the development of the NAROM UAS, an Unmanned Aircraft System for educational use by the Norwegian Centre of Space Related Education (NAROM). The NAROM UAS is a small, inexpensive and modular platform intended for technological courses. This UAS enables students to plan and carry out UAS operations while also flying their own experimental payloads.

A Skywalker EPO airframe was successfully selected as the platform for the Unmanned Aerial Vehicle (UAV), providing a flight endurance of about one hour and a tested payload capacity of 550 g. The NAROM UAV also holds an ArduPilot Mega autopilot (APM). The APM proved reliable and sturdy once correctly set up.

A meteorological payload was also developed for the NAROM UAV, based on a CanSat kit. This payload includes pressure, temperature, and humidity sensors in combination with a GPS receiver. Spatial weather data was transmitted to a Ground Control Station (GCS) and recorded in real-time. Consistent weather pattern data was collected in flight although the full potential of this platform could only be fully demonstrated by a scientific weather mapping study; however, this proved to be outside the scope of this master thesis.

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Nomenclature

ABL	Atmospheric Boundary Layer. Behavior of the ABL is influenced by contact with the planetary surface.
ADC	Analog Digital Converter
AGL	Above Ground Level.
AIC	Aeronautical Information Circular. A notice issued by an aviation authority providing information about operational, technical, or administrative matters.
AIS	Automatic Identification System. AIS is an automated identification and tracking system for localizing nearby marine vessels.
AMSL	Above Mean Sea Level.
APM	ArduPilot Mega autopilot controller.
ARR	Andøya Rocket Range.
ATC	Air Traffic Control.
Autonomous	Autonomous vehicles are capable of intelligent motion and decision making without the continuous need of human guidance.
BEC	Battery Elimination Circuit. The BEC is a circuit inside the ESC that diverts power to the servos, eliminating the need for a separate battery.
CG	Center of Gravity. CG is determined as the mass center of the vehicle, and the CG location largely affects airplane stability and performanc.
Drone	Simple non-autonomous military aerial vehicle. Generally employed for targeting practice.
ESC	Electronic Speed Controller.

FM — Frequency Modulation. FM radio transmitters convey information by shifting the carrier frequency as a function of the input signal.

FPV (airplane) — First Person View. FPV airplanes are RC airplanes adding live video-feed through an onboard camera and radiolink, enabling the pilot to operate beyond VLOS.

GCS — Ground Control Station. The GCS is a software application displaying real-time flight data for the UAV operator on ground. GCS communicates with the UAV via telemetry, acting as a virtual cockpit.

GPS — Global Positioning System. GPS is a satellite-based navigation and positioning system. In UAVs GPS is often employed for navigational control.

GUI — Graphical User Interface. Allows user interaction with e.g. an autopilot through graphical images rather than text commands.

IC — Integrated Circuit.

IDE — Integrated Development Environment

IMU — Inertial Measurement Unit. The IMU is the main component of the INS (Inertial Navigation System), and provides attitude control using a combination of gyroscopes and accelerometers.

IR — Infrared radiation. Electromagnetic radiation with a wave length ranging from 0.7 to 300 μm, corresponding to thermal radiation by objects near room temperature.

K_v value — Motor constant indicating the unloaded motor velocity in RPM per volt.

LiPo — Lithium Polymer battery technology.

LOS — Line of Sight.

NAROM — The Norwegian Centre for Space Related Education, co-located at ARR.

NOTAM — NOtice To AirMen. NOTAMs are filed with an aviation authority, and contain information for airmen regarding hazards en route, or around a specific location.

PWM — Pulse width Modulation. Control signals from the RC receiver is transmitted as PWM signals.

RC (airplane)	Remote Controlled airplane unable of autonomous flight. RC airplanes are intended for recreational use, and are controlled by an operator within VLOS under 400 ft AGL.
RF	Radio Frequency.
RH	Relative Humidity.
RPV	Remotely Piloted Vehicle. Refers to a complex and often instrumented non-autonomous UAV that is designed for flights beyond VLOS. RPVs are generally intended for professional use.
S/N	Signal-to-Noise ratio. The S/N ratio gives a measurement of how much a signal is corrupted by noise, defining the ratio of signal power to the noise ratio.
SUMO	Small Unmanned Meteorological Observer. Operating as a recoverable radiosonde, the SUMO UAS from UiB is intended for meteorological research.
UAS	Unmanned Aircraft System. Refers to the overall system including the UAV, ground-station, and support systems.
UAV	Unmanned Aerial Vehicles. Refers to the aerial vehicle, including payload, control, and navigational system.
VLOS	Visual Line of Sight.

Chapter 1

Introduction

Rapid development in micro-electronics and robotics combined with falling production-costs have in recent years opened a huge and growing market for unmanned aerial vehicles (UAVs). Originating from military target drones, today's UAVs are available for a wide range of applications; civilian as well as military. Recent examples of UAV applications include earth observation, traffic monitoring, metrology, search and rescue, surveillance, and intelligence.

Resulting from the growing importance of UAVs, the Norwegian Centre for Space Related Education (NAROM) decided to initiate the establishment of a Norwegian UAS summer camp. Named "Arctic EO - Arctic Earth Observation and Surveillance Technologies", the first of two planned camps will take place at the Andøya Rocket Range (ARR) in August of 2011.

In the fall of 2010, it was decided that an unmanned aircraft system (UAS) would be developed for the Arctic EO. Named "NAROM UAS", this UAS is intended to be a small, inexpensive modular platform, permitting easy operation and student hands-on experience. Entering in collaboration with NAROM, the development and testing of the NAROM UAS laid the foundation for this master thesis.

Chapter 2

Background

This chapter provides a background to the inspiration and motivation behind the master's thesis, as well as providing a short description of the objective and approach chosen for the project.

2.1 Inspiration

2.1.1 NAROM

The Norwegian Centre for Space Related Education (NAROM)[1] was formed in 2000 to organize and promote space education in Norway, as well as stimulating the interest for science in general. NAROM is co-located with Andøya Rocket Range[2] (ARR) i the northern part of Norway, two degrees north of the Arctic Circle.

In addition to operating sounding rockets, ground-stationed instruments for atmospheric studies, and ballon sondes, ARR has in recent years taken interests in a new and emerging enterprise; Unmanned Aerial Vehicles (UAVs). Its success with the Aranica UAS program inspired and motivated NAROM to establish a summer camp focusing on UAS operations[3] and earth observation. In doing this NAROM also decided to develop their own UAS, eventually leading to the creation of this master thesis.

[1] NAROM home page: `http://www.narom.no/`
[2] Andøya Rocket Range home page: `http://www.rocketrange.no/`
[3] UAS: Unmanned Aircraft System

2.1.2 Arctic EO

The first of two summer camps is planned for August 2011, and is named "Arctic EO: Arctic Earth Observation and Surveillance Technologies"[6]. This introductory course consists of both theoretical lectures and practical UAS operations. Top researchers will give lectures on UAS technology and instrumentation, earth observation, and remote sensing. For the first camp a group of 20 international Master and PhD students have been selected to attend. In hosting this camp NAROM is collaborating with the ARR, Narvik University College (HiN), the University of Tromsø (UiT), the University of Bergen (UiB), and the Northern Research Institute (NORUT)[4].

Already flight proven UAVs belonging to UiB and ARR will primarily be used for the first camp, in addition to the NAROM UAS that is to be developed. In contrast to the larger Cryowing UAV from ARR (see figure 2.1 and 2.2), NAROM wanted their UAS to be a smaller inexpensive and modular platform. This would permit students to plan and carry out the UAS operations themselves, adding valuable hands-on experience to the course.

2.2 Motivation

The establishment of the Arctic EO camp set the background for the master thesis. Already working part-time as an instructor for NAROM (since early 2010), the author was invited into a collaboration with NAROM by Jøran Grande, the educational manager of NAROM.

Personal motivation for the project also came from a life-long interest in radio controlled aircrafts, as well as having previously investigated terrain tracking for low-cost UAVs in the project thesis[46]. The NAROM initiative seemed an interesting and relevant master project, and this joint effort led to the development of the NAROM UAS.

2.3 Objective

The objective is primarily to develop an autonomous UAS for use at Arctic EO, as well as other technological courses by NAROM. Referred to as the NAROM UAS, this system intends to provide a small, modular, and inexpensive airborne platform. Locating a meaningful payload constitutes the secondary task of the development project, and the NAROM UAV should have the ability to carry a wide range of payloads for various mission types.

[4]For more information on the Arctic EO, see appendix A.

Figure 2.1: *The ARR Cryowing UAV approaching landing at Ny Ålesund, on the island of Spitsbergen, Norway. Photo by Torbjørn Houge, during the 2011 Svalbard campaign.*

Figure 2.2: *Close-up photo of the Cryowing UAV. The wingspan of this UAV is* 3.8 m*, maximum take of weight is* 30 kg*, and the maximum range is* 500 km*/5 hours[26]. Photo by Torbjørn Houge.*

While NAROM calls for the complete UAS development, the focus of the master thesis is wider, further focusing on presentation of flight data, measurement data, and on the development of a small instrumental payload. Instrumenting the UAV with a simple camera may for instance be of interest to NAROM, but will on the other hand be less interesting with respect to the thesis goal. Fulfilling the expectations of NAROM, as well as those expected from a master's thesis, will be challenging, requiring extensive planning and organization.

2.4 Approach

2.4.1 Study Tour to UiB

Before starting on the master thesis the author was invited by professor Joachim Reuder and PhD student Marius Jonassen at UiB, to examine their SUMO UAS. Visiting their laboratory in Bergen and exchanging ideas and experiences was of great value and relevance to the early project phase. Issues that were discussed included autopilot technologies, frequency allocation, mission planning, and airframe and payload selection. This trip proved important for chosing a payload, and again later when selecting the autopilot technology. Figure 2.3 shows the SUMO lab, including two of their SUMO UAVs.

2.4.2 Preliminary Work

Upon project start several decisions had to be made. First, a flight permit had to be aquired by Luftfartstilsynet (the Norwegian Civil Aviation Authority)[5], and second, a special UAV insurance had to be granted. At this point it was also decided to use a smaller area of a UAV flight range at Andøya, previously dedicated to the ARR Cryowing UAS. Selecting this site would facilitate the flight permit application, but would consequently imply that all future flight testing would take place on Andøya, at the specified range. This implication further lead to the author's decision to stay and work at Andøya for the larger part of the thesis.

NAROM donated the necessary funding for the UAS, but required several restrictions and guidelines for the project. Even what was regarded an "inexpensive UAS" had to be investigated and approved. Preliminary research concluded with a budget of NOK 26,000, and this budget was then approved by NAROM[6]. The author then worked out the complete plans for

[5] Luftfartstilsynet home page: `http://www.luftfartstilsynet.no`

[6] Budget included in appendix B.

Figure 2.3: *Examining the SUMO UAVs at Geofysisk institutt (Geophysical institute), during the study tour to UiB.*

the NAROM UAS, also wording the problem description for the thesis.

Much of the first 1-2 months were spent on practical matters, including meetings at the ARR, at NORUT in Tromsø, working out the budget, investigating UAV regulations, writing the flight application, and acquiring the UAV insurance. As a consequence of this activity, staying and working at ARR provided unique experiences and insight into actual project planning, as well as into a prospective employment situation.

Chapter 3

Introduction to UAV

This chapter introduces the field of Unmanned Aerial Vehicles (UAVs) with its definitions and various concepts. The first section presents the formal UAV definition, with the following section examining various UAV classifications in use. Section 3.3 briefly reviews the history of UAVs, and section 3.4 explores the benefits of employing unmanned aircrafts. The last section of this chapter outlines the future of UAVs.

3.1 Definition of UAVs

The term UAV describes the aerial vehicle including its navigational system and payload. While UAV only covers the airborne part, UAS, -an acronym for Unmanned Aircraft System, describes the overall system, including ground-station and ancillary systems. A formal definition describes UAVs as "*powered aerial vehicles sustained in flight by aerodynamic lift over their flight path and guided without an onboard crew*"[15].

Following this definition UAVs may be either autonomous, or remotely piloted. In the latter case they are often referred to as Remotely Piloted Vehicles, or RPVs. It is also common to categorize UAVs by their level of autonomy. Autonomous vehicles are generally defined as vehicles capable of intelligent motion in unstructured environments without continuous human guidance. In the context of aerial vehicles this typically corresponds to the ability of controlling and navigating the vehicle through a three-dimensional flight path.

One commonly presented misconception by media is the description of autonomous UAVs as drones[31]. However, drones are large but simple remote controlled airplanes that are employed by the military as targets for gun-exercises and radar training, and should not be confused with UAVs.

3.2 Categories of UAVs

Today there exist a wide variety of UAV designs and configurations. Some UAVs have a mass of only a few grams, while others are large airplanes capable of mid-air refueling and virtually unlimited operation[21]. It may not always be easy or even possible to clearly separate the boundaries between different UAV categories. However, from the aspect of control engineering, a useful approach is to categorize UAVs by their level of autonomy. It is important to note that the UAV terminology is still a subject of much discussion, and this section should be seen as a general outline.

3.2.1 Non-autonomous UAVs

RC

At one side of the scale we find Remote Controlled (RC) airplanes that offer no built-in control or navigation, and that are completely dependent on continuous input from the operator. The safety code of the American Academy of Model Aeronautics states that model aircrafts may not exceed a take-off weight of 55 pounds including fuel (25 kg), and must be flown within continuous visual contact[1], and may not fly higher than 400 feet above ground level (AGL)[39].

The main section of the AMA safety code has also shaped RC aviation laws abroad. Within Norway it is the Norwegian Air Sports Federation that regulates RC flying. The Norwegian regulations further adds that RC planes must under no circumstances exceed a range of 2 km from the pilot, and that RC flying is entirely regarded a recreational hobby[34], ruling out commercial use.

RPV

The term RPV is sometimes reserved for larger and more complex non-autonomous or semi-autonomous UAVs. Usually equipped with powerful radiolinks and onboard cameras and instruments these vehicles may be piloted far beyond the visual line of sight (VLOS). Even though one could argue that an RC airplane is also a RPV, -or vice versa, it may be useful to only apply this designation to non-autonomous UAVs intended for professional use, in contrast to RC planes intended for recreational use.

[1] Visual contact without visual enhancements other than corrective lenses prescribed for the pilot

FPV

Making UAV classification even more troublesome, a new class of RC airplanes sharing similarities to RPVs has emerged. Named First Person View or FPVs, these are non-autonomous RC airplanes equipped with a videolink, enabling the pilot to fly beyond VLOS relying on the live video-feed. Unlike RPVs, FPVs are used by hobbyists and may have a range of several kilometers.

In Norway and most other western countries FPVs are not permitted to fly beyond VLOS, as they are regulated as RC planes[31]. Nevertheless, many users choose to operate their FPVs in an illegal manner, representing a growing challenge for the national aviation federations and air traffic control.

3.2.2 Semi-Autonomous UAVs

A great number of UAVs combine remote control with computerized control, enabling the aircraft to maintain its position, bearing and speed on its own. Assisted flight control can also prevent risky situations arising from stalls, spins, high-g maneuvers[2] or critical winds through improved handling.

Although these UAVs may be able to sustain control, they are generally unable of performing path-planning or navigation on their own, making them dependent on human control. Because their flight-system only assists the human pilot, this category of UAVs is referred to as semi-autonomous.

3.2.3 Autonomous UAVs

The vast majority of UAVs are remotely piloted during take-off and landing due to the increased complexity and risks associated with automating these tasks. Path planning and obstruction avoidance is in most cases considered too risky because the aircraft may potentially interfere with other airspace traffic. Moreover, only state-of-the-art UAVs feature situational awareness and vision-based sense-and-act systems[21], and still at a technological level far inferior to human pilots.

A strict interpretation of the UAV definition from section 3.1 would categorize almost all existing UAVs as non-autonomous. A more reasonable and common approach would be to define UAVs capable of flight-path navigation as autonomous. This definition of will also be used for this thesis.

[2] In a high-g maneuver the aircraft accelerates sharply, exposing the airframe to increased stress.

3.3 History of UAVs

This section gives a brief historic introduction with a special focus on meteorological research.

3.3.1 Military Use

The history of unmanned flight began in 1915 when Nikolai Tesla envisioned how a fleet of armed pilotless aircrafts could be used to defend the United States against enemy attacks. Just a year later, the American Archibald M. Low constructed an aerial target for military use[16], and in 1919 Elmer Sperry[3] caught the attention of the US military when sinking a captured German battleship by a pilotless aircraft.

The first unmanned airplanes were however crude and often limited in control following take-off. For the most part they saw use as flying bombs or military target drones, and the term UAV was not invented until much later[31]. The defense industry has traditionally lead the way, spear-headed by the United States, and later joined by Israel.

3.3.2 Civilian Use

Civilian use did not become widespread until the 1980s when compact gyro-stabilized platforms became available on the civilian market. RC enthusiasts had previously attempted to make autopilot-assisted airplanes but with varying success[17]. The real revolution started when GPS receivers showed up on the market in the 1990s, enabling navigational systems to be built and implemented into smaller UAVs.

3.3.3 Weather Research

A group that caught early interest in UAVs was weather researchers. Despite the relatively low cost of the actual weather balloon, the logistics related to covering large areas on a regular basis are often high[17]. Utilizing recoverable UAVs with onboard radiosondes was seen as a way to dramatically cut costs when remote controlled airplanes for meteorological measurements was proposed in the early 1970s. However, only very limited success was accomplished, much owing to the lack of compact and lightweight meteorological sensors.

[3]Elmer Sperry was also the co-inventor of the gyrocompass

As smaller sensors and GPS modules eventually made the market, the effort to create unmanned airplanes with meteorological sensors resurged. Today researchers in several countries have developed UAV platforms for meteorological measurements, each with their unique design characteristics. Additional advantages of employing UAVs over weather balloons is the ability to perform measurements in horizontal layers, as well as in remote areas with minimal infrastructure[43].

3.3.4 Weather Research: SUMO

One such system for atmospheric profiling of the lower troposphere is the Norwegian UAS named SUMO, belonging to Geofysisk institutt (Geophysical Institute) at the University of Bergen. SUMO, an acronym for Small Unmanned Meteorological Observer, has been developed as a mobile and cost-efficient platform for determining the vertical distribution of humidity, temperature, wind speed and wind direction within the Atmospheric Boundary Layer (ABL)[19]. Operating as a "recoverable radiosonde", SUMO is based on a commercially available RC plane fitted with a meteorological sensors, telemetry, and an autopilot system. Figure 3.1 shows the SUMO UAS during a campaign onboard the Norwegian coast guard vessel KV Svalbard, in 2008.

3.4 Benefits of UAVs

In comparison with traditional aviation, the advantages of employing unmanned airplanes are vast. The cost often associated with manned aircrafts can be much lower for UAVs in respect to infrastructure, training, maintenance, and support. By also leaving the pilot out of the picture, unmanned airplanes can stay aloft for extensive time periods, as well as performing operations otherwise too risky for manned flights[31].

These benefits of UAVs enable increased performance in aspects such as range, payload capabilities, fuel consumption, maneuverability, and aerodynamics. Moreover, smaller UAVs do often not require traditional airfields, also allowing for more flexible operations.

3.5 Future of UAVs

The unparalleled benefits of unmanned vehicles have paved way for a massive and growing interest within research, environmental surveillance, and resource management. The calculated global market for UAVs in 2007 alone

Figure 3.1: *The SUMO UAS (Small Unmanned Meteorological Observer) operates as a recoverable radiosonde, and is based on the model airplane "FunJet" by Multiplex. Photo by Marius Jonassen.*

was approximately $5.6 billion in total revenues. According to Visiongain[4] the global market is driven by the defense industry and is expected to exceed $10 billion by 2010, and $15 billion by 2016[47].

Largely depending upon the "*successful integration of UAVs into controlled airspace*"[36], the civilian market is also expected to expand. As these numbers illustrate there is no doubt that UAVs have came to stay. UAVs are presently being developed and deployed all around the world, and has become the fastest emerging sector within the aviation industry[31].

[4]Visiongain is an independent business information provider. Visiongain home page: `http://www.visiongain.com/`

Chapter 4

Requirements Specifications

Some preliminary requirements for the NAROM UAS were stipulated in chapter 2. This chapter presents the subsequently established requirement specifications for the NAROM UAS, including various test scenarios.

4.1 Discussion of the Requirements Specifications

The NAROM UAS consist of mainly three systems:

1. Airplane System
2. Autopilot System
3. Payload System

The following subsections investigate the airplane, autopilot, and payload system in detail. The final system requirements will be presented in the following section, based on this discussion.

4.1.1 Airplane Considerations

Airframe

The central part of the NAROM UAS is the aircraft system, consisting of a fixed-wing airframe equipped with standard RC equipment for controlling the plane. The airplane itself should be stable and simple to fly, enabling NAROM to easily make use of the UAV on their own. A high-winged monoplane[1] with a low Center of Gravity (CG) would serve these needs well. A

[1]Monoplane: Airplane with only one wingset.

delta winged airplane as the one used by the author for the project thesis[46] could also perform well, but may require greater piloting skills, also providing less stability if used as a camera platform.

It is further desirable that the airplane features a pusher propeller. The main reasoning behind this requirement is improved safety in the case of an airplane loss. Secondly, a traditional airplane design with a propeller in the nose section would cause turbulence from the propeller to interfere with meteorological or pressure based airspeed sensors.

Airframe Size

The size of the airplane should not be bigger than that it can be easily accommodated in an ordinary car, in order to facilitate UAS operation. This requirement generally constrains the maximum span of the wing segments to less than 2 m. Moreover, the plane should be small enough to be hand-launched into the air to allow for versatile operations away from ordinary flying fields[2]. This requirement can be met by selecting a plane with a span of less than 3 m, hence airplane size is largely constrained by transport considerations.

Payload Capabilities

As previously established, the NAROM UAV should provide a high level of modularity as to supporting a broad range of payloads, hopefully later to be developed by NAROM. The maximum payload capability supported by the airframe is thus of major importance, measured both in mass as well as in available airframe volume. Maximizing the payload support capability within the size limits as outlined is essential. 150 g has been estimated to be adequate for a smaller payload including its power supply. Also the autopilot system is expected to weigh between 50 and 150 g. As a minimum, the airplane is required to carry 300 g of payload including its autopilot.

Flight Endurance

The range of a UAV depends on its cruising speed and total flight time. Most electric and gas-powered RC airplanes yield a flight time of only 5 to 15 minutes; however, some models intended for FPV flying allow much longer flights. Based on typical FPV performance a flight endurance of 20

[2]Hand-launching airplanes is quite common and fasciliates operation by only requiring a relatively flat landing spot. The ARR Cryowing UAS in contrast requires a large catapult vehicle.

minutes should be expected, but a longer flight endurance would also be highly desirable. Due to operational limitations set by Luftfartstilsynet, the maximum operational range of the UAV is expected to subordinate the maximum flight time. Therefore the cruising speed will not be essential for the NAROM UAS as long as the specified endurance requirement is met.

Airplane Components

Selecting standard RC components facilitates construction by enabling a huge selection of low-cost parts to be used. Another important aspect is the easy access to replacement and upgrade parts, avoiding compatibility issues. As for the propulsion system, electric motorization is regarded highly desirable. Brushless electric motors in combination with Lithium Polymer (LiPo) batteries have in recent years revolutionized the RC hobby with their superior power-to-weight ratio. This technology offers a cleaner and simpler alternative to gas engines, also minimizing engine vibrations and noise.

A drawback of electric propulsion to gas motors is the increased electromagnetic noise produced by the electronic speed controller (ESC) and motor. This issue was experienced in the project thesis[46], and was then solved by moving the sensors mounted in the airplane further away from the ESC. As the NAROM UAV will be considerably larger and more spacious electromagnetic noise is not expected to be a challenge, but is in any case a factor that must be considered. Nevertheless, the benefits of employing an electric motor is considered to greatly outweigh the drawbacks, making this combination an easy choice.

Also belonging to the airplane part is the RC transmitter and receiver, with the latter being operated by an experienced pilot on ground. The pilot is needed for monitoring the UAV during autonomous flight, as well as taking manual control if a critical situation arises.

4.1.2 Autopilot Considerations

The second major component of the NAROM UAS will be the autopilot system, truly transforming the RC airplane into an autonomous UAV.

Functionality

An autopilot enables missions to be safely carried out beyond VLOS without continuous human assistance. The autopilot for the NAROM UAS shall provide capability for autonomous attitude control and navigation. Take-offs and landings may however be performed manually by using a standard

RC transmitter. This is currently regarded the safest and easiest way to launch UAVs, but does require functionality for transferring control between manual and autopilot. Such functionality is any case essential for handling critical situations that may arise during flight, and must be regarded an absolute requirement.

Telemetry

A unidirectional telemetry link is desirable for receiving in-flight data, while a bidirectional link may enable in-flight commanding. A bidirectional link will however be required for the NAROM UAS due to the necessity of enabling the UAV to return immediately to base in case of an emergency. This is regarded an important safety element for UAVs operating behind VLOS. Bidirectional telemetry may also be used for altering the pre-programmed flight plan or tuning the autopilot control-loop in-flight.

The range of the telemetry link shall as a minimum cover flights within VLOS. This requirement corresponds to an estimated minimum range of 500 m, depending on airframe size and visibility. Longer range is highly desirable, and will be needed for flights outside VLOS. Transmitters, receivers and antennas shall be selected in order to maximize the practical range of the system while complying with the Norwegian broadcasting laws[40][41].

Ground Control Station

Onboard sensors will be needed for determining the current position, speed, heading, and attitude of the UAV. As a safety-measurement, this information should at all times be made available for the operator on ground. A Graphical User Interface (GUI) of this real-time flight data is preferable because it makes data easily accessible and comprehensible, improving safety. Such software can be run on a dedicated laptop, and this application is often referred to as a Ground Control Station (GCS).

Mission Planning

Software for performing mission planning prior to flight is also a key functionality needed in the autopilot system. Mission planning must as a minimum include functionality for waypoint planning (setting latitude, longitude, and altitude). Functionality for reprogramming the fligh-plan while in-flight (beyond transmitting "Return to Base" commands) is desirable but not an absolute requirement.

Flight Logging

Either the autopilot or GCS must include functionality for storing flight-data. Flight-logging may be helpful during troubleshooting, especially in the unfortunate case of a total flight loss. As a minimum requirement, the flight log must include GPS-data for at least 60 minutes of operation. Logging of other key-data such as flight commands, sensor readings and telemetry is desirable, but not required.

Flight Controls

Autopilot compatibility with standard RC electronics is a requirement. I.e. the autopilot must be able to read pulse width modulated signals (PWM) from the RC receiver[3] and output PWM signals to the ESC and servos. Mostly all RC airplanes employ four channels for flight controls[4], and this should also be regarded a minimum requirement for the NAROM UAV. Figure 4.1 illustrates the aircraft control surfaces of a standard airplane, along with its axes of motion.

Ease of Use

Although programming, configuring, installing and tuning the autopilot is expected to be challenging, it is essential and required that the autopilot is relatively user-friendly and easy to maintain for NAROM. This involves easy autopilot connection, setup and programming, comprehensible mission planning and GCS software, as well as easy access to online support. These details are too often left out in development projects, but are highly important as the UAS is developed for future use by NAROM.

Size and Weight

The autopilot including sensors, telemetry components, antennas, cables and power supply is required to not exceed a maximum mass of 150 g. This should provide for the majority of the payload capability to be used for the scientific payload. It is however hard to specify a physical size limit of the autopilot hardware, as it will likely consist of several distributed units.

[3]RC PWM signals typically repeat every 20 ms (50 Hz frequency), emitting a pulse ranging from 1 and 2 ms in the extremes. For further details on PWM signals for servo control see Avayan's Roboticus Projecteria: `http://robot.avayanex.com/?p=48`.

[4]These channels are usually assigned the following way: Ch1: Aileron, Ch2: Elevator, Ch3: Throttle and Ch4: Rudder

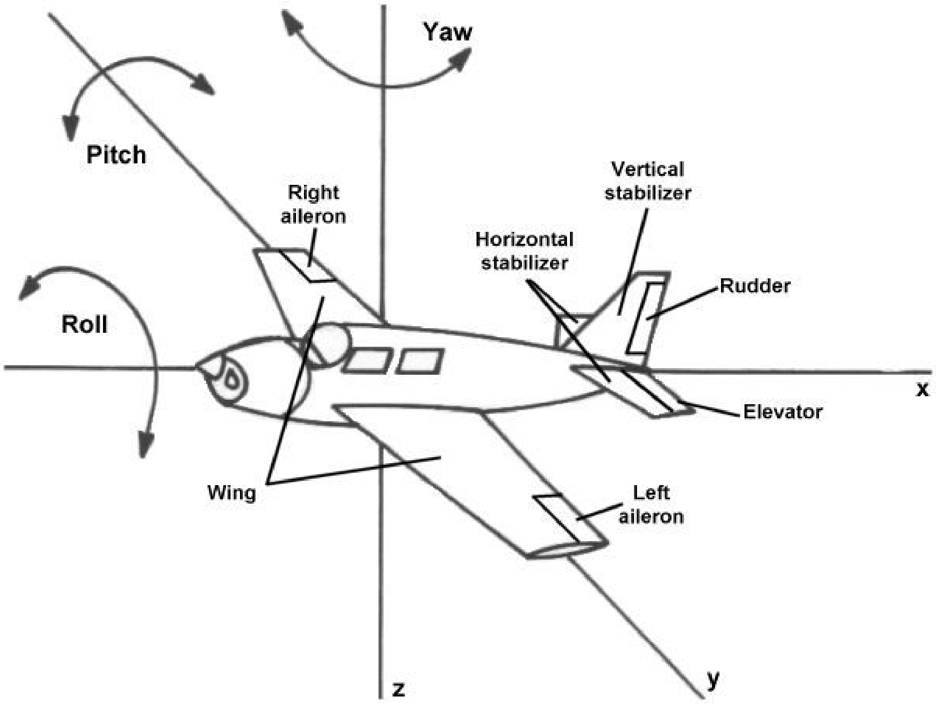


Figure 4.1: *Aircraft control surfaces and axes of motion. Image reproduced by permission from* `http://www.aerospaceweb.org/`.

Nevertheless, selecting a small and compact autopilot system is of utter importance, making this an important selection criteria.

4.1.3 Payload Considerations

The third and last component of the NAROM UAS is the payload system, consisting of adherent sensors, processing capabilities, power source, and downlink capability. Selecting a payload to fulfill the NAROM and master thesis requirements proved challenging and time-consuming. This subsection presents the considerations and discussion of the payload, leading up to the requirements specifications.

Payload Categories

Some of the payloads identified and considered for the NAROM UAS are listed below:

- Airborne AIS (Automatic Identification System) transceiver to extend the identification and tracking range of vessels along the nearby coast.
- Optical or infrared (IR) camera for earth observation, surveillance, or search and rescue operations.
- Aerometry sensors for aerial mapping of (ash) particles, pollution, e.g.
- Meteorological sensors for weather-research.

Although only one payload would be selected for the initial development, the author hopes NAROM will pursue other payloads for Arctic EO and other future UAS courses.

Payload Selection

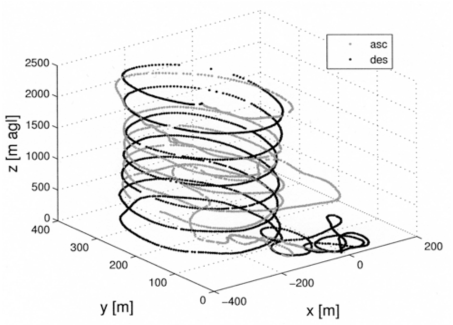
All of the suggestions above represent meaningful and interesting payloads that are anticipated to fit the outlined airframe. As mentioned in the introduction, the main selection criteria should largely depend on the expected scientific output. This criteria is expected to rule out the AIS and camera proposal as unsatisfactory.

Learning of UAVs as an important tool in weather research during the visit at UiB, lead to the selection of a meteorological payload. Meteorological payloads may also be constructed light and compact, an additional advantage when the payload is required to fit inside a small experimental UAV.

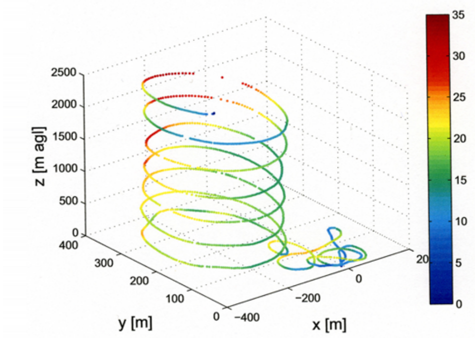
Payload Instrumentation

With SUMO, wind profiles are created during automated ascent and descent along a pre-programmed helical flight path[19]. Wind induced drift influences the UAV groundspeed (as based on GPS-data), warping the flight path. A wind profile based on the recorded flight path can then be derived indirectly. When combined with pressure, temperature and humidity data a full atmospheric profile can be reproduced.

The flight path in figure 4.2 illustrates the altitude range typically needed for atmospheric wind profiling. Because the planetary surface influences the lower atmosphere by causing rapid fluctuations and strong vertical mixing it is necessary to exceed the ABL[37], requiring relatively high altitudes. In the example of the Icelandic FLOHOF campaign[19] SUMO reached altitudes of $2,5$ km. Obtaining a flight permit for this kind of altitude with a newly developed UAS within the short timeframe of a master thesis is moreover considered unlikely.



(a) *Example of a typical flight pattern during atmospheric profiling.*



(b) *As in figure 4.2(a), but only showing descent. Colors indicate the ground speed given in* m/s

Figure 4.2: *Atmospheric profiling from the SUMO UAS during the 2007 FLOHOF campaign on Iceland[19].*

Based on these findings it was decided to focus on pressure, temperature and humidity measurements, enabling the NAROM UAV to perform horizontal atmospheric surveys. Similar strategies for deriving wind profiles may nevertheless be employed by NAROM at a later stage, but will in any case be outside the scope of this master thesis.

Payload Telemetry

To provide spatial and temporal data the meteorological sensors must be linked to a GPS receiver. Measurement data must be stored either locally in the UAV or at the ground station employing a telemetry downlink. Based on a minimum sensor sampling frequency of 1 Hz, a minimum 60 minutes of flight data must be collectable per flight. A downlink is however prefered as it enables data to be reviewed and verified upon mission start, also securing data in the unfortunate event of loosing the UAV.

4.2 Establishing the Requirements Specifications

The requirements specifications for the NAROM UAS is based on the discussion and findings from section 4.1. This section presents the separate requirements for the airplane, autopilot and payload system. Note that the words *"shall"* or *"shall not"* define an absolute requirement. The word *"should"* indicates a desirable property, although there may exist other valid reasons to ignore this item in particular circumstances. The word *"may"* indicates an optional property.

4.2.1 Airplane Requirements

(a) The airplane *shall* be a fixed wing monoplane

(b) The airplane *should* be a high-winged airframe for improved stability

(c) Maximum span of the wing segments *shall not* exceed 2 m

(d) The airplane *shall* accommodate a payload of minimum 300 g

(e) The airplane *should* feature a pusher propeller

(f) The airplane *shall* be able to operate away from ordinary flying fields

(g) The airplane *should* accommodate hand-launching

(h) The airplane *shall not* require a catapult launcher

(i) The airplane *shall* provide a flight endurance of minimum 20 minutes

(j) Airplane control components *shall* consist of standard RC parts

(k) The airplane *should* feature full 4 channel control (aileron, elevator, throttle and rudder)

(l) Airplane propulsion *should* be electric

(m) Available payload volume *shall* be an important selection factor

(n) The cost of the airplane system *shall not* be a selection factor as long as the approved budget is not surpassed

(o) Delivery time *may* be a selection factor

4.2.2 Autopilot Requirements

(a) The NAROM UAV *shall* employ an autonomous autopilot

(b) Take-offs and landings *may* however be performed manually

(c) The autopilot *shall* control a minimum four functions/channels; aileron, elevator, throttle, and rudder

(d) Total mass of the payload *shall not* exceed 150 g

(e) Physical size of the complete autopilot system *should* be an important selection factor

(f) The cost of the total autopilot system *shall not* be a selection factor as long as the approved budget is not surpassed

(g) The autopilot *shall* provide attitude control and GPS-based navigation of the UAV

(h) Waypoints *shall* include longitude, latitude and altitude coordinates

(i) The UAV *should* be able to hit waypoints within an accuracy of 30 m

(j) The autopilot *should* employ a bidirectional telemetry link

(k) The operator *should* be able to activate and deactivate the autopilot instantly

(l) The operator *shall* be able to transmit "Return to Base" commands that the autopilot executes immediately

(m) Telemetry of flight data *should* include (but is not restricted to) the current heading, speed, position and attitude of the UAV

(n) Flight data *may* be presented to the operator in real-time

(o) Flight data *may* be presented in a GUI

(p) Software for performing mission planning prior to flight *shall* be available

(q) The operator *should* have the ability to alter the flight plan during flight

(r) The operator *may* alter autopilot tuning parameters during flight

(s) Either the autopilot or GCS *shall* log flight data for a minimum of 60 minutes

(t) The flight log *shall* include GPS data as a minimum

(u) Logging of other data such as flight commands, sensor readings, telemetry signals and battery voltage *should* be possible

(v) The autopilot *shall* be compatible with standard RC components

(w) User-friendliness *should* be a selection requirement[5]

(x) Comprehensible online support as well as a large user group *may* be important selection factors

4.2.3 Payload Requirements

(a) The NAROM UAV *shall* employ a meteorology payload

(b) This payload *shall* collect pressure, temperature and humidity data

(c) The payload *shall* further provide temporal and spatial relation of data collected

(d) Payload sampling rate *should* be at 1 Hz or more

[5] User-friendliness as to the end-user!

(e) Measurement errors *should* be limited to less than 2% of actual values

(f) Total mass of the payload *should not* exceed 150 g

(g) Data *may* be stored locally in the airplane during flight

(h) Collected data *should* be transmitted to a ground station during flight

(i) Minimum 60 minutes of flight data *shall* be recordable per flight

(j) Meteorology data from the complete flight *shall* be downloadable to a PC for review and analysis after flight

(k) The cost of the payload system *shall not* be a selection factor as long as the approved budget is not surpassed

Chapter 5

UAS Equipment Selection

Selecting the equipment and technology to fulfill the requirements specifications proved both challenging and time-consuming. Throughout the project a total of 19 orders were placed at 10 different suppliers, both in Norway and abroad. Combined, this series of interlaced purchases made up the complete NAROM UAS, putting the total hardware cost to NOK 15,044.

In studying this chapter the reader should find that it contains much more than just a listing of products or specifications. This chapter intends to demonstrate the thorough planning behind the complete system. Moreover, -and perhaps more importantly, it should substantiate and explain the many decisions and choices made en route.

In many cases these decisions would prove decisive for the performance and limitations of the NAROM UAS, further requiring a deeper understanding of the underlying technology. This is especially true for selecting the autopilot and telemetry system. Although cumbersome, this effort proved highly rewarding while also ensuring a solid result.

This chapter is similarly organized to the previous chapter. The first section discusses the airplane system, section 5.2 reviews the autopilot system, and section 5.3 examines the payload system.

5.1 Airplane System

5.1.1 Airframe

Selecting the right airframe would be vital in reaching the projected goals because it will also serve as a platform for the whole NAROM UAS. The requirements specifications (as specified in chapter 4.2.1) are summarized below, serving as a general selection guideline:

- Stable design
- Ability to carry extra weight
- Roomy fuselage
- Ability to operate away from flying fields
- Flight endurance

A large number of RC airframes were examined for the NAROM UAV, most of which were intended for FPV RC flying. The top three final candidates were the Multiplex Easy Star, the HobbyKing EPP FPV, and the Xen Skywalker EPO airplane, all high-winged monoplanes with a wing span of less than 2 m. All three airframes feature electric motor drive with a pusher propeller, accommodate hand-launching, are designed for standard RC components, and priced at less than $100 (airframe price only).

Model Name:	**Easy Star**	**EPP FPV**	**Skywalker EPO**
Manufacturer:	Multiplex	HobbyKing	Xen
Wing Span:	1370 mm	1800 mm	1680 mm
Weight:	680 g	800 – 1000 g	800 – 900 g
Payload Weight:	300 g	500 g	500 g
Payload Volume:	Small	Large	Very large
Battery Size:	3s, 2100 mAh	4s, 5000 mAh	4s, 5000 mAh
Flight Endurance:	20 minutes	45 minutes	45 minutes

Table 5.1: *Airplane mass budget.*

The specifications in table 5.1 were collected from the Multiplex[2], HobbyKing[10] and BevRC home page[12], with the three candidates shown in figure 5.1, 5.2, and 5.3. Note that data on payload weight, volume and flight endurance are only estimates, based on an extensive compilation of online discussions, photos, and user reviews. Actual values depend on factors such as motor choice, propeller and battery selection, airframe construction, and flying conditions. These general specifications were nevertheless useful in selecting the right airframe.

Easy Star is a well-known and versatile airframe, although it lacks in payload capacity and flight endurance as when compared to the other candidates. The shorter wing span also leaves the airplane more susceptible to wind, and the airplane additionally offers only 3 control channels: elevator, rudder and throttle. As the NAROM UAV should be based on a fully functional airplane, this is considered a shortcoming. Although this airframe is often

Figure 5.1: *Multiplex Easy Star RC airplane. Image from the MultiPlex home page.*

Figure 5.2: *HobbyKing EPP FPV RC airplane. Image from the HobbyKing home page:* `http://www.hobbyking.com/`

Figure 5.3: *Xen Skywalker EPO RC airplane. Image from the BevRC home page:* `http://www.bevrc.com/`

recommended for FPV and UAVs, the author concluded it to be better suited for smaller and simpler UAV projects.

Skywalker EPO and FPV EPP share many specifications, and are both excellent candidates. Performance wise they are expected to be about equal; however, judging from photos the FPV EPP appears to have more fragile tail construction. As neither airframe will be equipped with an undercarriage, the Skywalker EPO with its T-shaped tail seems more robust and better suited for landings in rough and undulating terrain. Requirement 4.2.1(f) specifies that the UAV shall be able to operate away from ordinary flying fields, and the Skywalker EPO is assumed to be more agile under these conditions.

The payload capability of both airframes is expected to satisfy the requirements, although the Skywalker EPO seems to offers the largest payload volume. Figure 5.4 illustrates the amount of available payload volume in the Skywalker airframe, also picturing its main parts. This airplane is produced in a highly durable and forgivable EPO foam[1], with figure 5.5 illustrating the remarkable and favorable properties of this material. Delivery time is expected to be about the same for both EPO and FPV EPP as they are both offered through Chinese webshops.

[1] EPO: Expanded PolyOlefin foam.

Based on these findings the Skywalker EPO airframe was selected for the NAROM UAS airplane platform and ordered through FPVhobby[2], along with a second replacement airframe.

Figure 5.4: *Skywalker EPO airframe and parts. The available payload volume equals the size of* 1.5 l *bottle. Photo from the "Modellflynytt" web-page:* `http://tinyurl.com/68c5ff9`.

5.1.2 Motorization

Motor

Once the airframe was selected an electric motor could be purchased for the NAROM UAV. The motor chosen for the Skywalker EPO airframe was the AX2814, a brushless outrunner motor customized for this airplane. Unlike "conventional" DC motors, the relationship between the coils and magnets is reversed on outrunners, a term referring to the physical motor configuration[3]. This motor technology typically provides higher torque at low RPMs, which may be favorable for low-speed cruise.

The AX2814 motor offers a K_v rating of 980, a power efficiency of 85%, and a motor thrust of 150 N when using a 4 cell LiPo battery with a 9x4.5 sized propeller. The K_v value indicates the unloaded motor velocity in RPM per volt, and the motor RPM is easily calculated using equation 5.1.

[2] FPVhobby webshop: `http://www.fpvhobby.com/`

[3] Outrunners have stator coils forming the center core of the motor, with the permanent magnets spinning the motor core.

$$RPM = K_v \times U \tag{5.1}$$

In this equation U indicates the peak voltage as measured on the wires connected to the motor coils. Using the 980 K_v motor the unloaded motor speed will exceed 16,400 RPM when supplied by a standard 4 cell (16.8 V) LiPo battery. Based on 150 N of thrust, the AX2814 motor provides a thrust-to-weight ratio at between 0.75 and 1.00[4], rendering steep climbs and flights in heavy winds possible. Motor specifications can be found on `http://www.bevrc.com/ax2814-special-customed-for-skywalker-p-205.html`, and a photo of this motor is shown in figure 5.6.

Electronic Speed Controller (ESC)

The AX2814 motor requires an electronic speed controller (ESC) that can supply up to 45 A of continuous current. The AX 45A brushless ESC is rated for 2-6 cell LiPo batteries (7.4 to 22.2 V), tolerates bursts up to 55 A, and 45 A continuous current. In addition to supplying current to the motor, the AX 45A features a switch mode Battery Elimination Circuit (BEC) for diverting power directly to the servos, eliminating the need for a separate battery. This BEC can supply 3 A at 5 V, providing all the power needed for the servos. The AX 45A ESC is shown in figure 5.6, and was purchased from the BevRC webshop along with the AX2814 motor. This picture also shows the ferrite core on the top cord, suppressing electromagnetic noise from the ESC.

5.1.3 Battery Power

Battery

To maximize flight endurance a LiPo battery was chosen for the NAROM UAV. LiPo battery technology offers nearly twice the energy density[5] of NiCad and NiMH[6] battery packs, and maintains its voltage during high loads[45][42]. The flight battery was selected on basis of providing the highest possible capacity, while also fitting the frontal section of the Skywalker EPO. A four cell 16.8 V 5000 mAh Kong Power battery from Elefun[7] seemed to be a perfect match, and this battery is depicted in figure 5.8.

[4] Calculated thrust-to-weight ratio based on an expected airplane mass in the range of $1.5 - 2.0$ kg.

[5] Energy density as measured in both Wh/kg and Wh/m^3.

[6] Nickel Cadmium (NiCad) and Nickel Metal Hydride (NiMH) used to be the dominant battery technology in the RC segment.

[7] Elefun webshop: `http://www.elefun.no/`

Figure 5.5: *The EPO foam is extremely forgivable and can retain its former shape even after heavy strains. This picture displays an actual Skywalker EPO wing section. Photo from the RC group web-page:* `http://tinyurl.com/6zo6sf5`.

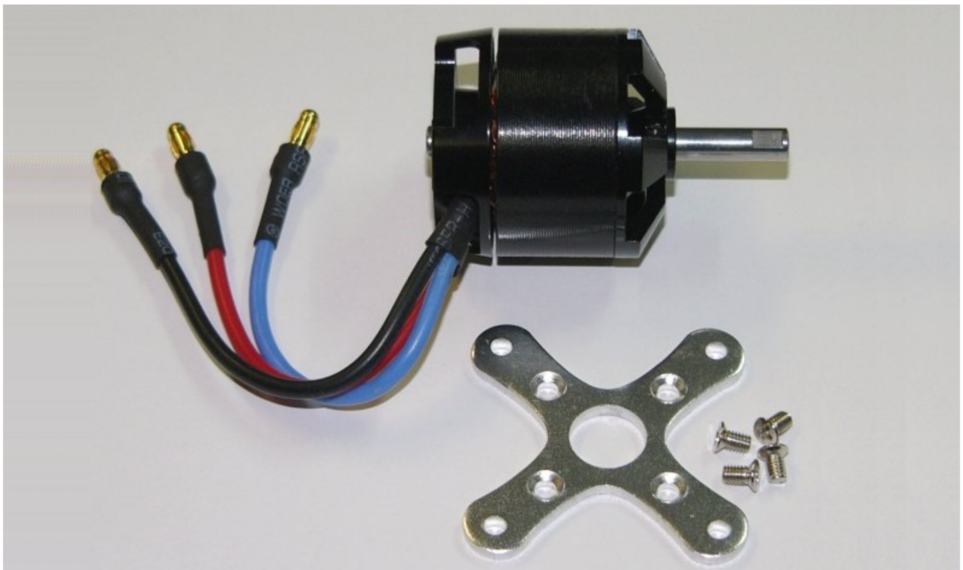


Figure 5.6: *The brushless AX2814 motor selected for the Skywalker EPO. Motor bracket shown in the foreground. Image from BevRC.*

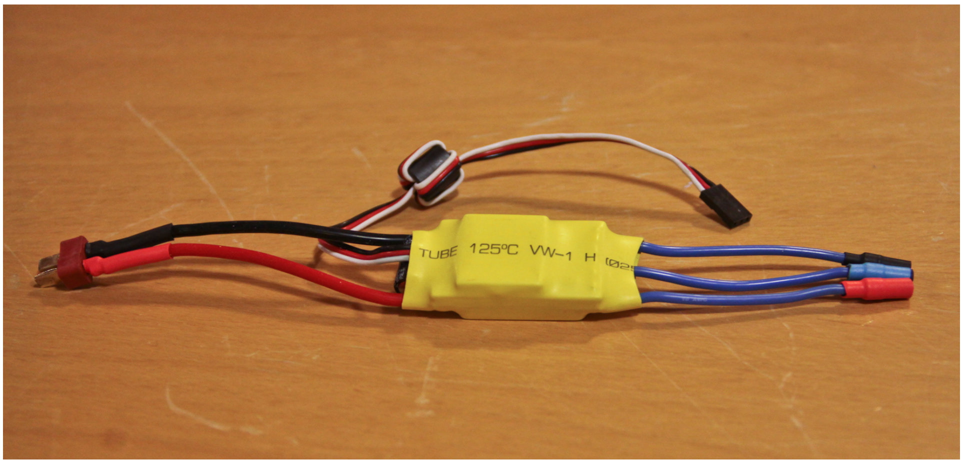


Figure 5.7: *The AX 45A ESC selected for the AX2814 motor. The battery connectors are shown to the left, and the motor connectors to the right. The cord on the top connects to the RC receiver.*

Figure 5.8: *Kong Power battery for the NAROM UAV. Power is supplied through the thicker wires while the white connector is used for balancing the battery cells during charge.*

Battery Specification:	Value:
Cell number:	4 cells, in series
Nominal Voltage:	16.8 V (3.7 V per cell)
Capacity:	5000 mAh
Max. Continuous:	26 C (130 A)
Max. Bursts:	45 C (225 A)
Dimensions:	167 × 47 × 35 mm
Weight:	504 g

Table 5.2: *King Power battery specifications.*

Table 5.2 lists the key specifications of the King Power battery, with the letter C indicating the maximum discharge rate as a multiple of the battery capacity. I.e. 26 C corresponds to a maximum continuous discharge rate of 130 A, easily supplying sufficient power.

Battery Charger

LiPo batteries require a special type of charger. The Hyperion EOS 1420i NET3 charger (5.9) from Elefun offers 550 W of charging power, limited to 20 A when charging, and 10 A when discharging. This charger further features a built-in 12 bit balancer circuit that monitors each battery cell, also necessary for achieving safe and optimal charging. Using a USB cable the charger also connects to a computer, enabling battery performance to be monitored and recorded over time.

Power Supply

The Hyperion EOS 1420i NET3 charger requires a DC power supply for operation. A HW-1200R30A switch mode power supply was ordered from SmallSize[8], offering an output peak current of 30 A at 13.8 V and 21 A continuous current[9]. The power supply is pictured in figure 5.10.

[8] Smallsize webshop: `http://www.smallsize.no`

[9] The charger transforms the voltage up or down to the voltage level required for charging.

Figure 5.9: *Hyperion EOS 1420i NET3 LiPo battery charger. Connection boards for balancing LiPo batteries are shown in the right corner.*

Figure 5.10: *HW-1200R30A power supply.*

5.1.4 RC Transmission

RC Transmitter Frequency

Early in the project it became clear that allocation of concurrent frequency bands for the RC transmitter, autopilot and payload link could be challenging. The preferred radio frequency (RF) band for FPV and UAV links is usually the 900 MHz band, as transmissions in this band allows greater outdoor LOS ranges to be achieved using relatively low output power. In the example of the popular XBee PRO 900 RPSMA module, this 50 mW unit promises up to 10 km outdoor LOS range at a serial data rate of 156 Kbps when using high gain antennas[29]. However in Norway and most parts of Europe, the 900 MHz band is already occupied by the GSM network, requiring other bands to be used for the autopilot RF link. The 2.4 GHz band was eventually selected for the autopilot at the expense of the RC transmitter[10].

Although the 35 MHz VHF band[11] was commonly used for RC aircrafts, mostly all RC transmitters of today employ the 2.4 GHz band using spread spectrum technology. This relatively new transmitter technology offers superior interference resistance by greatly improving the signal-to-noise (S/N) ratio, employing frequency-hopping, robust data coding with error checking, as well as bonding the RC receiver to the transmitter with a unique global identifier. Returning to the 35 MHz band would later reveal just how troubled this frequency could be regarding RF interference.

Transmitter and Receiver

Prioritizing the autopilot RF link consequently resulted in the selection of 35 MHz RC transmitters. The requirements for the RC transmitter were otherwise quite simple, only requiring four channels for airplane control, as well as an additional fifth channel for on/off operation of the autopilot. While the first four channels are related to the position of the two sticks, the fifth channel is usually added in the form of a toggle switch.

An old Hitec *Flash 5* transmitter (from personal possession) was used for initial testing, but later found to suffer serious range problems when used with the standard Hitec HFS-05MS single conversion[12] micro receiver. Following the three first test flights, this receiver was replaced by a 6 channel

[10]For more information on selecting the autopilot link, jump to section 5.2.5.
[11]VHF: Very High Frequency. This band ranges from 30 to 300 MHz
[12]Dual conversion receivers offer improved signal through advanced signal processing and noise filtering.

Hitec Electron 6 FM[13] dual conversion receiver. Dual conversion receivers generally offer improved S/N ratio, but due to a continuation of the serious range problems the whole RC system was eventually replaced for the fifth flight.

(a) *The five channel Hitec Flash 5 RC transmitter initially used in the project. The two-position toggle switch for channel five is located on the top left.*

(b) *The seven channel Futaba 7CAP transmitter purchased for the NAROM UAS. The three-position toggle switch is located on the top left.*

Figure 5.11: *The two 35 MHz RC transmitters used for the NAROM UAS.*

A Futaba 7CAP seven channel computer radio was purchased to replace the Hitec Flash 5 radio. The newer transmitter features far more advanced menus and options than the Hitec Flash 5, while at the same time being much more user-friendly as a consequence of increased display size and added cursors. More importantly, the 7CAP features a three-position toggle switch. For most other uses this toggle switch would not be of much importance, but when the transmitter is used in combination with the autopilot[14] it would offer a third extra flight mode to be activated in-flight. This switch was actually the decisive detail in selecting this transmitter. The 7CAP transmitter also includes a full range 7 channel dual conversion FM receiver by Futaba, and fortunately no serious noise issues were experienced after

[13] FM: Frequency Modulation. In contrast to AM (Amplitude Modulation), FM transmitters convey information by shifting the frequency of the carrier signal.

[14] For autopilot selection, jump to chapter 5.2.

this replacement.

Servos

The Skywalker EPO requires a total of four servos for airplane control; two for the ailerons, and one each for the elevator and rudder. Six BEV-ES08MA metal gear servos were purchased from BevRC together with the Skywalker airframe, with the two extra servos kept in spare, as servos tend to wear out over time. The BEV-ES08MA servos were reasonably priced and would fit the servo mounts with no extra modifications. Key specifications for the servos are listed in table 5.3, reproduced from BevRC (`http://www.bevrc.com/beves08ma-p-203.html`). Figure 5.12 depicts the BEV-ES08MA servos.

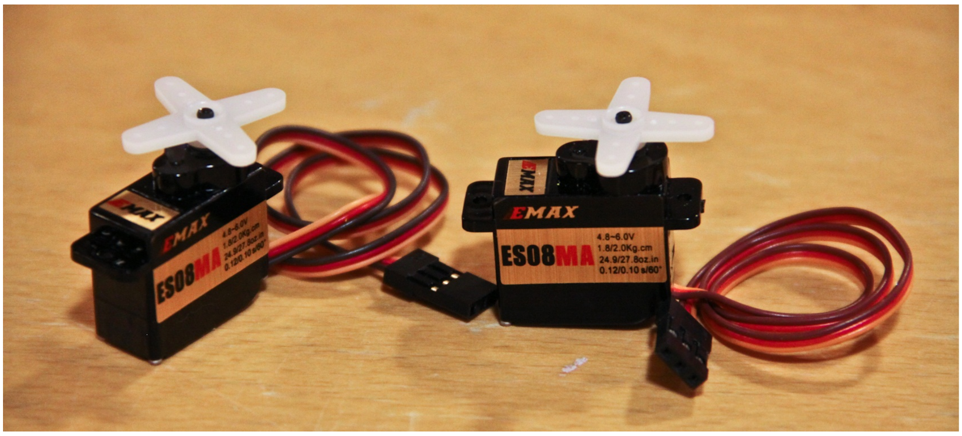


Figure 5.12: *BEV-ES08MA metal gear servos.*

Specification:	BEV-ES08MA
Voltage:	4.8/6.0 V
Torque:	1.8/2.0 kgcm
Speed:	0.12/0.10 s/60°
Weight:	12 g
Size:	32 × 11.5×24 mm

Table 5.3: *BEV-ES08MA servo specifications.*

5.2 Autopilot System

5.2.1 Purchase versus Develop

Although developing an autopilot from scratch would be interesting, rewarding and relevant to the field of control engineering, this approach would likely not be reasonable, practical nor manageable on a project of this size. Especially when combined with the additional aspects of the NAROM UAS. To exemplify, NORUT and ARR have spent four years on developing the Cryowing autopilot. In spite of having a larger team of scientists and technicians, their autopilot is still at a crude and experimental stage.

Achieving an equivalent level of reliability and functionality to existing autopilots is regarded near impossible in this short development time. Another element of major importance is related to code maintainability and user-friendliness, owing to the fact that NAROM is to later take possession of the UAS. Gaining access to an active society of developers should be regarded an important reason to select an open source system. This is especially regarded true with respect to future updates and support, expectedly being highly beneficial for NAROM.

5.2.2 Commercial versus Open Source

The next step would be to choose between an open source or a commercial autopilot system. Commercial autopilots even for smaller UAVs were however found to cost several multitudes of the hardware cost of comparable open source systems. An example of this is the commercial Boomerang UAS by AttoPilot International[15] that is priced at \$19,500[8]. The IMU-based AttoPilot 6DOF AHRS autopilot by itself is priced at \$3,300[8]. Yet another commercial system in this same segment is the Unicorn UAV platform from Procerus Technologies, intended as an "*inexpensive, durable air vehicle for UAV research and development*"[16]. This UAS is shown in figure 5.13, and has an estimated cost of \$12-15,000[11] excluding the laptop and video monitor. The independent cost of the Kestrel 2.4 Autopilot is currently \$5,000[11], although apparently not being any more sophisticated than some open source autopilots reviewed.

It should be further noticed that these commercial systems are based on RC airplanes, comparable to the Skywalker EPO. By contrast, autopilots offering path planning and "see-and-avoid" intelligence for professional use are priced at a substantially higher level, ranging far outside the financial

[15] AttoPilot International home page: `http://www.attopilotinternational.com/`
[16] Procerus Technologies home page: `http://www.procerusuav.com/`

Figure 5.13: *Unicorn UAS from Procerus Technologies. Picture reproduced with permission by Procerus Technologies®. All right reserved. 2011.*

scope of the NAROM UAS. The examples stated above are considered to be at a comparable technical level to that of the NAROM UAS. In contrast, open source autopilots are priced much lower, and usually in the range of $200-800[14].

Aside from the cost issue, another major advantage of open source is that the code is available for making changes in software, such as adding new hardware components or features in software. Having the source code available as a troubleshooting tool is of further advantage. The personal opinion of the author is that the selection of an open source autopilot best serves the needs of NAROM in considering elements such as costs, user support, and adaptability towards future needs. Also of major importance: this author believes that an open source autopilot better serves the academic needs and requirements of the master's thesis, while at the same time profiting NAROM.

5.2.3 Autopilot Candidates

As specified in section 4.2.2 the autopilot must as a minimum employ four channels for autonomous flight control, enabling UAV navigation through a preprogrammed set of waypoints. This will necessarily require sensors for attitude control, as well as a GPS receiver for navigational control. The autopilot must also be able to react on "return to base" and "on/off" commands in real time. The requirements specifications also list absolute requirements related to mission planning and flight logging.

Two of the most popular open source UAV autopilots are the Paparazzi Project and the ArduPilot project. Both systems meet the prescribed requirements specifications and were major candidates for the NAROM UAS. In the end it would be the attitude control technology settling the autopilot selection.

The Paparazzi Project

The Paparazzi Project is an open source hardware and software project that is freely available under the GNU licensing agreement. Paparazzi is intended to be a versatile and powerful autopilot for fixed wing aircrafts and multicopters[17], and is developed by a community of software programmers, university students, and enthusiasts of various backgrounds[18].

Since its inception in 2003, the Paparazzi system has been used on dozens of airframes around the world. In addition to the airborne part, the project

[17] Multicopter: Aircraft lifted and propelled by more than one rotor, usually in a quadcopter configuration.

Figure 5.14: *Principle drawing of the Paparazzi UAS components. Illustration from the Paparazzi main site, reproduced under the GNU agreement.*

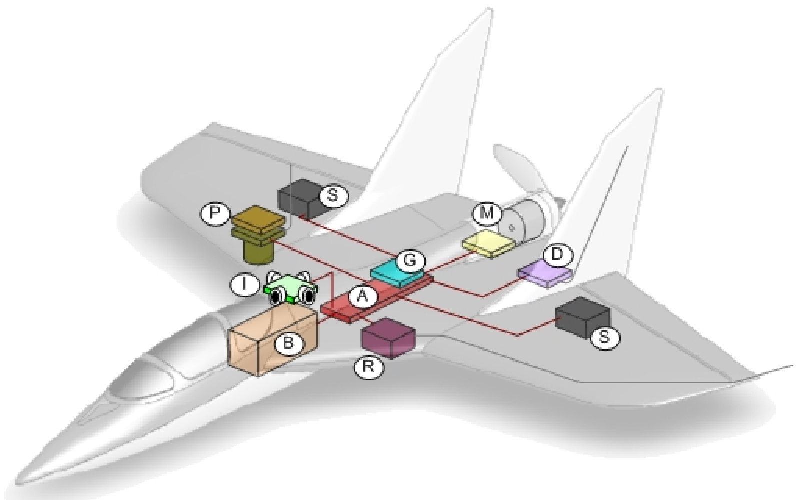


Figure 5.15: *Multiplex Funjet airframe integrated with the Paparazzi autopilot system. This airframe and setup is very similar to that of the SUMO UAS.*
A*: Autopilot,* B*: Battery,* D*: Datalink,* G*: GPS,* I*: IR sensors,* M*: Motor,* R*: RC receiver,* S*: Servos,* P*: Payload. Illustration from the Paparazzi main site, reproduced under the GNU agreement.*

covers an array of ground based software and hardware such as modems, antennas and ground control software. Figure 5.14 presents the Paparazzi UAS including its main components, and figure 5.15 illustrates the Paparazzi system as it is integrated in a Multiplex Funjet airframe.

The Paparazzi autopilot is available in several hardware configurations that are offered by various vendors. The most popular version is presently the Tiny V2.11, offered at a hardware cost of $425 ($600 including telemetry)[18]. This version of the Paparazzi hardware features a 32-bit low-power LPC214 microcontroller clocked at 60 MHz, an integrated GPS receiver and patch antenna (4 Hz update), a 5 V 3 A switching power supply, PWM control and connectors for of up to 8 servos/channels, RC receiver input, connectors for motor control, an SPI bus, I^2C bus, and a USB client. The Tiny V2.11 is based on a two-layer PCB design, measuring 70.8×40 mm, and weighing only 24 g. Figure 5.16 displays a typical Paparazzi setup.

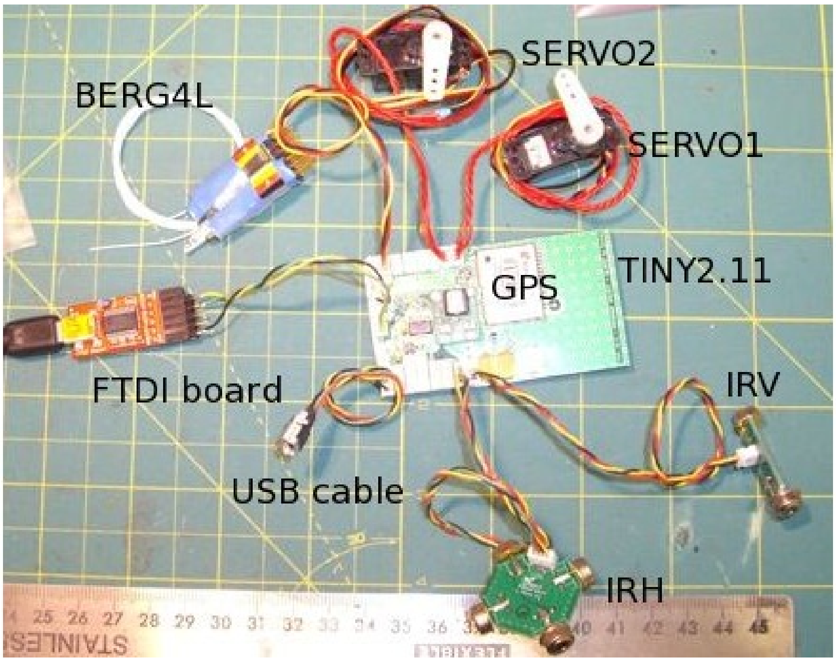
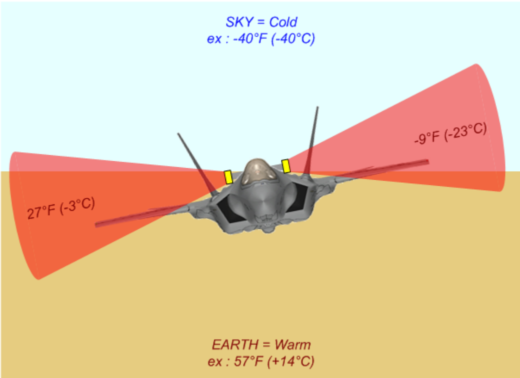


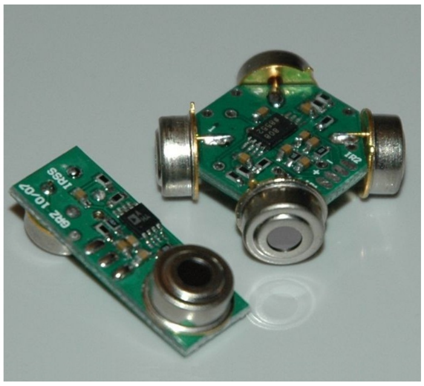
Figure 5.16: *Typical two-servo Paparazzi setup. BERG4L is the RC receiver name. IRH marks the IR sensor for the horizontal plane, and IRV for the vertical plane. Photo from the Paparazzi main site, reproduced under the GNU agreement.*

In keeping cost low the Paparazzi stabilization and navigational guidance system relies on a minimum set of sensors. Position and altitude are obtained using a GPS receiver, while attitude is estimated using a set of

[18]"Getting started with Paparazzi": `http://tinyurl.com/3ufpvjr`



(a) *Illustration of the Paparazzi thermopile attitude control. Roll angles are deducted from the measured temperature differences.*



(b) *Photo of the Paparazzi IRH (horizontal) and IRV (vertical) sensor boards. The IRH board employs four thermopile sensors, and two more are needed for the IRV.*

Figure 5.17: *Illustration of the Paparazzi attitude control system based on the thermopile principle. Pictures from the Paparazzi site, reproduced under the GNU agreement.*

infrared (IR) sensors, referred to as infrared thermopiles. The roll angle is deduced from comparing the temperature difference as measured during roll and pitch angles. In theory, temperature difference should be zero at zero bank, and maximum at 90° roll or pitch angles. In order to determine vertical orientation a third pair of thermopiles is employed along the vertical axes. Figure 5.17 illustrates the ingenious attitude control principle. More information on the Paparazzi project is available at `http://paparazzi.enac.fr/wiki/Main_Page`.

The ArduPilot Project

The second autopilot candidate is the open source software and hardware project ArduPilot Mega; based on the 32-bit Arduino[19] Mega platform[1]. Paparazzi and ArduPilot Mega (from here denoted APM for short) share many similarities, including the UAS system layout illustrated in figure 5.14.

Like the Paparazzi autopilot, APM handles both fixed-wing aircraft and quadcopters, providing autonomous stabilization and GPS-based navigation. The APM project page can be found on `http://diydrones.com/notes/ArduPilot`, and is like Paparazzi developed and supported by a community

[19]Arduino is an open source prototyping platform. Arduino home page: `http://arduino.cc/en/`

of programmers and academia. While the Paparazzi autopilot relies on IR thermopile sensors for attitude control, APM on the other hand employs an Inertial Measurement Unit (IMU), claiming to be the "*most advanced IMU-based open source autopilot available*"[20]. Despite their many similarities, the technology behind the attitude control is the main difference between these autopilots.

As a consequence of the open source philosophy, a wide array of extra software and hardware has been made available for the APM. Advanced features include full mission scripting, bidirectional telemetry with in-flight commanding and parameter setting, on-board video display, several available ground station applications, and full "hardware-in-the-loop" simulation using PC flight simulators. The main specifications for the APM are listed below:

- ATmega 1280 microcontroller clocked at 16 MHz
- Separate fail-safe circuit for transferring control from the autopilot to the RC system
- Built-in fail-safe functionality for return-to-launch upon radio loss
- Ability to reboot the main processor in mid-flight
- 128k flash program memory, 8K SRAM, 4K EEPROM
- Hardware-driven servo control, reducing processor overhead
- Support for 8 RC channels
- Built-in FTDI chip for native USB support
- DIP switch for simple servo reverse
- GPS connection
- 3-axis gyroscope
- 3-axis accelerometers
- Barometric pressure sensor for altitude measurements
- 12 bit ADC for gyroscope, accelerometer and airspeed readings
- Six 10 bit expansion ports for additional analog sensors
- Dual 3.3 V regulator (one dedicated for analog sensors)
- 16MB flash memory data logger
- Relay-switch for cameras or other payloads

[20] ArduPilot Mega introduction: `http://tinyurl.com/3pgauoa`

- Status LEDs and reset button
- Optional I^2C port for magnetometer connection
- Optional port for airspeed sensor
- APM size 40×69 mm
- Weight of processor and IMU board is only 40 g

Figure 5.18 presents the Arduino Mega platform, consisting of the main processor board (figure 5.19) and IMU shield (figure 5.20). The current costs for the processor and IMU boards are $59.95 and $159.95 respectively. The total hardware cost adding telemetry is about $400.

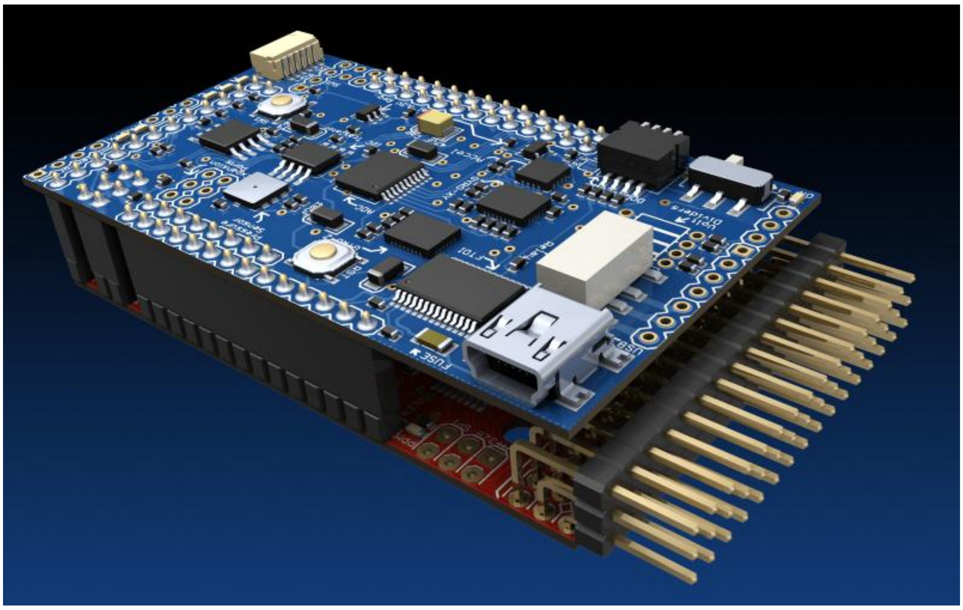


Figure 5.18: *ArduPilot Mega platform, consisting of the processor board with the IMU shield mounted on-top. Illustration reproduced with permission by DIY Drones.*

5.2.4 Autopilot Selection

UiB selected the Paparazzi autopilot system for their SUMO; however they had their UAS purchased and completed by a German company. The visit at UiB was nevertheless useful in getting a first-hand impression of the Paparazzi autopilot, in addition to learning of its strengths and limitations. The author was further able to examine the hardware and its integration into the airframe, as well as reviewing the telemetry equipment, ground control station, and flight simulation software.

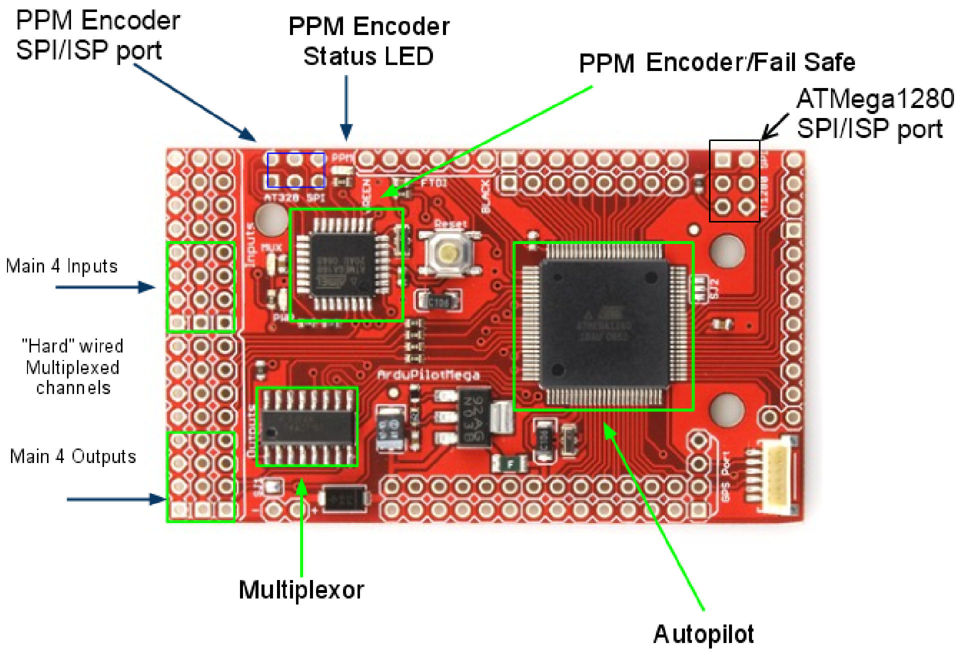


Figure 5.19: *The ArduPilot Mega main board. Photo reproduced with permission by DIY Drones.*

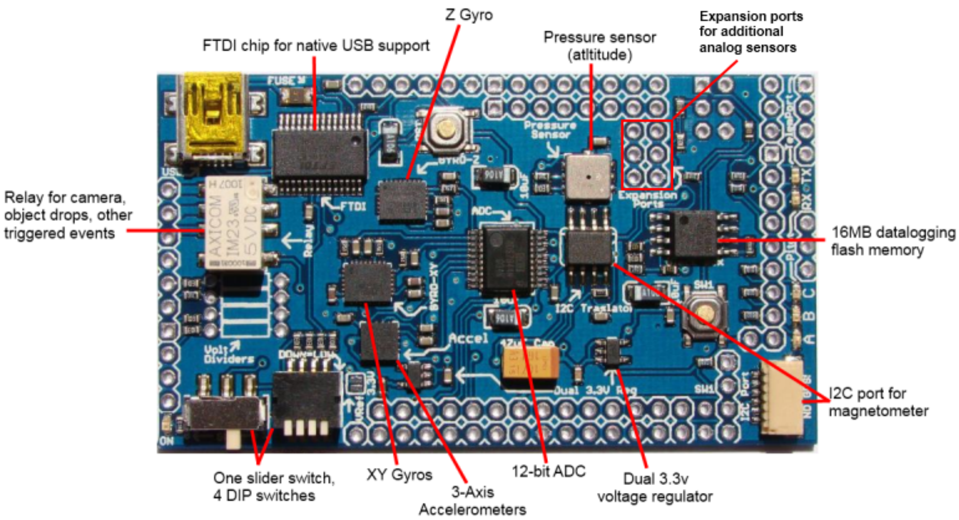


Figure 5.20: *The ArduPilot Mega IMU shield. Photo reproduced with permission by DIY Drones.*

Despite its otherwise attractive aspects, the Paparazzi autopilot seems to have a shortcoming related to its thermopile attitude control. Paparazzi is known to suffer when flying in foggy conditions or passing through clouds because the thermopile sensors may lose track of the horizon, consequently disorienting the UAV[18]. Additionally, Jonassen mentioned that SUMO has experienced problems during conditions when the temperature difference between the sky and ground dropped below 6° Celsius.

The weather conditions at Andøya may sometimes be challenging due to its exposed coastal location in the Norwegian arctic. Although the UAV will mostly fly in good conditions, -and this is especially true under testing, the weather conditions are known to change quickly. Even though SUMO has previously been successfully employed on campaigns in the arctic[21], the author came to the conclusion that an IMU-based autopilot would be a more reliable choice, leading to the selection of the ArduPilot Mega instead.

It is also the opinion of the author that APM seems to employ a more comprehensive safety system than Paparazzi, further supporting the choice. It should however be mentioned that the author is also under the impression that Paparazzi may better suit larger and more complex development projects, such as if employed in a doctoral dissertation. According to the Paparazzi project page there are also several university groups currently working on future IMU-based versions, expectedly to become available in 2011. In any case APM seems the better choice for the NAROM UAV, while also fulfilling the requirements specifications set forth in section 4.2.2.

A larger section was nevertheless devoted to Paparazzi and its thermopile system because selection of APM was largely based on understanding its technology in order to perceive these limitations. These two autopilots share many similarities, -not only of technical character, but also regarding its community of developers and use within academia.

5.2.5 Autopilot Radiolink

Radiolink Frequency

The ArduPilot APM is intended to employ the XBee PRO 900 MHz RF modules[29], largely because of the advantageous range achievable using this frequency band. In this case however, use of the 900 MHz band is not approved and the recommended suggestion is then to employ the 2.4 GHz XBee PRO modules[7]. As previously explained in section 5.1.4, this alternative excludes use of 2.4 GHz spread spectrum RC transmitters to prevent band conflicts.

[21]SUMO has been flown on Iceland in 2007, and Svalbard in 2008[19]

Other RF frequencies for this radiolink were also investigated, among these the 868 MHz and 433 MHz band. The latter is to be used for the payload downlink, but the 868 MHz band seemed promising at first. Despite offering great range (up to 40 km with a dipole antenna[28]), the 868 MHz RF unit is limited to a duty cycle of only 10%, putting the throughput down to only 2.4 Kbps. By comparison, the XBee PRO 900 MHz version offers 156 Kbps[29].

This 10% duty cycle is required by the ETSI European Telecommunication Standard, limiting data to be transmitted for only 6 minutes in a full hour. This link is in other words intended for short bursts, and not continuous data streaming. A "quick and dirty fix" based on rebooting the XBee link every 6 minute has been suggested by some users of the APM community[9] but is not in any case regarded an appropriate solution for the NAROM UAS.

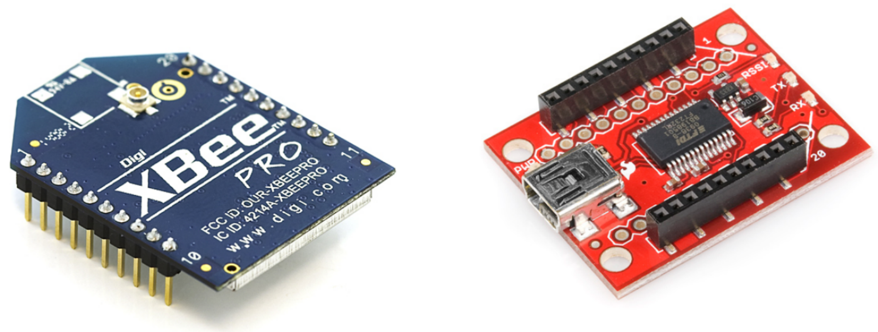
XBee PRO 2.4 GHz

The recommendation of selecting 2.4 GHz XBee PRO modules were followed instead. However, these RF links are exported in an international version where the output transmission power is reduced from 60 to 10 mW, limiting the specified maximum range from 1600 to 750 m when used in an outdoor LOS environment[30]. A letter "J" added to the silkscreen print was (perhaps) a bit disappointingly found to confirm that the received RF link belonged to the international edition. Beyond that, these XBee links share the same specifications. Even though the limited output power may be a bit confined, NAROM can easily replace these links at a later stage. By acquiring a radio amateur license the legal output power can be increased to as much as 100 W[40].

The 2.4 GHz RF modules are also available in two versions; the *S1 series* for point-to-point or point-to-multipoint node communication, and the *S2 series* for mesh configurations[27]. The *S1* version was selected because the UAV and GCS resembles a point-to-point system. Also the *S1* XBee PRO 2.4 GHz is further available in three different variants; chip antenna, whip antenna, and lastly a version with no antenna. The latter choice includes a U.FL connector for mounting an external antenna of choice. According to the "XBee & XBee PRO OEM RF Module Antenna Considerations" document by MaxStream[22], the XBee PRO whip antenna has a range advantage over the chip antenna[35]. The range can presumably be further increased by adding a high-gain antenna, using the U.FL connection.

Two XBee PRO 2.4 GHz S1 version RF links with the U.FL connector was ordered from SparkFun Electronics[23] along with the APM processor board,

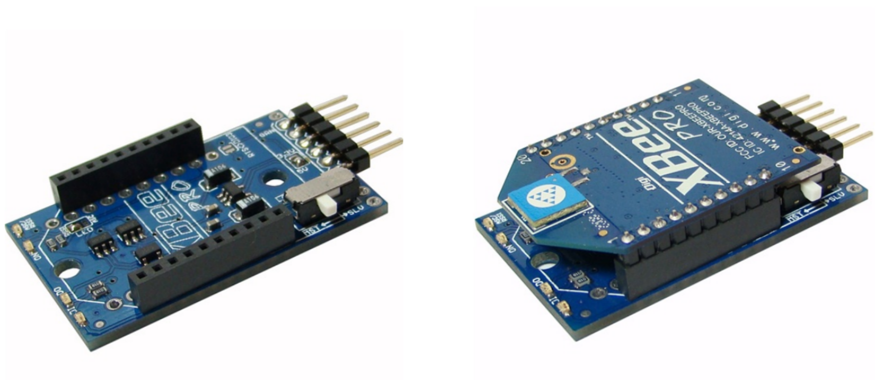
[22] MaxStream is now a part of Digi.
[23] SparkFun Electronics home page: `http://www.sparkfun.com/`



(a) *XBee PRO* 2.4 GHz *S1 version with U.FL connector.*

(b) XBee Explorer *board for USB communication with the XBee.*

Figure 5.21: *XBee PRO* 2.4 GHz *RF modules were employed for the UAV and Ground Control System (GCS) side of the UAS. Photos reproduced with permission by SparkFun Electronics.*



(a) *DIY Drones* XtreamBee Board *for the airborne XBee.*

(b) *XBee PRO mounted on top of the* XtreamBee Board.

Figure 5.22: *The* XtreamBee Board *from DIY Drones. This interface board connects to the airborne XBee module. Photos reproduced with permission by DIY Drones.*

and an *XBee Explorer* USB to serial board for simple communication and configuration of the XBee Pro. Figure 5.21a displays the selected XBee PRO radiolink, and 5.21b displays USB adaptor board. On the airborne side of the UAS an *XtreamBee Board* board[13] from DIY Drones[24] was purchased for interfacing the XBee PRO unit. This board was ordered from the *DIY Drones UAV Store* along with the APM IMU shield[25]. The DIY Drones *XtreamBee Board* is shown in figure 5.22.

Antenna Selection

Selecting the correct antennas for the UAV required a study of radio and antenna technology, a topic unfortunately not covered in previous classes. Upon purchase of the XBee modules, two identical 5 dBi 2.4 GHz dipole antennas were also ordered from SparkFun Electronics. This purchase was however purely based on comparison of antenna gain, caused by the misperception of higher gains being more effective than those of lower gain. Reading more on radiation patterns caused the author to realize that the 5 dBi antenna is highly unsuited for the airborne part, as will be explained in the following section. The original 5 dBi antenna was nevertheless successfully employed for early testing of the APM autopilot system. Figure 5.23a depicts the original antenna with the 2 dBi replacement antenna shown in figure 5.23b.

During radio transmissions the specified gain describes how efficiently input power is converted into radio waves in the direction specified. When receiving signals the gain similarly describes antenna sensitivity in the specified directions. A 3 dB increase in antenna gain corresponds to a doubling of the power intensity, extending the range by a factor of $\sqrt{2}$ as the radiation propagates in a spherical pattern. Hence a gain of 6 dB corresponds to a doubling of the theoretical range. The effective length of the antenna is also proportional to the square root of the antenna gain at particular frequencies, causing the high-gain 5 dBi antenna to have twice the length of the 2 dBi antenna[48].

While *5 dB* specifies the relative power gain measured in decibel, the letter *i* indicates the reference gain based on a hypothetic isentropic equivalent of the antenna. Although impossible to reproduce, an isotropic antenna would have a radiation pattern resembling a perfect sphere, with gain defined as 0 dBi in all directions. Antenna gain is achieved by changing the directivity, redistributing radiation power[48]. In the case of dipole antennas, this usually corresponds to increasing gain in the horizontal direction. But this

[24] DIY Drones UAV Store home page: `http://store.diydrones.com/`

[25] As a consequence of American export regulations the APM IMU shield was ordered from a non-American state, separate from the APM processor board.

(a) *The much larger* 2.4 GHz *5 dBi dipole antenna.*

(b) *The newer* 2.4 GHz *2 dBi dipole antenna.*

Figure 5.23: *The 5 dBi dipole antenna was later replaced by the smaller 2 dBi antenna. Photos reproduced with permission by SparkFun Electronics.*

comes at a cost: increasing gain in one direction reduces the gain in other directions correspondingly. Unless an active amplifier is used the total output power remains the same.

A plot of antenna gain as a function of direction is called the radiation pattern, with "H" indicating the horizontal plane, and "E" indicating the vertical plane. Figure 5.24 illustrates the radiation pattern of the original 5 dBi antenna, and 5.25 illustrates the pattern of the 2 dBi antenna. These plots were reproduced from the corresponding datasheets[20][32].

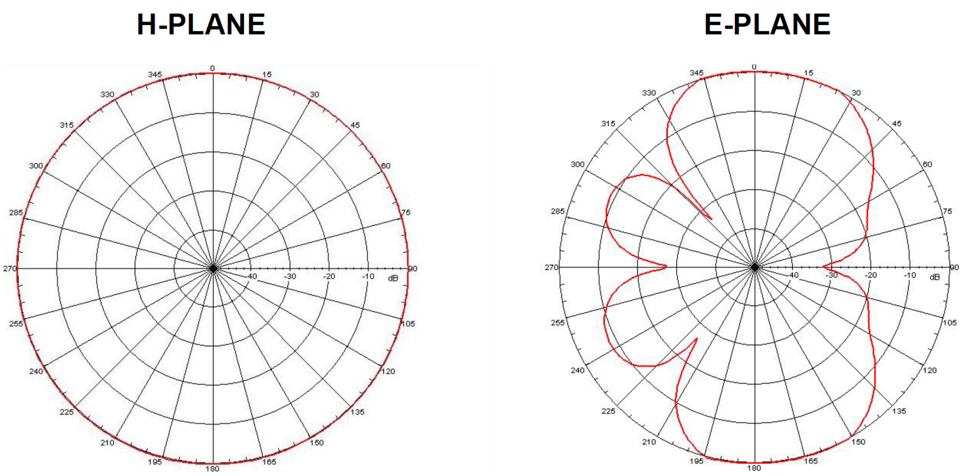


Figure 5.24: *Radiation pattern of the 5 dBi dipole antenna[20].*

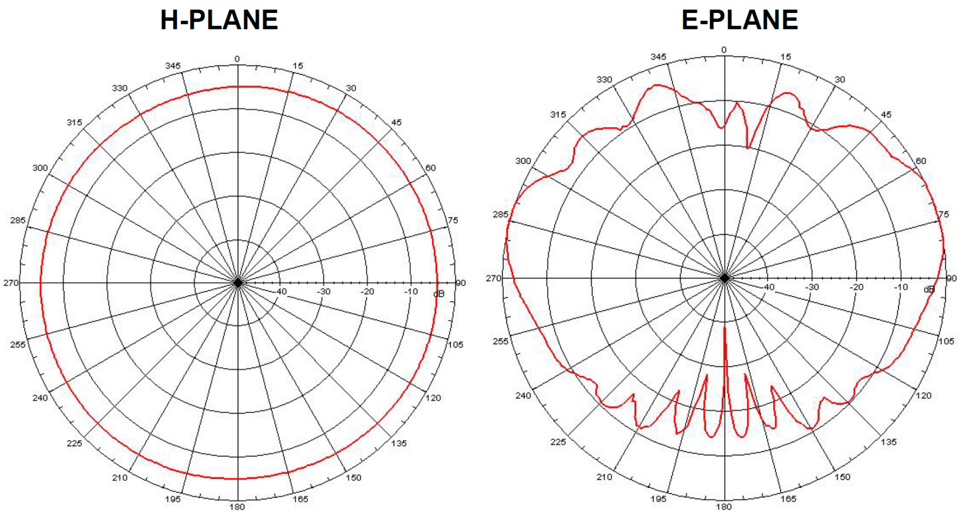


Figure 5.25: *Radiation pattern of the new 2 dBi dipole antenna[32].*

Figure 5.26 relates the previous plots to a model of a dipole antenna, illustrating the relationship between the E and H planes. As seen in the radiation plots, both antennas are omnidirectional in the horizontal plane, meaning that they display a nondirectional radiation pattern. The 5 dBi antenna has greater horizontal range at the expense of poor performance in the vertical plane, and at certain orientations the signal will be very weak. This is especially true outside the main and side lobes, with minima's clearly visible at angles of 90, 270, 315, and 220 degrees. At 90 degrees the gain reaches -32 dB, substantially reducing the range by a factor of 40.

The practical consequence of the reduced gain in the vertical plane at certain orientations is that contact with the GCS may easily be lost. The UAV will be constantly moving, and using the original pair of 5 dBi antennas poor S/N performance is expected at high elevations, or simply during high pitch and roll turns. A less directive antenna would performs better in these situations, providing a more robust link. Nevertheless, the 2 dBi antenna will suffer when overflying the ground-based antenna, and this situation should be avoided during flights using telemetry.

In conclusion a low dBi omnidirectional antenna should be employed on the airplane side, while a high gain antenna may be used on the ground side. The 5 dBi antenna should provide satisfactory performance as the UAV will mostly be circumnavigating the GCS during initial testing. At later stages a directional antenna may be preferable for the ground control station. In this case, a patch antenna with a horizontal and vertical beam width between 60 and 90 degrees should be desirable.

The much smaller size and weight of the 2 dBi antenna further makes it a

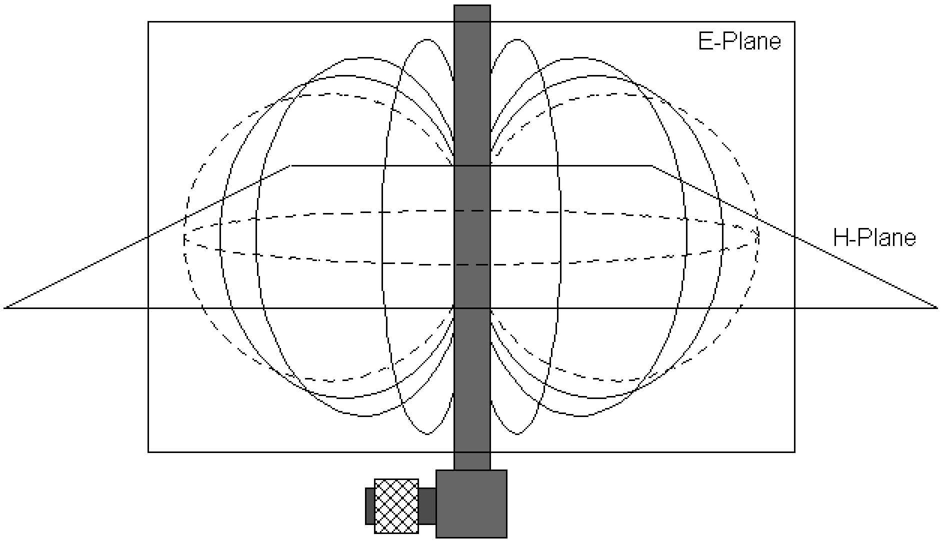


Figure 5.26: *Dipole antenna radiation. Picture reproduced with permission by* Data Alliance*: http://www.data-alliance.net/Page.bok?template=antennas-omnidirectional-dipole.*

better choice for the airborne antenna. The new 2 dBi antenna was ordered through RangeVideo[26], and used for later testing. The XBee PRO 2.4 GHz also required an RP-SMA to U.FL interface cable for connecting the antennas, as well as an extra RPSMA male to SMA female adapter for the 2 dBi antenna.

5.2.6 Airspeed Sensor

The ArduPilot Mega (APM) autopilot allows for an additional airspeed sensor to be added, increasing autopilot performance. When the APM is used without the airspeed sensor the autopilot relies solely on GPS-based groundspeed estimations. In calm weather this should work well, but windy conditions may cause problems. To illustrate this issue suppose the NAROM UAV is flying in a steady 8 m/s crosswind, while keeping a constant groundspeed of 16 m/s. When turning and flying downwind the airspeed would suddenly drop from 16 to only 8 m/s, reducing appreciable lift, possibly causing loss of control.

One way to prevent this from happening would be to increase cruise speed, ensuring that it remains at a far greater than the wind speed at all times. This would nevertheless cause reduced flight performance and flight time, wasting battery power. Another obvious would be to choose to fly only on

[26]RangeVideo home page: `http://www.rangevideo.com/`

days with little wind, but this may not always be an option, such as during the week of the Arctic EO summer camp. A much better approach would then be to ensure a constant airspeed, justifying the need for the additional sensor.

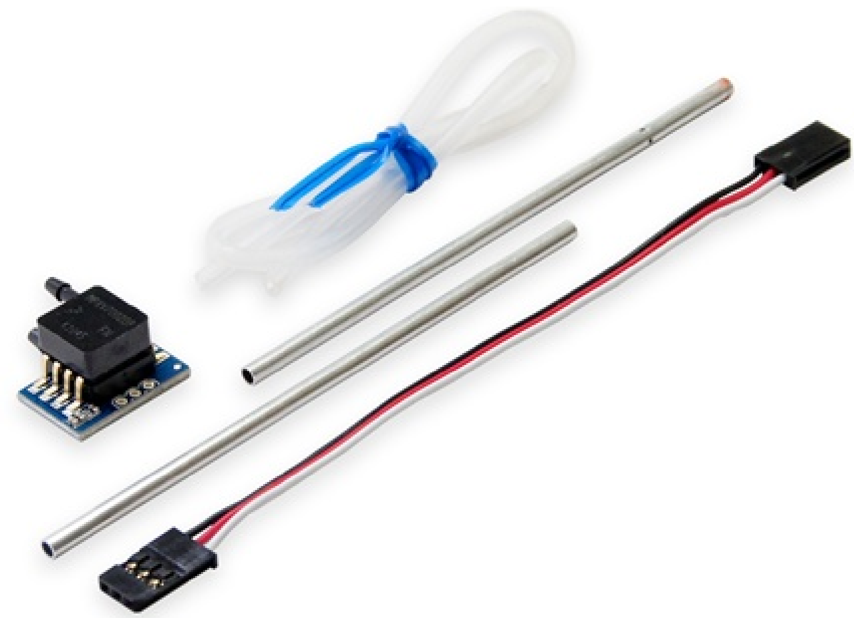


Figure 5.27: *Airspeed sensor kit for the ArduPilot Mega autopilot. The static tube with the sealed front is shown at the top, with its small port holes visible. Photo reproduced with permission by DIY Drones.*

Figure 5.27 depicts the recommended airspeed sensor from DIY Drones. This kit is based on the MPXV7002DP differential pressure sensor, and provides an analog signal ranging from 0.5 to 4.5 V. The offset voltage is at 2.5 V, to allow for positive and negative pressure measurements[5].

$$p_d = p_s + \left(\frac{\rho V^2}{2}\right) \tag{5.2}$$

$$V = \sqrt{\frac{2(p_d - p_s)}{\rho}} \tag{5.3}$$

The airspeed sensor employs two pitot tubes; one active, and one passive. While the active tube is open at the front, the passive tube is sealed, only allowing air to pass through a set of four smaller holes drilled into the side of the tube. The active tube measures both the static (p_s) and dynamic (p_d)

pressure[27], while the passive tube only senses the static pressure. In equation 5.2 ρ denotes the air density, and V denotes the airspeed. Subtracting the passive measurement from the active cancels atmospheric pressure. Using Bernoulli's equation airspeed velocity can then be easily estimated (5.3), and inserted into the control-loop to regulate the airspeed.

5.2.7 GPS

The APM requires an external GPS for determining the position, heading, and speed of the UAV. A MediaTek 3329 GPS unit from DIY Drones was selected for the APM, offering a built-in patch antenna, -165 dBm high sensitivity tracking, 66 channels, an update rate of 1-10 Hz (firmware configurable), a serial interface (default baud rate of 38400 bps), and a stated accuracy of 3 m without aid[3]. Figure 5.28 shows the MediaTek GPS unit. This GPS is very small, measuring only 16×16×6 mm in size, and weighing 8 g.

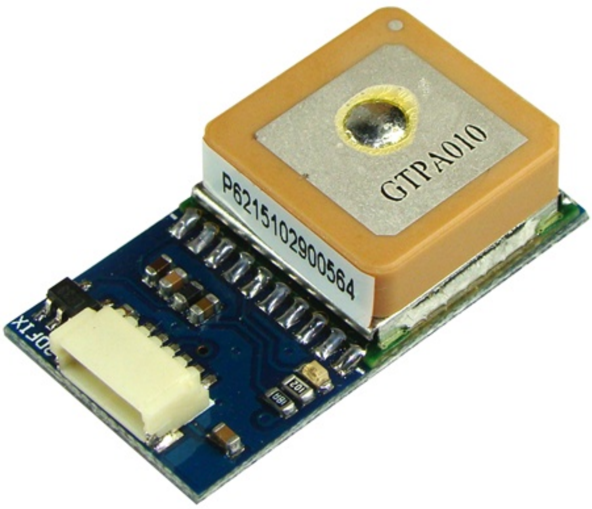


Figure 5.28: *MediaTek MT3329 GPS for the APM. Photos reproduced with permission by DIY Drones.*

[27]The static (atmospheric) and dynamic pressure together make up the stagnation pressure: $p_{stag} = p_s + p_d$

5.3 Payload System

5.3.1 Embedding the Payload into the Autopilot System?

Even though the APM autopilot comes with six additional 10 bit ADC ports, it was decided to develop a separate payload system. The alternative would have been to share the XBee link, microcontroller, and battery of the APM, saving both weight and room inside the airframe. Thus this decision deserves some extra attention and substantiation.

There were nevertheless several reasons for this decision, with the main reason being related to safety. In talking with Torbjørn Houge from ARR Aranica this solution was proposed, being seen as a way to maintain safety by avoiding larger changes to the autopilot code. Keeping the autopilot and payload system completely separate was also expected to faciliate the fligh permit application[28], and additionally, -and perhaps most importantly, make the flight permit independent of the developed payload system. In contrast, Aranica needs to submit an updated application when altering the payload instrumentation. Thus this approach would allow the UAV to be a more flexible platform, as according to the thesis description. Morten Raustein in Luftfartstilsynet further confirmed by phone that this would also be a desirable approach.

This procedure was also helful in that the two systems could be independently tested and developed, also simplifying code alteration and maintenance. Morever it was expected to be beneficial for NAROM by allowing them to make changes without altering the behavior of the autopilot.

5.3.2 Selecting CanSat as the Payload Platform

Once it had been decided to separate the payload system further planning became possible. Jøran Grande and Torstein Wang from NAROM both suggested to employ a CanSat kit as the basis for the payload system. The CanSat is a "*simulation of a real satellite*"[23], and is usually launched on top of a rocket to an apogogee of 1-3 km.

The CanSat collects and transmits data throughout the flight, and returns on a parachute. Typical missions include communications, navigation, atmospheric measurements or video capture. CanSat's are also required to fit inside a standard soda can[29], thus easily fitting inside the airframe. The CanSat module also includes a robust structure, an additional advantage as

[28]This combined with the VLOS and 400 ft AGL limits allowed for a simpler and quicker case proceeding.

[29]Standard 333 ml soda can.

it protects the payload in the case of a rough landing. The total weight of the CanSat hardware and structure is about 100 g.

5.3.3 The CanSat Kit

The CanSat hardware is available as a kit, and is shown in figure 5.29. The hardware kit consists of a processor board, a sensor board, and a transmitter board. A block diagram of the CanSat is illustrated in figure 5.30.

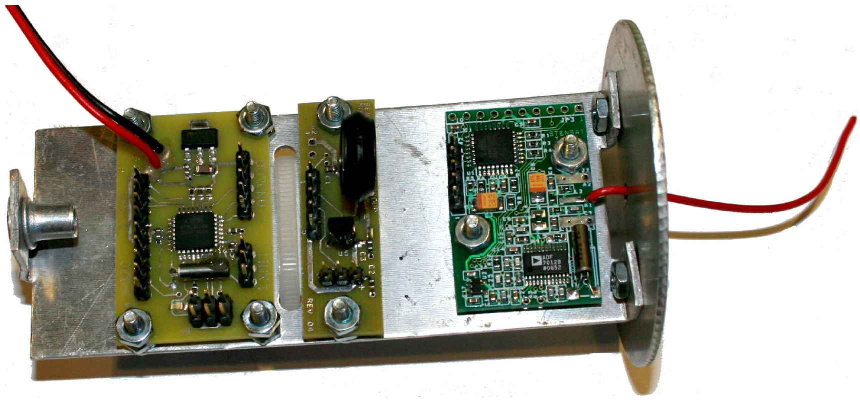


Figure 5.29: *The CanSat kit, with the processor board shown in the left, the sensor board in the middle, and the transmitter on the right. Picture by NAROM.*

The Processor Board

The processor board is based on the Atmel Atmega168 microcontroller, and includes a 5 V voltage regulator, programming ports, and three ports for adding analog sensors. It is powered by a standard 9 V battery, providing about 5 hours of operation. The board plugs into the PC's USB port using a serial connector.

The Sensor Board

The sensor board includes two IC sensors -a pressure sensor and a temperature sensor. The pressure sensor MPX4115A is produced by Motorola, and employs a piezoresisistive material that changes resistance based on the pressure applied. The MPX4115A provides an analog output signal (0.135-4.725 V), proportional to the applied pressure. It features temperature compensation, and the maximum error is stated as ±1.5% at 0 to 85°C, with the pressure range given as 15 to 115 kPa[38].

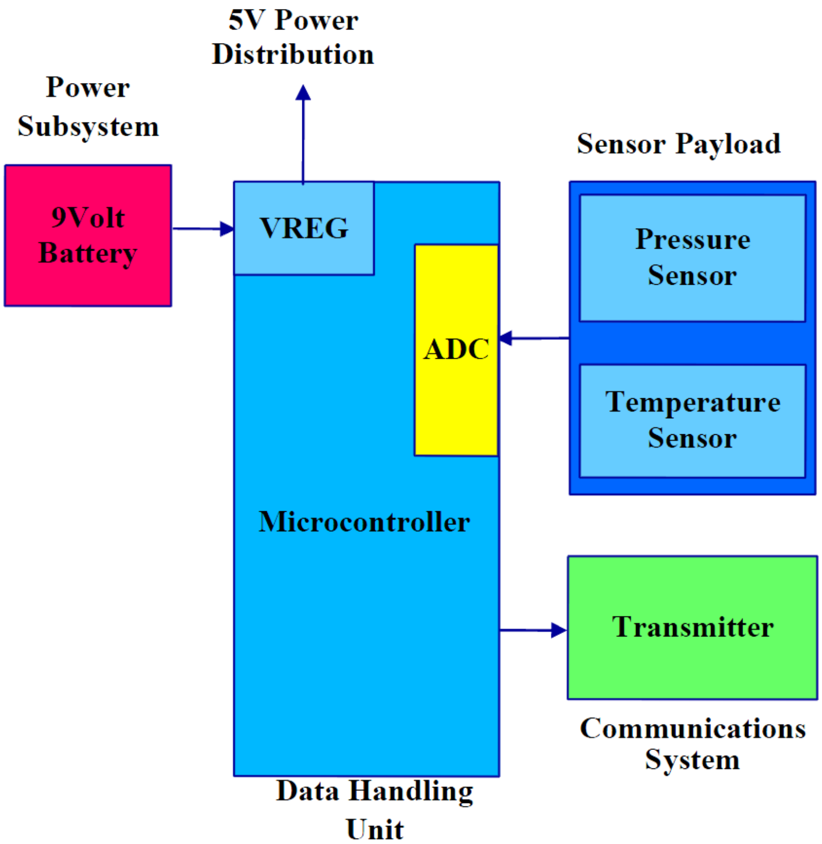


Figure 5.30: *Block diagram of the CanSat subsystems.*

Recommended applications for the MPX4115A include aviation altimeters, weather stations and weather reporting devices. Combined with a response time of only 1 ms, this pressure sensor should be well suited for use in the NAROM UAS. One should however recall that initial flights will take place at less than 400 ft AGL, and only small variations in pressure are expected within this interval. Although the full potential may only be attained when flying much higher altitudes, the stated accuracy and short response time should nevertheless make this sensor fitted for use in the NAROM UAV.

The TPM37 temperature sensor is produced by Analog Devices, and is made for measuring temperatures between 5 and 85°C. The sensor provides a voltage output that is linearly proportional to Celsius temperatures (typically ±0.5°C linearity), a scale factor of 20 mV/°C, and a typical accuracy of ±2°C[22]. The supply current is only 50 μA, providing little self-heating (<0.1°C in still air). The TPM37 is nevertheless scaled a bit high, and is thus planned to be replaced by a temperature sensor for measurements in the range of ±25°C, depending on available time after initial testing.

The Transmitter Board

The CanSat kit also includes a communication subsystem, consisting of a simple 433 MHz 1200 bps transmitter module. Although 1200 bps is a slow data rate, this rate is fully adequate when streaming smaller amounts of data, such as sampling a set of meteorological sensors. The low bit rate also keeps the circuitry and ground station equipment simple and inexpensive.

Header:	**Data Bytes**	**Check Sum**
8 bits	32 bytes	16 bits

Table 5.4: *AX.25 protocol.*

The transmitter module consists of both a processor and transmitter IC. The processor collects data from the processor board, and employs the AX.25 protocol. The AX.25 protocol is a digital communciation protocol for amateur radio. The first 8 bits represent the header, and is used by the receiver to recognize the start of the message. The next 32 bytes are reserved for data that is transmitted, while the last 16 bits constitute the checksum[23]. The transmitter IC frequency modulates the 433 MHz carrier signal with this data, and transmits the carrier signal on the wire antenna.

5.3.4 Additional Sensors

Humidity Sensor

The payload requirements specify that humidity data should be collected in-flight. The HIH-4000-001 from Honeywell was selected for this task, delivering instrumentation-quality performance[25]. The sensor provides a near linear voltage output vs Relative Humidity (RH) in the range of 0 to 100% RH, and has a stated accuracy of ±3.5%. The operating temperature is stated as ±40°C, -well within the expected flying environment. Settling time is stated as less than 70 ms, and it draws about 200 µA. The datasheet mentions meteorology as a potential application, and combined with the small weight and size this sensor seems to be well suited for the NARMO UAS payload. The HIH-4000-001 sensor is pictured in figure 5.31.

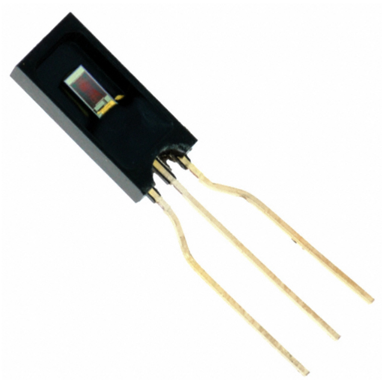


Figure 5.31: *Humidity sensor HIH-4000-001 sensor from Honeywell.*

Payload GPS

To provide spatial and temporal weather data, a GPS receiver was also needed. Although the GPS of the autopilot system could have been reutilized, a separate GPS was added for the same reasons stated in section 5.3.1. A GlobalSat EM-411 GPS module was selected because it fits the needs, and was additionally available at ARR. The EM-411 unit provides a position with an accuracy below 10 m, feauturing an integrated -159 dBm patch antenna and 22 channels[24]. The baud rate is 4800 bps, and the EM-411 supports the NMEA 0183 protocol[30] that will be used for providing the position and altitude.

[30]NMEA 0183 is a standard that uses simple ASCII serial communication.

5.3.5 Ground Station

The ground station consists of three basic components:

- Receiver
- Antenna
- Storing device

NAROM has previous experience with successful use of this equipment from CanSat campaigns, and this equipment was already available at ARR.

Receiver Device

A Uniden UBC69XLT-2 hand-held radio receiver and scanner was available for use. This receiver can scan the 406-512 MHz FM band, and has a BNC connector for switching to different types of external antennas. A 3.5 mm mini-jack plug can be used for connecting the receiver to a laptop for signal decoding and storage. The BC69XLT-2 receiver is shown in figure 5.32, and the user manual is included on the DVD in appendix F.

Figure 5.32: *BC69XLT-2 handheld FM receiver for the payload system.*

Antenna

The UBC69XLT scanner includes an omni-directional antenna, but optional antennas may be connected with the BNC connector. A directional Yagi antenna was available through NAROM, and based on their experience with CanSat's this antenna would increase the range of the payload system to several kilometers, extending the range as compared with the autopilot RF link. Using a Yagi antenna does however require an extra assistent because of its directional sensitivity.

Storing Device

A laptop with a 3.5 mm stereo input is needed for storing the payload data, and connects to the scanner with a mini-jack stereo cable. A dedicated laptop that is also water and dust proof would be recommended, with a long battery life also being advantageous.

Chapter 6

Flight Permit Application

Before any flight testing could take place, a temporary flight permit had to be assigned by Luftfartstilsynet (the Norwegian Civil Aviation Authority[1]). The first section of this chapter outlines the prevailing laws that regulate UAV flying in Norway. The next section describes the work on the flight permit application, as well as its implications and limitations on the future use of the NAROM UAV. The third chapter briefly comments the authorization granted by Luftfartstilsynet. The original application is included in appendix C.

6.1 Background

Currently no national legal framework on Unmanned Aerial Vehicles exists in Norway, but Luftfartstilsynet is presently preparing a set of regulations to be adopted. For this reason only an AIC[2] announcement directs UAV and FPV flying in Norway. This specific AIC is formally known as AIC-N 25/09, and stipulates that UAV and FPV flying must be authorized by Luftfartstilsynet until new regulations are passed[33].

AIC-N 25/09 further informs that Luftfartstilsynet should be notified about future planned UAS operation at an early stage, and that all cases will be individually evaluated. According to Luftfartsloven (Regulation on delegation of authority to the Civil Aviation Authority), it is also mandatory to take

[1] Luftfartstilsynet home page: `http://luftfartstilsynet.no/`

[2] AIC is short for Aeronautical Information Circular. Citing NATS Aeronautical Information Service[44], AIC is defined as the following: *"Aeronautical Information Circulars (AIC) are notices containing information that does not qualify for the origination of a NOTAM (Notice to airmen). They are furthermore used to publish advanced warnings of impending operational changes, and to add explanation or emphasis on matters of safety or operational significance."*

out insurance on aerial vehicles, without respect to take-off weight. ARR fortunately provided the necessary insurance for the NAROM UAV[3].

6.2 Application

NAROM and ARR concluded that the flight application would only include flights within VLOS and 400 feet AGL, hoping that these limitations would shorten the expected processing time. By contrast, flight authorization beyond VLOS may take several months to process[33], making it difficult to perform the intended flights within the assigned time span[4]. An application for flights beyond VLOS would further require an extensive probabilistic risk assessment, including a complete presentation of corrective safety measurements. Yet the author hopes that the first application can serve as a strong foundation for future applications by NAROM.

Flights within VLOS and 400ft AGL would further be restricted to conditions of adequate daylight, and wind speeds less than 8 m/s. These wind conditions are based on personal experience with similar sized RC airplanes, and the upper limit of 8 m/s should ensure an ample margin. Further discussing the application with Morten Raustein from Luftfartstilsynet, it was also agreed that the Andøya Air Traffic Control (ATC) should be informed prior to flight.

Latitude:	**Longitude:**
69.2502 N	16.0990 E
69.2502 N	16.0772 E
69.2403 N	16.0688 E
69.2306 N	16.0156 E
69.2117 N	15.9886 E
69.2014 N	16.0614 E
69.2108 N	16.0842 E

Table 6.1: *Coordinates for the Breivika flight range.*

Coordinates for the flight area are listed in table 6.1, and describes the flight range referred to as "Breivika". This range is uninhabited, and consists of vast areas of flat and open terrain, as well as some mountainous regions in the inland. The location of the Breivika range is illustrated in figure 6.1, also showing the location in respect to the ARR, the town of Andenes,

[3]The company insurance would cover most incidents with the exception of of hitting a satellite, -however an unlikely event!

[4]The author originally hoped to expand the authorization (as also mentioned in the letter to Luftfartsverket), but this was later dropped because of the short time constraint.

Figure 6.1: *The Breivika flight range, as shown in Google Earth.*

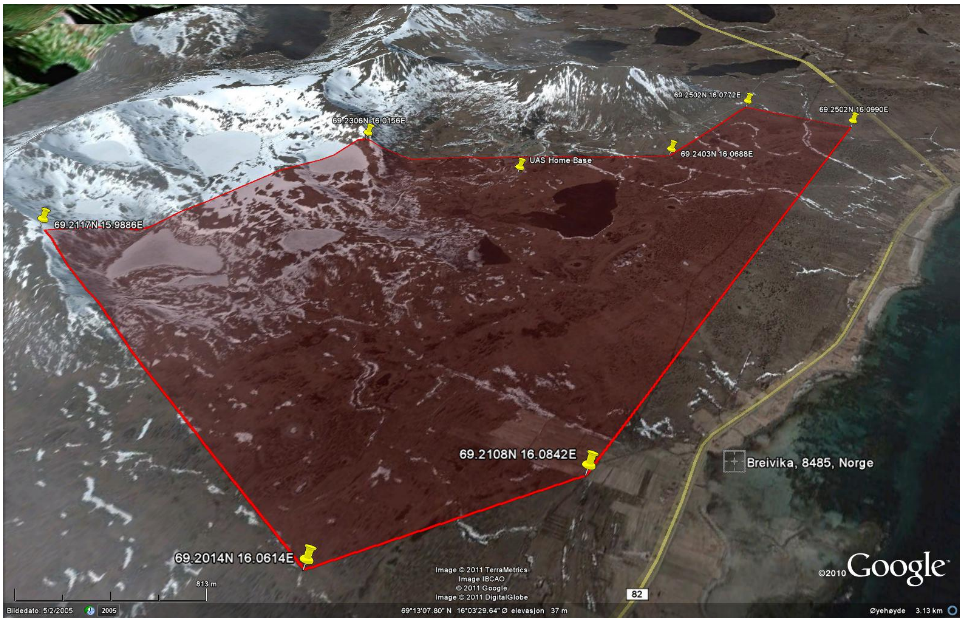


Figure 6.2: *A more detailed view of the Breivika terrain, as shown in Google Earth*

and Andenes Airport. A more detailed view of the terrain including coordinates of the range is presented in figure 6.2. The author wrote the flight application and selected the flight range based on the discussions with ARR and NAROM. The original application to Luftfartstilsynet is included in appendix C.1, and also contains details of technical and operational character.

6.3 Authorization

The application was sent to Morten Raustein in Luftfartstilsynet on February 23rd, asking for a test period starting on March 10th, and lasting till May 20th. The flight authorization was granted by Luftfartstilsynet on March 8th, and given case number 200902205-30. The authorization is included in appendix C.2, and was highly successfull in that it complied with all the requested needs put forward in the application.

Chapter 7

Airplane Construction and Testing

This chapter reports the work on the airplane part of the NAROM UAS. The first section deals with the construction of the airplane, and the next following sections deal with flight preparation and flight testing. The results and experiences gained from these test flights are discussed in section 7.4, and a short conclusion is presented in section 7.5.

7.1 Airplane Construction

Before any flight testing could take place the Skywalker EPO aircraft had to be assembled. Special foam compatible cyanoacrylate (CA) glue[1] was used for foam parts, providing a strong bond while minimizing weight. Epoxy glue was used for most structural parts, including attachment of the carbon tube reinforcements inside the tail boom, main wing and horizontal stabilizer. Figure 7.1 presents the airplane and RC components prior to assembly.

Aligning the two halves of the fuselage together while achieving a snug and sturdy bound proved a demanding task requiring extra hands. A small but fully functional hatch was improvised and added to improve payload access. Next control surfaces were cut out, fitted with servo horns and linkage, and reattached using special hinge tape.

As a consequence of the airplane design the two servos mounted into the vertical tail stabilizer will be near impossible to replace after completing the fuselage. These servos were therefore thoroughly tested prior to installation. Figure 7.3 shows the T-tail with the servos installed. To prevent wing

[1] CA glue is commonly known as "super glue".

Figure 7.1: *NAROM UAS airplane components lined up prior to assembly.*

flexing during positive G turns, bands of high strength fiberglass tape were applied underneath the main wing. The fiber glas tape is also visible in figure 7.2, where also the aileron rudder linkage and servo mount is shown. High strength fiberglass tape was also wrapped around the tail to reduce tail flex.

Motor attachment proved however a bit trickier as a customized plywood bracket had to be fitted and added to the original motor mount. The original design seemed wimpy so extra care was taken to improve the motor mount. A close-up photo of the finished mount with the motor and propeller installed is shown in figure 7.4. Composite propellers of size 9x6 and 9x4.5 were both acquired and bored to fit the motor shaft. The 9x6 propeller has a higher pitch, but because of the impressive motor thrust the 9x4.5 became the propeller of choice. The electronic speed controller (ESC) was mounted inside the small compartment directly underneath the wing, and attached with a band of velcro.

Following assembly, the airframe and wings were given a fresh layer of paint. Orange fluorescent paint was selected to improve visibility. The leading edge including the tip of the main and tail fin was painted orange on both sides. Bright yellow color was applied beneath the airframe, as well as around the nose of the airplane. As an extra finishing touch, a large NAROM sticker was added to each side of the airframe. The finished airplane is shown in figure 7.5. Table 7.1 states the total mass of the finished airplane and its

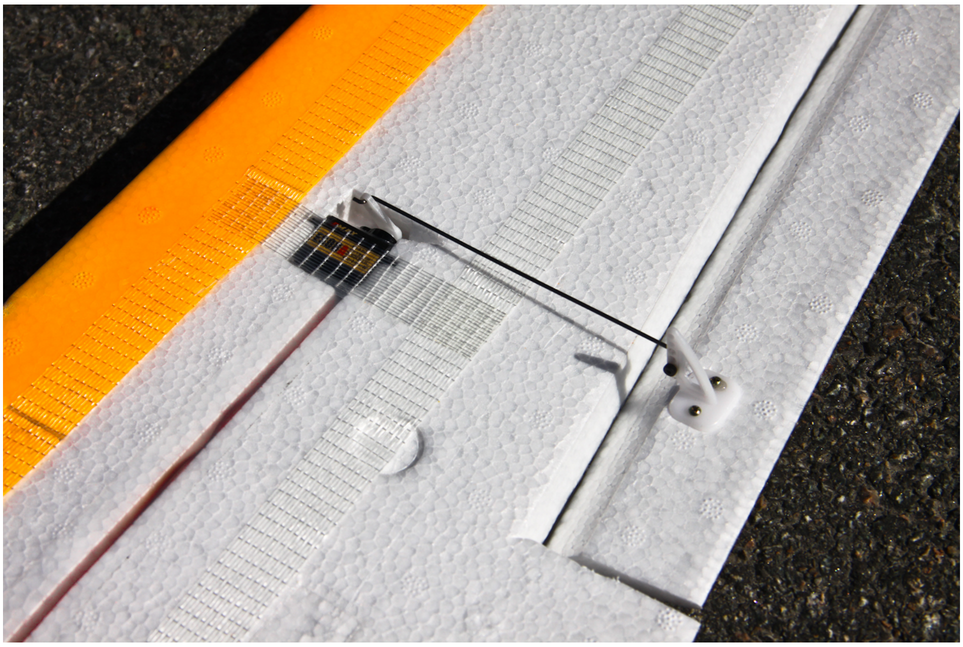


Figure 7.2: *Aileron servo mount. Notice the two fiberglass reinforcement tape bands running between the wing tips.*

Figure 7.3: *Airplane T-tail section. Rudder and elevator servos and links are visible.*

Figure 7.4: *Close-up photo of the motor mount. The AX2814 motor is an "outrunner", meaning that the motor spins its outer shell around its windings. Notice the rubber band used for wing attachment.*

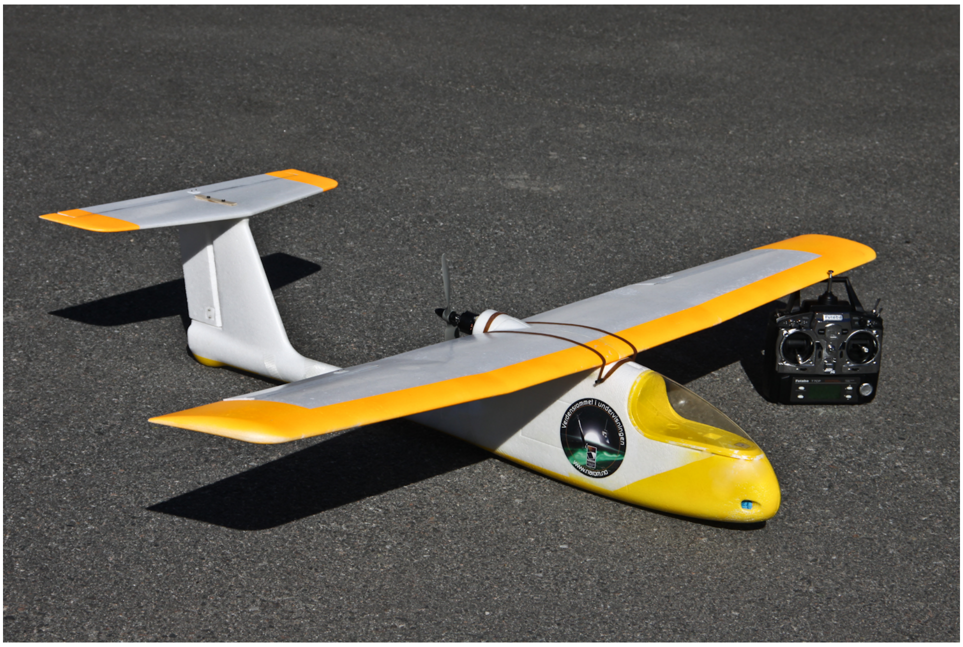


Figure 7.5: *The finished NAROM UAV Skywalker EPO airplane. The battery (azure blue) is visible through the ventilation opening in the nose. The Futaba 7CAP RC transmitter is shown in the background.*

main components.

Part Description:	***Mass:***
Airframe	755 g
Motor, ESC and propeller	157 g
RC receiver, 4 servos and cables	96 g
4s 5000 mAh battery	504 g
Total airplane mass:	**1512 g**

Table 7.1: *Airplane mass budget.*

7.2 Flight Preparations

7.2.1 Radio Setup

In preparing for the first and generally most risky flight, thorough preparations were done to ensure success. The RC transmitter had been programmed with exponential rates[2] for the rudder, aileron and elevator to ease flight control. Each of these three channels were additionally set up with "dual rates", meaning that extra rudder deflection (increased servo travel) could be activated by flipping a switch on the transmitter if needed.

7.2.2 Stability Check

To ensure the aircraft is safe and stable the center of gravity (CG) needs to be located within the recommended CG range. In most cases this corresponds to a distance of between 25 and 50% of the wing chord as measured from the leading edge. Without modifications the airplane was found to be a bit tail heavy, but by placing the battery in the extreme front of the nose section the CG was relocated to 8 cm behind the leading edge, corresponding to approximately one third of the wing chord. This should result in a stable and well balanced airplane.

7.2.3 Range Check

Next a range check of the RC system was performed to ensure safe operation. This test is repeated prior to every test flight. Leaving the RC transmitter antenna retracted while walking away from the airplane an assistant looks

[2]Exponential rates: Exponential rudder response relative to the stick position, making servo movement less sensitive around neutral.

for possible servo jitter as the servo controls are constantly being worked. No servo jitter should be observed within a distance of 30 m, also when repeating the range test with the motor running. The airplane passed the range check and was now ready for its maiden flight.

7.3 Flight Testing

The first three flights were performed March 29th, on a clear and calm winter day. Jøran Grande and Torstein Wang (both from NAROM) assisted in the flights. Following the range check and a call to the civilian Air Traffic Control (ATC) permission to fly in Breivika was granted. With the motor running at about 50% throttle, Jøran Grande (a former javelin thrower) threw the airplane into the wind, and the airplane started to climb as throttle was increased to 100%. Once a confident altitude had been reached, the pilot could get familiar with the airplane and trim the flight controls.

Following the first two flights a third flight carrying extra weights was performed to simulate a large payload. Airplane requirement 4.2.1(d) specifies the need to accommodate a minimum load of 300 g for the autopilot and payload combined. Based on the airplane size and motor power a much higher payload capacity had been anticipated for the Skywalker EPO. As such, a total of 500 g of weights was loaded into the airframe in the form of 48 AAA batteries. The battery weights represented a fairly compact and modular payload that could easily be inserted and moved within the airframe. To ensure that the batteries did not accidentally move within the fuselage, an additional 50 g of padding was used, increasing the total mass to 550 g. The weights were placed around the CG so as to not alter the stability point.

7.4 Flight Results and Discussion

7.4.1 Control and Handling

Flight control was very smooth and dual rate functions were not needed for control. The power output exceeded expectations with the airplane maintaining a steady climb of 45° without stalling. Airspeed was on the other hand less impressive, and only a marginal speed increase was observed when raising the throttle past 60%. During the first two flights a comfortable cruise speed was about 35% throttle, and 45% when carrying the extra payload. With the motor turned off the airplane descended in a nice controllable glide, also with the extra weight of the simulated payload. During landing

Figure 7.6: *The NAROM UAV photographed shortly after take-off during the third flight.*

Figure 7.7: *The NAROM UAV photographed during its maiden flight. Notice the RC antenna hanging from below the airframe.*

approaches the UAV still offers excellent handling even in speeds as low as an estimated 20 km/h.

7.4.2 Stability

Airplane stability exceeded expectations, and after the rudders had been trimmed the airplane could maintain the heading for as long as 3-4 seconds without any hands on the sticks. When exiting turns the airplane would quickly stabilize itself. These properties are highly inspiring with respect to prospective autopilot installment. Moreover, the airplane would likely perform well as a camera platform even without the use of gyro stabilization.

7.4.3 Payload Capability

The airplane performed excellently with the extra 550 g of payload, although throttle was increased from 35% to 45%. On full throttle the airplane climbed very well, and flight characteristics were not noticeably altered by the simulated payload. It is likely that the airplane may carry a lot more weight, perhaps an extra 250 g. In any case, the test payload of 550 g exceeded airplane requirement 4.2.1(d), and is regarded a success. Even with the 48 AAA batteries inside the airframe there was plenty of extra room for additional payloads.

7.4.4 Transmitter Issues

While the two first flights lasted about 8:30 minutes and 6:30 minutes respectively, the third flight of 5 minutes ended a bit short. A signal glitch caused temporary loss of control during the final landing approach, but luckily and thanks to the low altitude and speed, the airplane took no damage from the rough landing. This signal glitch may have been caused by a combination of low terrain altitude, the simple single conversion RC receiver that was used, and the rapid transmitter voltage decrease that was experienced shortly thereafter. The voltage of the transmitter battery was later found to be somewhat unpredictable because the NiMH battery was quite old. Even though the airplane had passed the range check before flight, it was concluded to replace the receiver with an upgraded dual conversion version for future flights[3].

[3] Dual conversion receivers offer better signal-to-noise ratio through advanced signal processing and noise filtering

7.4.5 Flight Endurance

Because of the low outside temperature it was decided to not deplete the entire battery. Thus only a total flight time of 20 minutes was completed. Recharging the battery after the flights yielded a depletion of 1849 mAh for the flights combined. Based on the total battery capacity (5000 mAh) only 37% of the battery power had been depleted, indicating a feasible flight time of 54 minutes. Requirement 4.2.1(i) specifies a minimum endurance of 20 minutes. These flight results prove that requirement 4.2.1(i) is far exceeded.

7.5 Conclusion

The flight test was regarded highly successful despite the rough landing. For future flights the RC receiver will be upgraded for improved signal reception. The airplane handled very well, and flight characteristics surpassed expectations. The requirements for the airplane as presented in section 4.2.1 have all been met, and far exceeded the flight endurance and payload capability requirements. The Skywalker EPO proves highly promising and suitable for the NAROM UAS project, and the next step will be to install the autopilot and transform it into an autonomous UAV.

Chapter 8

Payload Integration and Testing

This chapter deals with the third and final independent system of the NAROM UAS; the payload system. The first section goes through development of the payload system, focusing on the hardware and software design and operation. Section 8.2 ....

8.1 Payload Development

This section covers the development of the payload system. Work on the payload system was mainly related to programming, although the hardware also needed to be assembled, and verified through ground testing.

8.1.1 Hardware Setup

Figure 8.1 illustrates the CanSat processor board, providing an overview of the available ports and connectors. Connector *JP2* was used for connecting the three analog sensors. The pressure sensor was connected to *ADC0*, and the temperature sensor to *ADC1*. Only the pressure and temperature sensor board was connected during the first stage of the payload development to ease debugging.

As the code was written and verified, the humidity sensor was added to *ADC2*, and then the GPS receiver to the 2x3 header pin (pin number 2 (VCC), 4 (MOSI), and 6 (GND). The EM-411 GPS receiver employs a six pin connector, and the pin overview is presented in table 8.1[24]. Only VCC (5 V power supply), ground (GND), and TX (transmit channel) was connected to the processor board. A photo of the finished payload is shown in figure 8.2.

Pin Number:	**1**	**2**	**3**	**4**	**5**	**6**
Function:	GND	VCC	TX	RX	GND	NC

Table 8.1: *GlobalSat EM-411 GPS pin description.*

The total weight of the payload including the 9 V battery was 120 g, complying with requirement 4.2.3(f).

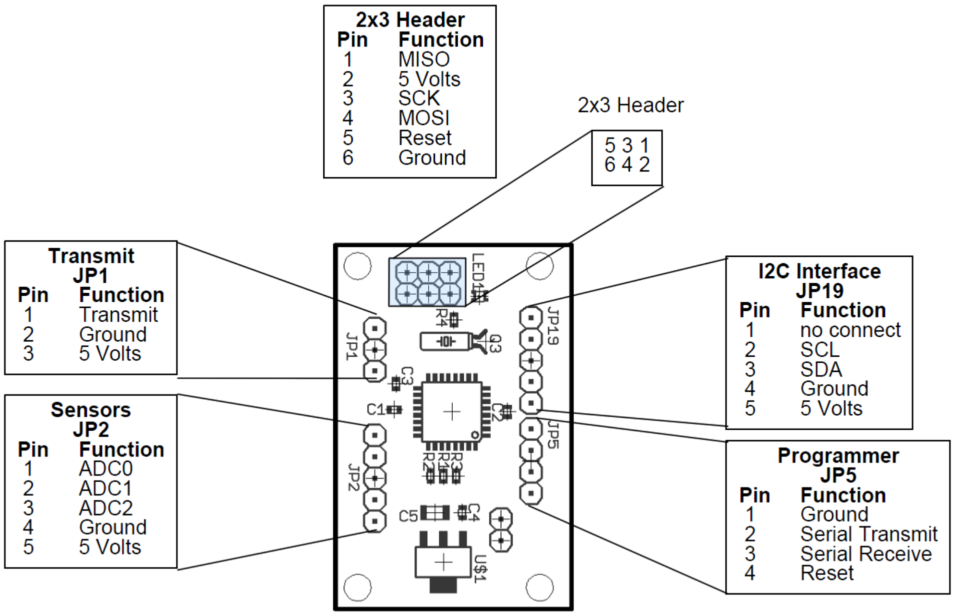


Figure 8.1: *Pin definition and layout of the CanSat processor board. Illustration by NAROM.*

8.1.2 Software Design

Arduino IDE

The CanSat controller was programmed in the C-language, using the Arduino Integrated Development Environment (IDE). The Arduino IDE includes a prewritten C/C++ library that faciliates microcontroller programming, also simplifying input/output operations. This program was also used for the ArduPilot Mega (APM) autopilot controller, as well as by NAROM for CanSat programming and development. Sharing the platform of the autopilot faciliates development, while also being an advantage for NAROM who will continuing development of the UAS.

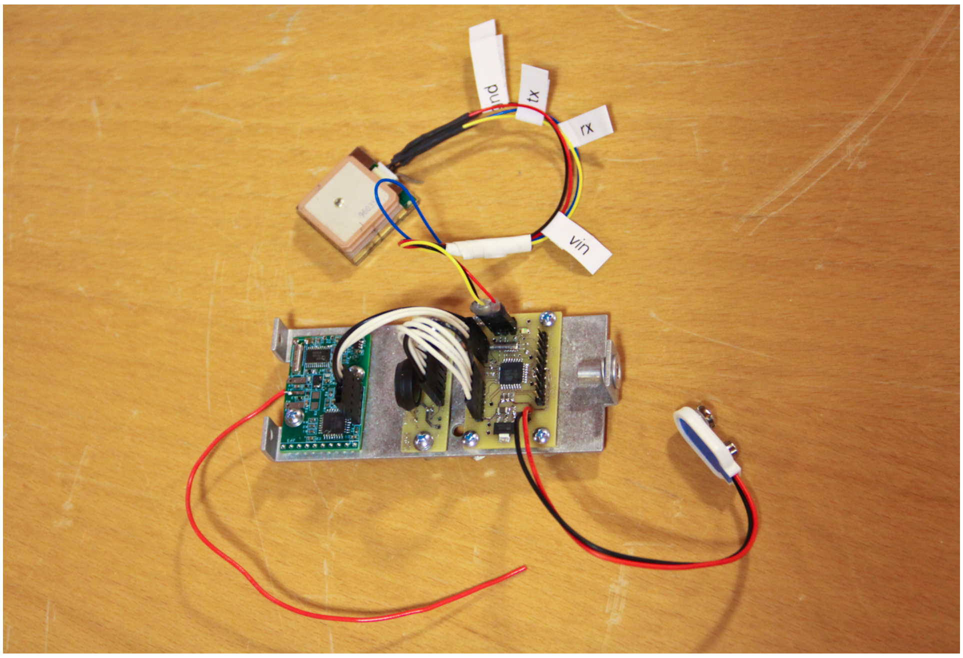


Figure 8.2: *The finished CanSat payload, only missing the HIH-4000-001 humidity sensor. GPS wires were marked with tape.*

Payload Operation

A flow diagram was drawn to represent the processing flow of the payload system, and is represented in figure 8.3. The operation of the payload begins with setting up the serial port, configuring the pin inputs, and the pin outputs. Next the frequency of the transmitter is configured to 433.500 MHz, by transmitting the message "F8D1D1" onto the serial port. Following a compulsory delay, a unique and randomly selected call sign is set by transmitting "CSTBNC7"[1].

Following initialisation, the program goes into an infinite loop, fetching GPS data, and then sampling pressure, temperature and humidity data from the sensors. Only raw data from the sensors are sent, minimizing onboard processing. The raw data will need to be converted to physical values during post-processing[2]. A frame counter was also added to enable easier tracking and post-prosessing of the received data. The code for the payload is included in appendix D. Note that the receiver station relies on receiving the letter "S" at the start of each message.

[1] See the "Supplemental Transmitter Information" document for a full list of available frequencies and commands[4].

[2] See section 8.1.3

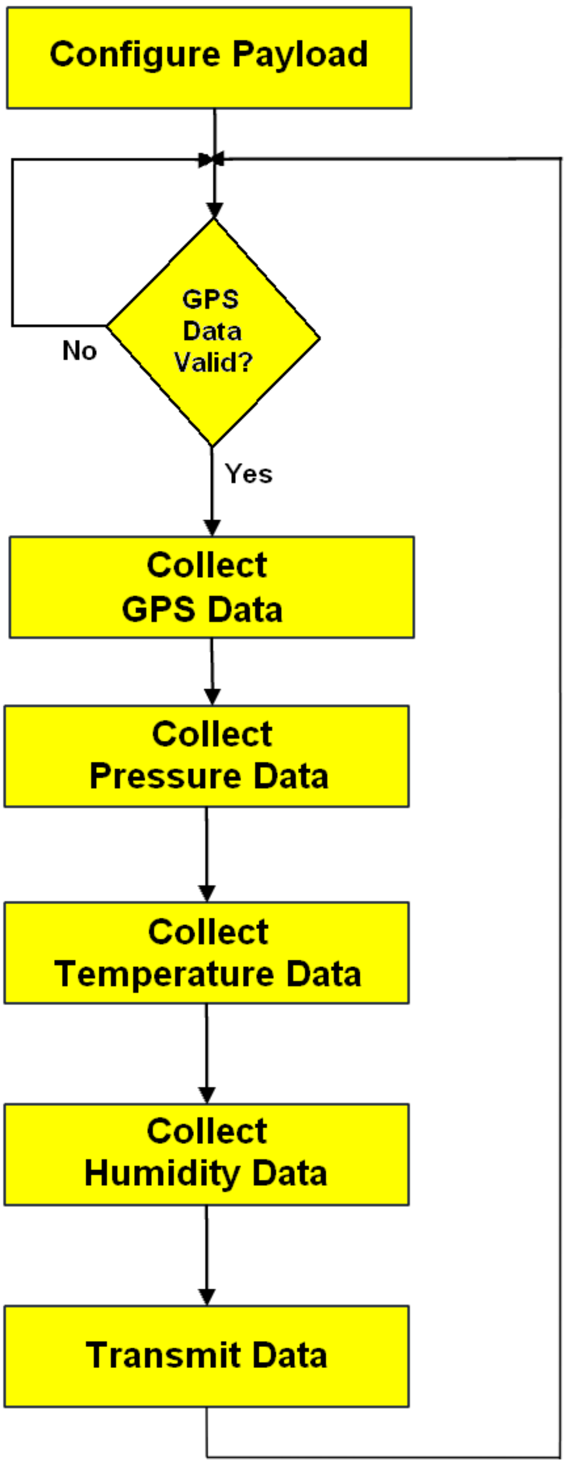


Figure 8.3: *Data flow diagram, illustrating the operation of the payload system.*

Upon transmission, a LED light is also turned on and off to indicate operation of the payload. This is further an advantage when the payload is loaded into the airframe, as the flashing LED should be easily visible. A total delay of 500 ms was also added, putting the payload sampling rate to about 2 Hz. This complies with requirement 4.2.3(d), and should provide sufficient resolution for horizontal mapping. A faster sampling rate may collect abundant data.

GPS Data Output

The GlobalSat EM-411 GPS module[24] supports the NMEA 0183 output protocol, and uses a simple ASCII serial communication. This protocol defines the contents of each sentence/message from the GPS, and consists of two letters defining the source, followed by three letters defining the type of message. As an illustration the *$GPGGA* sentence will be used as an example, where *GP* tells that the source is the Global Positioning System, and *GGA* defines the *Fixed Data* format.

In the case of the NAROM UAS payload system, only data on the position (latitude/longitude) and altitude is required, and for this reason only the *$GPGGA* sentence needs to be read and decoded. The program extracts latitude, longitude, altitude and sattellite data from the *$GPGGA* messages. The data is then rearranged and transmitted in a format that is easy to plot in Google Earth, also adding a colon between each field, to faciliate text delimitation during post-processing.

8.1.3 Converting Sensor Data

Datasheets for the MPX4115A pressure sensor[38], TMP37 temperature sensor[22], and HIH4000-001 humidity sensor[25] were used to deduct the transfer functions used to convert the measurement data into physical values. The general formula behind these convertions is shown below in equation 8.1, using the temperature sensor as an example:

$$\begin{aligned} SensorOutput(V) = {} & Sensitivity(V/^\circ C) \times Temp(^\circ C) \\ & + Output(V) at 0^\circ C \end{aligned} \tag{8.1}$$

Using the 10 bit CanSat ADC[3], the voltage level is calculated as:

$$Volt[V] = \frac{digitalValue}{1023} \times 5V \tag{8.2}$$

[3] Representing values from 0-1023

For the MPX4115A pressure sensor, the atmospheric pressure measured in kiloPascal is given as:

$$P[kPa] = 22.22 \times V + 10.56 \tag{8.3}$$

The transfer function for the TMP37 temperature sensor is given in equation 8.4, and outputs the temperature in centigrades.

$$T[^{\circ}C] = 50.00 \times V \tag{8.4}$$

The humidity level measured by the HIH4000-001 sensor is calculated with equation 8.5.

$$RH(\%) = 31.76 \times V - 26.24 \tag{8.5}$$

8.2 Testing the Payload

8.2.1 Ground-Testing

The Uniden UBC69XLT-2 hand-held radio receiver was connected to a laptop using a 3.5 mm stereo plug, and data was decoded on the computer using the *AGW packet engine*, and displayed in real-time using the *AGW monitor* software. A logfile from the *AGW monitor* could then be saved to the computer, and the data would later be reviewed and processed.

The payload was first tested on ground, verifying operation as new components were added. The payload system was next brought outdoors, and tested at ground-level at a range of 200 m using the standard antenna. This test was successfull as the packages were confirmed to have arrived, verified by reviewing the log. Adding the framcounter to the packet proved helpful in verifying that data is not lost during transmission.

8.2.2 Mission Planning

Following the highly successfull and fully autonomous flight #10 and #11, it was decided to attempt to perform a comprehensive horizontal weather pattern mapping when testing the payload.

The flight path was programmed using the APM Mission Planner, and this path is reproduced in figure 8.4. This flight consists of 21 waypoints, and a total distance of 7.4 km. The path crosses the terrain in a grid pattern, at a constant altitude set to 70 m above the designated home area. This would put the flight altitude at about 130 m above the Mean Sea Level (MSL). When doing this, it is of utter importance to verify that the terrain altitude is at all times well below the preset flight elevation. Figure 8.5 shows the flight and terrain altitude based on data from Google Earth.

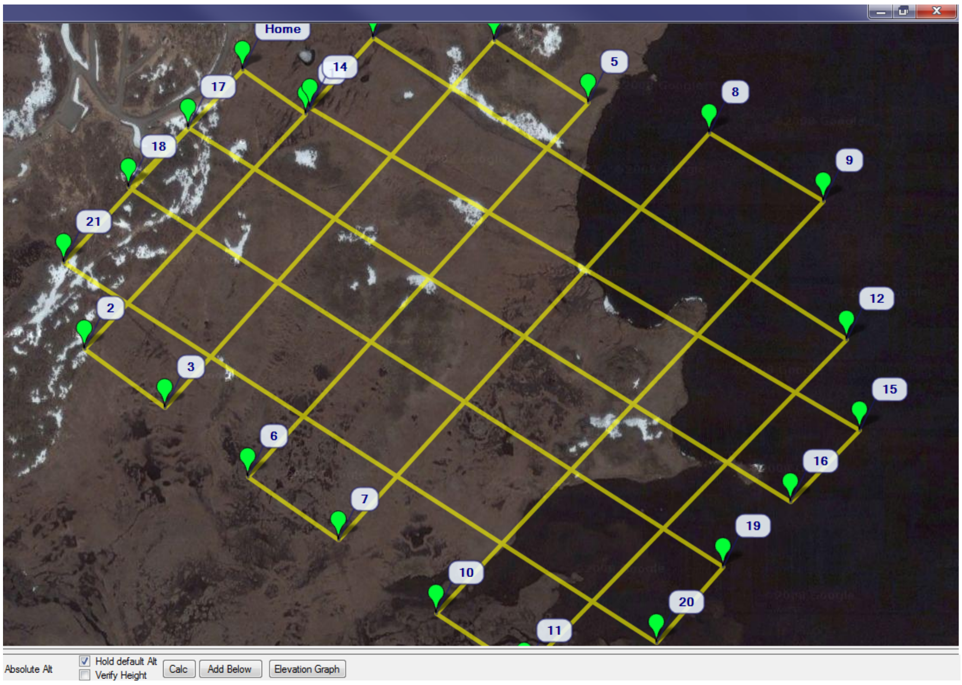


Figure 8.4: *Planned flight path for horizontal weather pattern mapping.*

8.2.3 Flight Testing

The meteorological payload was then installed into the NAROM UAV for the test flight, and placed near the CG to keep the airplane balanced. The 433 MHz wire antenna was placed in the far front of the airplane, protruding the forward part of the canopy. The GPS receiver for the payload was attached at the wing root.

Several days of strong winds made it har to achieve the planned flight. The NAROM UAV was in the end flown in a fresh breeze on May 31st, at estimated throws up to 10 m/s. Although anticapted, these strong winds unfortunately hindered the UAV in following the planned flight path, and most of the flight was performed under manual control instead. Data was nevertheless collected by the payload, and is presented in the next section.

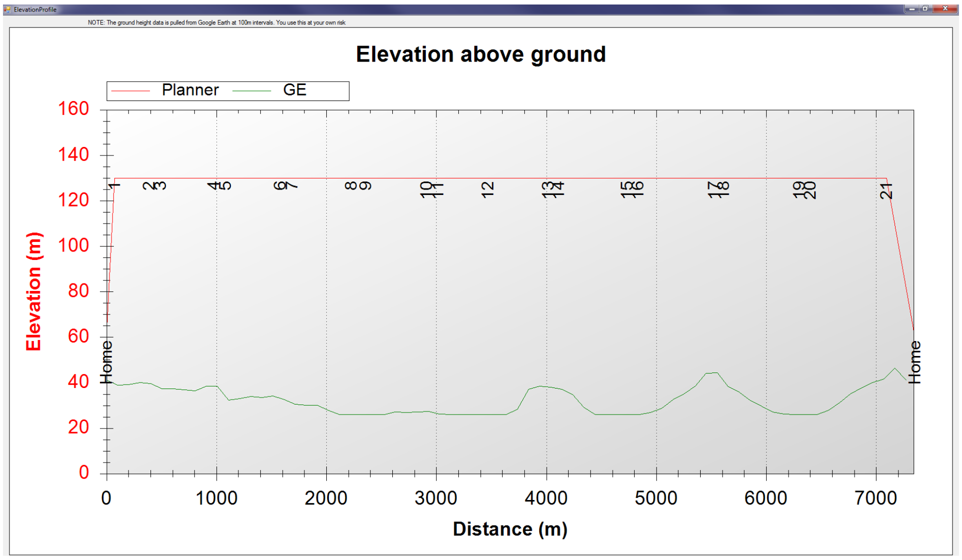


Figure 8.5: *Terrain and flight altitude for the planned flight.*

8.3 Results

Data from test flight #12 has been logged and presented in Google Earth. Although this section contains images from this flight, the author strongly recommends to review the actual Google Earth .kml files that are included.

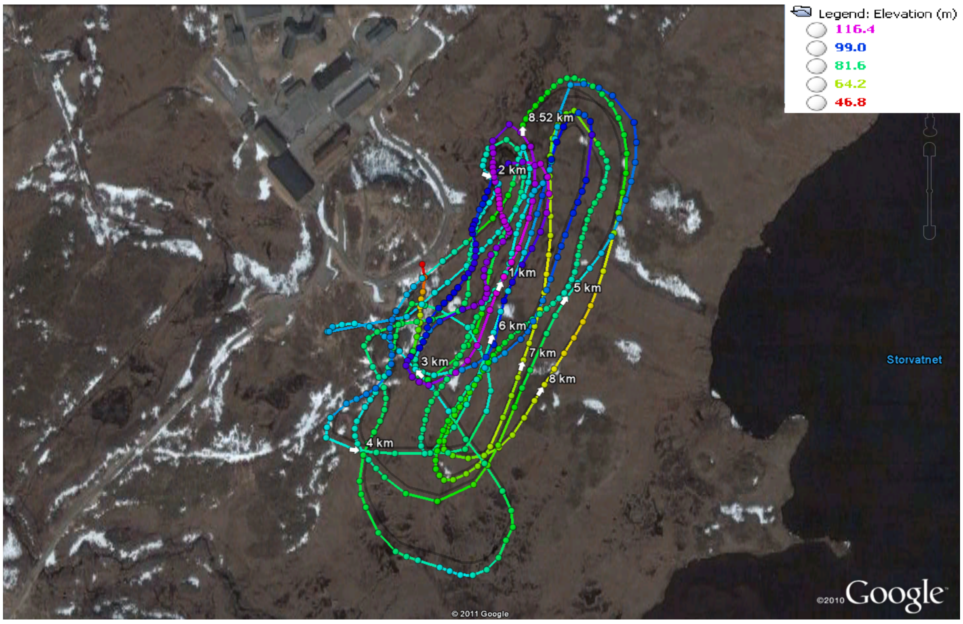


Figure 8.6: *Altitude data from the payload GPS. Vertical view.*

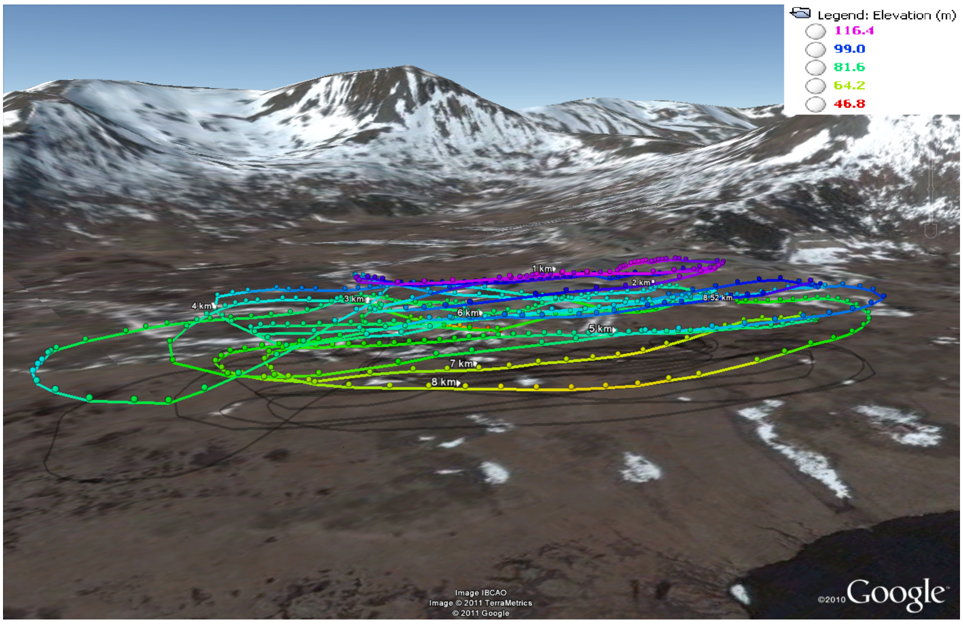


Figure 8.7: *Altitude data from the payload GPS. Horizontal view.*

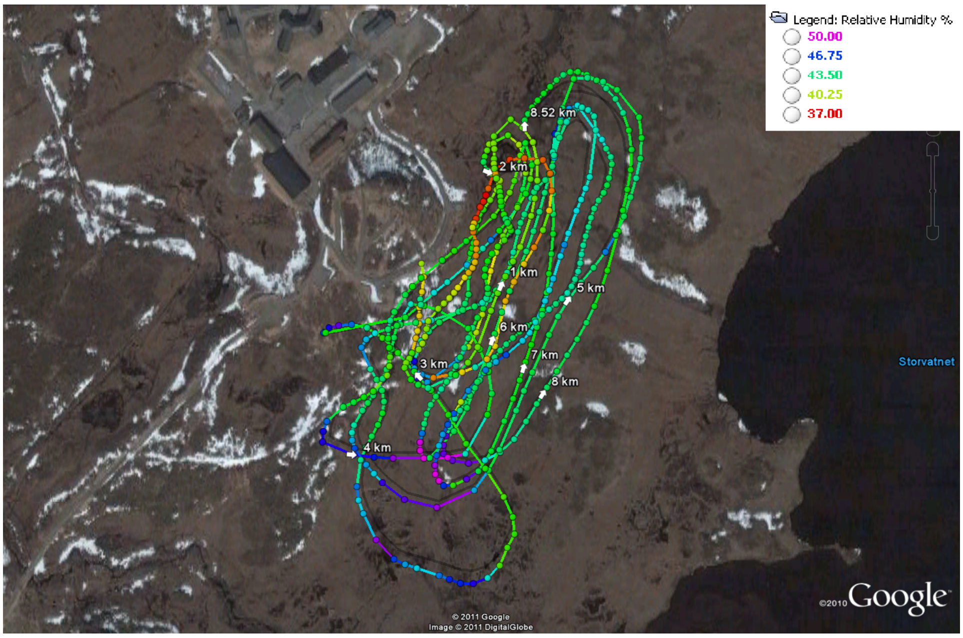


Figure 8.8: *Humidity data from the payload. Vertical view.*

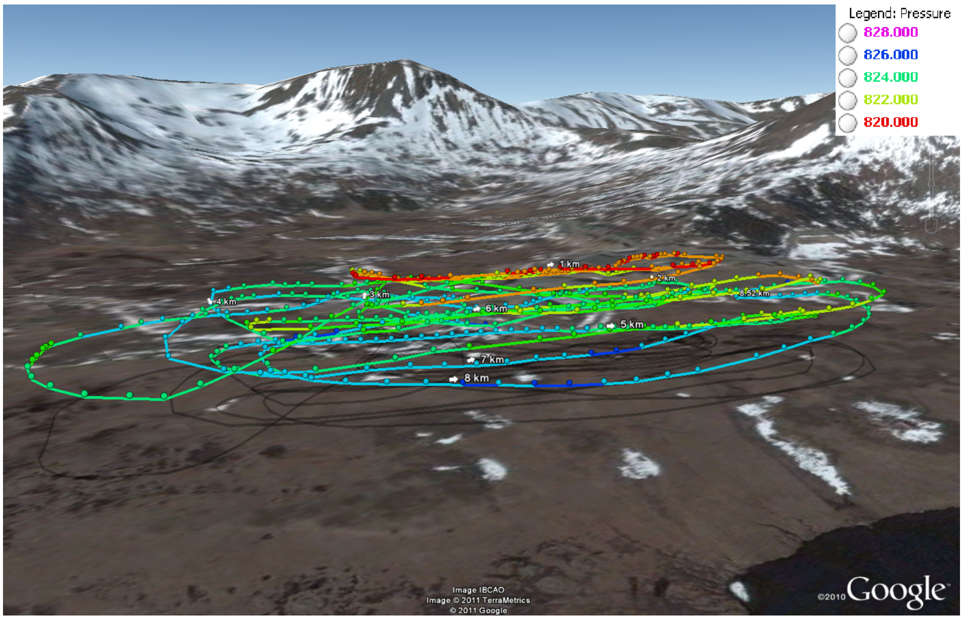


Figure 8.9: *Pressure data from the payload. Vertical view.*

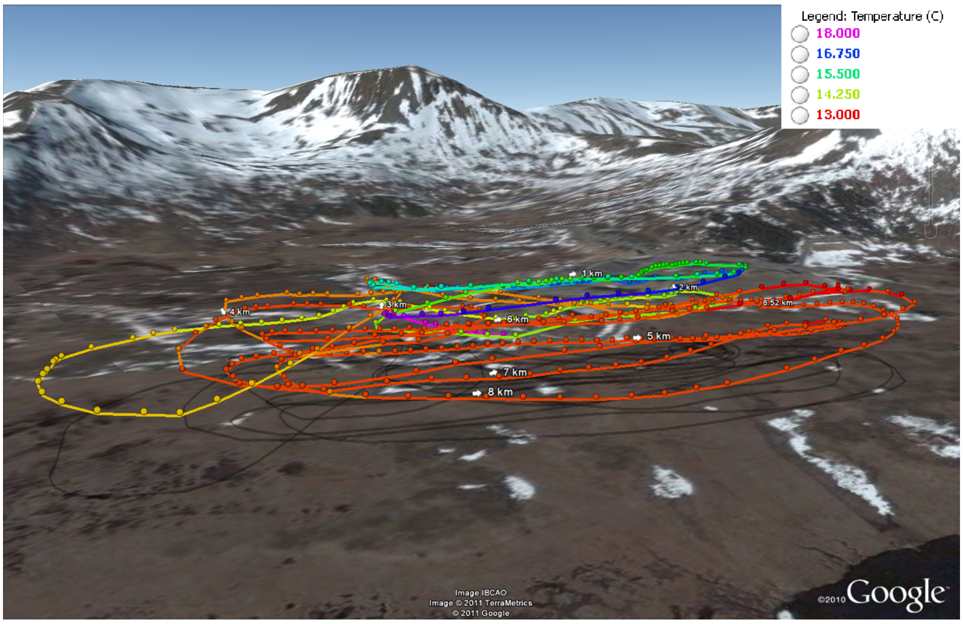


Figure 8.10: *Temperature data from the payload. Vertical view.*

Chapter 9

Conclusion

The main objective of this thesis has been to develop an Unmanned Aircraft System including an instrumental payload. This work has covered a complete development progress; spanning from budgeting and studies of aviation laws, to fully autonomous UAV flights and meteorological mapping. Working on this project has been both instructive and rewarding, while also requiring both practical and theoretical skills in a wide range of disciplines relevant to the field of control engineering.

The Skywalker EPO provided an excellent UAV platform, exceeding all expectations. Not only did this airframe result in a sturdy, stable, and easy-to-fly UAV, but the payload capability should accommodate fairly large and complex instrumental payloads.

In this thesis, only a fraction of the total payload capability was actually employed for the meteorological payload. A tested carrying capacity of close to 550 g provides development potential, enabling students at NAROM to come up with a wide range of payloads to be flown. Flight testing also indicates an endurance of about one hour, based on measured battery depletion. This further indicates a maximal flight distance of 36 km, assuming a conservative cruise speed of only 10 m/s.

Work on the autopilot proved to be more time-consuming and challenging than first anticipated, taking focus and development time away from the payload system. The author nevertheless believes that it was the right choice to select the ArduPilot Mega autopilot. The APM did provide high reliability and sturdy performance once correctly set up. This controller also provides great path planning and GCS software, and having the source code available was also highly valuable.

The CanSat kit also proved well in forming the basis of the meteorological sensor package. Good and consistent weather data was collected during flight testing, although the limitation of 400 ft AGL impeded larger variations in pressure and temperature from being observed. Consequently, the full potential of this platform could only be fully demonstrated by a scientific weather mapping study, which unfortunately falls outside the scope of this master thesis. Nevertheless, the data collected proves the concept of UAV assisted weather pattern mapping.

Chapter 10

Recommendations for Further Work

A project of this kind can always be improved, with recommendations for future work divided into two categories:

- Improvements of the developed system
- Additional work

Further improvements require NAROM to hold both knowledge and interest in this UAS. This chapter also makes mention of the important steps carried out as to enable NAROM to pursue future use of this system after thesis completion. As previously mentioned, the author hopes and intends for NAROM to use this UAS for other educational use in addition to the two Arctic EO summer camps.

A binder was also compiled for NAROM to provide full and easy access to this work, including datasheets, user manuals, and flight logs. The NAROM UAS was also displayed to the director and board of the Norwegian Space Centre, during a meeting at Andøya on May 18th. The author is happy for this interest, and hopes and believes that NAROM is also pleased with the finished result.

10.1 Improvements to the Developed System

In the course of this project the author has repeatedly invited colleagues from NAROM and ARR Aranica to the test flights. This was intended to expand the knowledge and interest for this project within NAROM. The developed UAS already works quite well, but more flights should be carried out and logged, also increasing piloting skills among the NAROM personnel. Although experienced pilots from ARR Aranica[1] may be available for help, basic piloting skills will also be a premise for NAROM in continuing use of this UAS.

There are mainly two improvements that should be prioritized, namely the XBee link and the airspeed sensor. Much time was spent fixing the autopilot link, and in the end it was concluded that the DIY Drones *XtreamBee board* was incompatible with the replacement XBee PRO 2.4 GHz RF link. Some users of the APM have since recommended to use the XBee adapter kit from Adafruit Industries[2]. If a simple replacement of the adapter board could get the link back up and running, this should definitively be tested, as it drastically improves the NAROM UAS capabilities.

Fixing the airspeed sensor should also be prioritized because it substantially improves the robustness of the NAROM UAS, enabling the UAV to safely fly in stronger winds. The author expects both of these solutions to be relatively simple, albeit time-consuming. Ordering the Adafruit XBee adapter from the USA also requires some delivery time, and testing and reconfiguring the airspeed sensor may require several test flights.

10.2 Additional Work

The natural next step is to have the flight permit extended for flights above 400 ft AGL, and beyond VLOS. The original application included in appendix C may serve as a template, saving NAROM paperwork. The new application must additionally be updated with an extensive probabilistic risk assessment, including a complete presentation of corrective safety measurements.

Flights beyond VLOS also requires an upgrade of the telemetry system, and the author recommends a directional patch antenna for the GCS. If the UAS is operated by a licensed radio amateur[3] the 10 mW XBee PRO autopilot RF links should be replaced as to increase the output power.

Another recommended update is to add tracking to the ground station, a feature currently developed for the GCS used in this project. Employing UAV tracking should enable even more narrow high gain antennas to be added, further increasing the range of the NAROM UAS.

It is also the intention that NAROM should be able to develop more payloads for the UAS in order to take full advantage of this UAV platform. Employing

[1] The Cryowing UAS project
[2] Adafruit Industries XBee Adapter Kit: `http://www.adafruit.com/products/126`
[3] NAROM personnel is currently undertaking classes.

Arduino-based CanSat kits as a platform for the payload system should be helpful in that several people within NAROM have first-hand experience with this equipment. With the original payload weighing only 120 g, there is still space and capacity for an estimated 400 g of payload instrumentation. Only the imagination should limit the use of this UAV platform, proving that the sky is certainly no limit!

Appendix A

Arctic EO Flyer

The Arctic EO Summer camp was central in inspiring the NAROM UAS project. To provide more background on the Arctic EO concept as well as NAROMs plans for UAS as an educational tool, this chapter includes the application flyer for 2011[6].

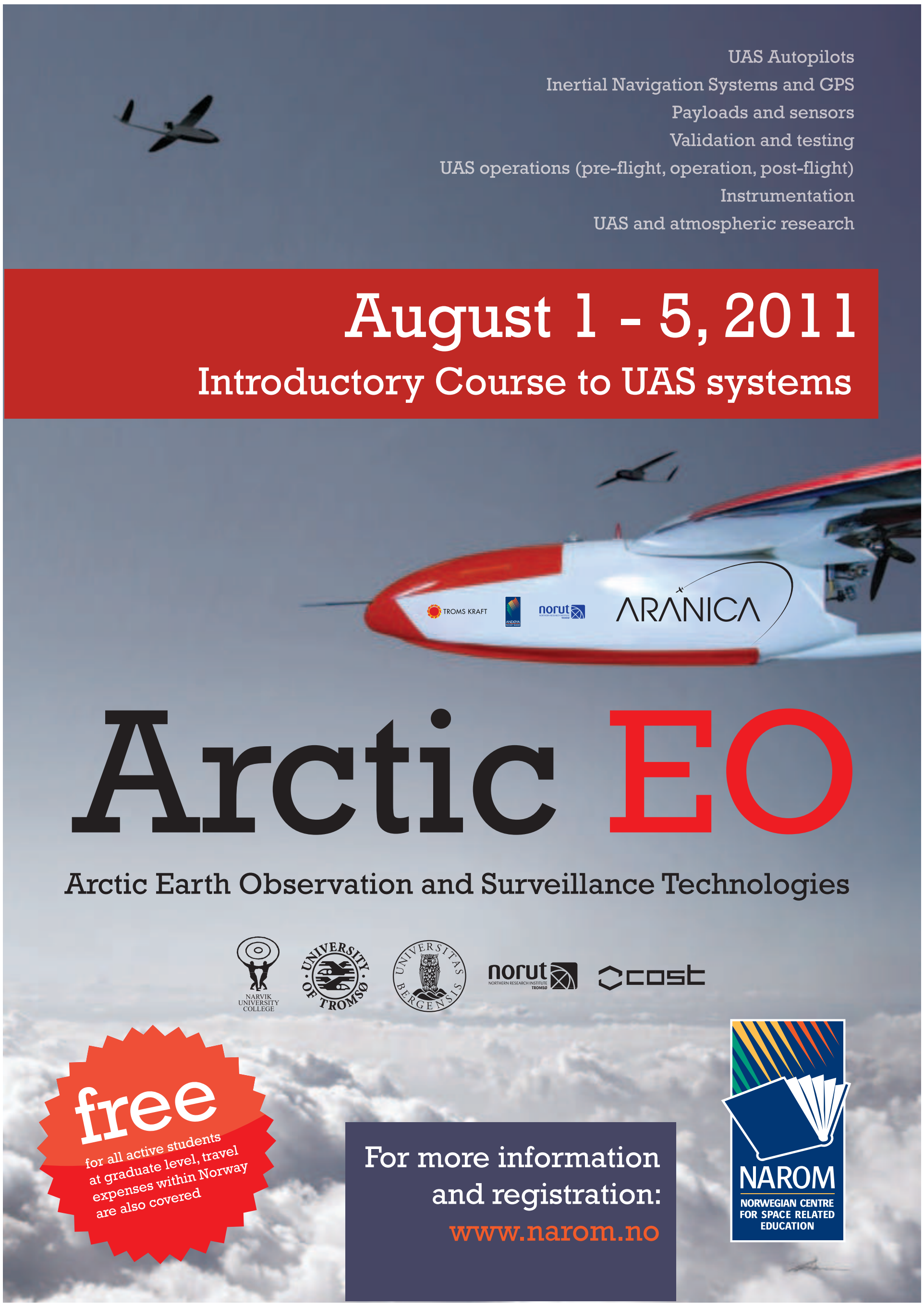


Figure A.1: *Page one of the 2011 Arctic EO flyer.*

Arctic EO Summer Camp

This summer 20 Master and Phd students can get a unique experience and learn about unmanned aircraft systems (UAS). NAROM together with Andøya Rocket Range, Narvik University College, University of Tromsø, University of Bergen and NORUT host the first summer school about unmanned aircraft systems with a technical approach at Andøya Rocket Range.

The summer School is an international summer school, also open for students outside Norway. The summer school is a part of the scientific project Arctic Earth Observation and Surveillance Technologies in cooperation with the European Cooperation in the field of Scientific and Technical Research (COST).

The course consists of theoretical lectures and practical operation of UAS and data analysis. Top scientists within their area will give lectures within UAS technology.

The main focus will be to plan a real UAS operation, build your own payload, integration within the UAS payload section, UAS operation and data handling and analysis.

Students will be enrolled under Narvik University College to be able to get the 5 ECTS credits for completing the course.

Topics

- Introduction to UAS systems
- Autopilots
- Inertial Navigation Systems and GPS
- Payloads and sensors
- Validation and testing
- UAS operations
- Instrumentation
- UAS and atmospheric research

Requirements

Mandatory requirements consist of a written report of approximately 30 pages, which summarizes the main points of the theoretical lectures as well as a description of the field operation and data analysis.

Cost

The full course, including lodging and accommodations is free for active students at graduate level.

Travel expenses within Norway will also be covered.

Application

The summer school is only open for graduate student at Master and Phd level. Send an application telling why you would like to participate in the summer school together with the following documentation:

- Personal and contact information
- Proof of active student at University / - University College graduate level
- Printout of your courses and grades

Applications to the course are to be sent to NAROM by April 1st, 2011: **narom@rocketrange.no** or **NAROM, PB 54, 8483 Andenes, Norway**.

Notification of acceptance April 15th.

For more information contact NAROM.
narom@rocketrange.no
+47 76 14 45 34

Register before

April 1st, 2011

Course period

August 1st - 5th, 2011

Arrival
July 31st, 2011 kl. 19:00

Departure
August 5th, 2011 kl. 15:30

In collaboration with

Narvik University College
University of Tromsø
University of Bergen
Norut
COST

NAROM
NORWEGIAN CENTRE FOR SPACE RELATED EDUCATION

Figure A.2: *Page two of the 2011 Arctic EO flyer.*

Appendix B

UAS Budget

NAROM UAS - Budsjettforslag 04.02.2011

	Produkt type	Beløp, NOK
Fly	UAV fly	3500
	Flymotor	1500
	Fartsregulator	1500
	Diverse	1500
	Sum fly:	**8000**
Radio	Flyradio og mottaker	4000
	Flyservoer	1500
	Sum radioutstyr:	**5500**
Autopilot	Autopilot inkludert IMU	4000
	Telemetri inkludert antenner	1000
	Sum autopilot:	**5000**
Nyttelast	Telemetri for nyttelast	1500
	Sensorer	1000
	Diverse	1000
	Sum nyttelast:	**3500**
Batteri	Batterilader	2000
	Flybatteri	2000
	Sum radioutstyr:	**4000**
	Sum NAROM UAS:	**26000**

Figure B.1: *Preliminary budget for the NAROM UAS .*

Appendix C

Flight Permit

C.1 Flight Permit Application

Arve Tokheim
c/o Andøya Rakettskytefelt
Postboks 54,
8483 Andenes
Mobil: 402 80 994

Morten Raustein
Flysikringsseksjonen ved luftfartstilsynet
Postboks 243
8001 Bodø

23.02.2011

Søknad om UAV flyging i Breivika, Andøya, for perioden 1.04-20.05.2011

Vi søker herved om tillatelse til å foreta UAS testflyging av en mindre UAV fra Andøya. Flytestingen vil være en viktig del av arbeidet med å forberede en UAS for bruk av NAROM (Nasjonalt senter for romrelatert opplæring). UAVen vil samtidig benyttes som en testplattform i undertegnedes masteroppgave ved Institutt for Teknisk Kybernetikk på NTNU. NAROM er et datterselskap av Andøya Rakettskytefelt (ARS), og vil være bruker av systemet. Det samme UAS systemet planlegges forøvrig brukt på en internasjonal UAS sommerleir i 2011, i regi av NAROM, NORUT, UiN, UiT, UiB og COST.

Primært søkes det om å fly innen visuell line-of-sight (VLOS), med en operasjonshøyde begrenset oppad til 400 fot AGL (Above Ground Level). Piloten vil hele tiden inneha visuell kontakt med flyet, og kan dermed ta manuell kontroll når som helst under flyging. Ved operasjonsstart vil vi også kontakte trafikkontrollen ved Andøya Flystasjon for klarering, og være tilgjengelig under operasjonen.

Uttestingen er tenkt å foregå i Breivika, og ønskes utført i perioden mellom 10. mars og 20. mai, 2011. Datoene er basert på når flyet forventes operativt. 20. mai er tidsfristen for undertegnedes masteroppgave, og anses derfor å være avslutnigsdatoen for prosjektet. Det aktuelle flygeområdet benyttes allerede til ARS sin Aranica UAS, og området det søkes om vil utgjøre et avgrenset utsnitt av tidligere innvilgede flygeområdet (se figur 1 i Appendiks 2).

Ytre koordinatene for testområdet er:

1. 69.2502N 16.0772E
2. 69.2502N 16.0772E
3. 69.2403N 16.0688E
4. 69.2306N 16.0156E
5. 69.2117N 15.9886E
6. 69.2014N 16.0614E
7. 69.2108N 16.0842E

Piloten har fra før av erfaring som modellflyger, og vil under uttesting assiteres av operatører fra ARS sitt Aranica program. Det planlegges kun testing i tidsrom med tilstrekkelig dagslys, og når værforholdene tillater flyging. NAROM UAS vil derfor ikke benyttes ved vindhastigheter over 8 m/s.

Hensikten med de initielle testflygingene er i hovedsak å gjøre NAROM UAS operativ. I første omgang som et modellfly, og deretter som en UAS. Testingen er ment å bygge erfaring med UAVens egenskaper, kapasitet og begrensninger, -så vel som operasjonsprosedyrer og planlegging. NAROM UAS er i neste fase tenkt utstyrt med en nyttelast for metrologimålinger (trykk, temperatur, fuktighet), der nyttelasten utvikles som en del av masteroppgaven.

Flymodellen som ble valgt for prosjektet er av typen "Skywalker EPO", og er et høyvinget fly med et vingespenn på $1,68$ m. Totalmassen inkludert nyttelast og navigasjonssystem er estimert til $2,5$ kg. Den planlagte nyttelastmodulen vil være både fysisk og elektrisk separert fra radio- og navigasjonssystem for økt sikkerhet, systemstabilitet og fleksibilitet. EPO styrofoam som byggemateriale sørger for lav masse, og minimerer samtidig flyets kinetiske energi. Lav materialtetthet begrenser videre skadene ved et eventuelt kræsj, og flyets skyvepropell er også med på å minimere skadepotensialet.

Autopiloten som skal benyttes er av typen ArduPilot Mega. Systemet er kommersielt tilgjengelig på open-source basis, og har en relativt stor brukermasse. Den store brukermassen har vært med på å gjøre ArduPilot til et velutprøvd og robust system. ArduPilot Mega er utstyrt med GPS-navigasjon, IMU, og hastighetsmåler (basert på pitotrør). Videre inneholder ArduPilot Mega en innebygget sikkerhetsanordning i en separat krets for overføring av kontroll mellom autopilot og R/C-system. Denne "failsafe"-anordningen kan også restarte systemet under flyging.

En radiolink sikrer 2-veis kommunikasjon med bakkestasjon og logger data under flyging. Flygeplan kan også redigeres undeveis. "Return-to-base" funksjonalitet er implementert i ArduPilot slik at flyet vender tilbake til startposisjon ved signaltap fra bakkestasjon. ArduPilot muliggjør også operasjonsplanlegging og gjennomgang i Google Earth. Teknisk og operasjonell beskrivelse av NAROM UAS er vedlagt i Appendiks 1.

Mot slutten av flyperioden vil det være ønskelig å fly også utenfor VLOS for for å oppnå metrologiske måledata av interesse. Etter anbefaling av Morten Raustein per telefon den 21.02.2011, sender vi i første omgang en forenklet søknad for VLOS flyging inntil 400 fot AGL. En mer omfattende søknad for etablering av segregert luftrom, slik beskrevet i AIC-N 25/09 (i dette skrivet definert som et "fareområde"), vil bli utarbeidet og forelagt Luftfartstilsynet innen kort tid.

Vennligst ta kontakt om det skulle være noen uklarheter, eller for eventuell tilbakemelding angående innledning av neste prosjektfase med tilhørende søknad.

Vennelig hilsen,

Arve Tokheim

Appendiks 1:

Tekniske og operasjonelle detaljer om NAROM UAS

Tekniske data om flytypen:

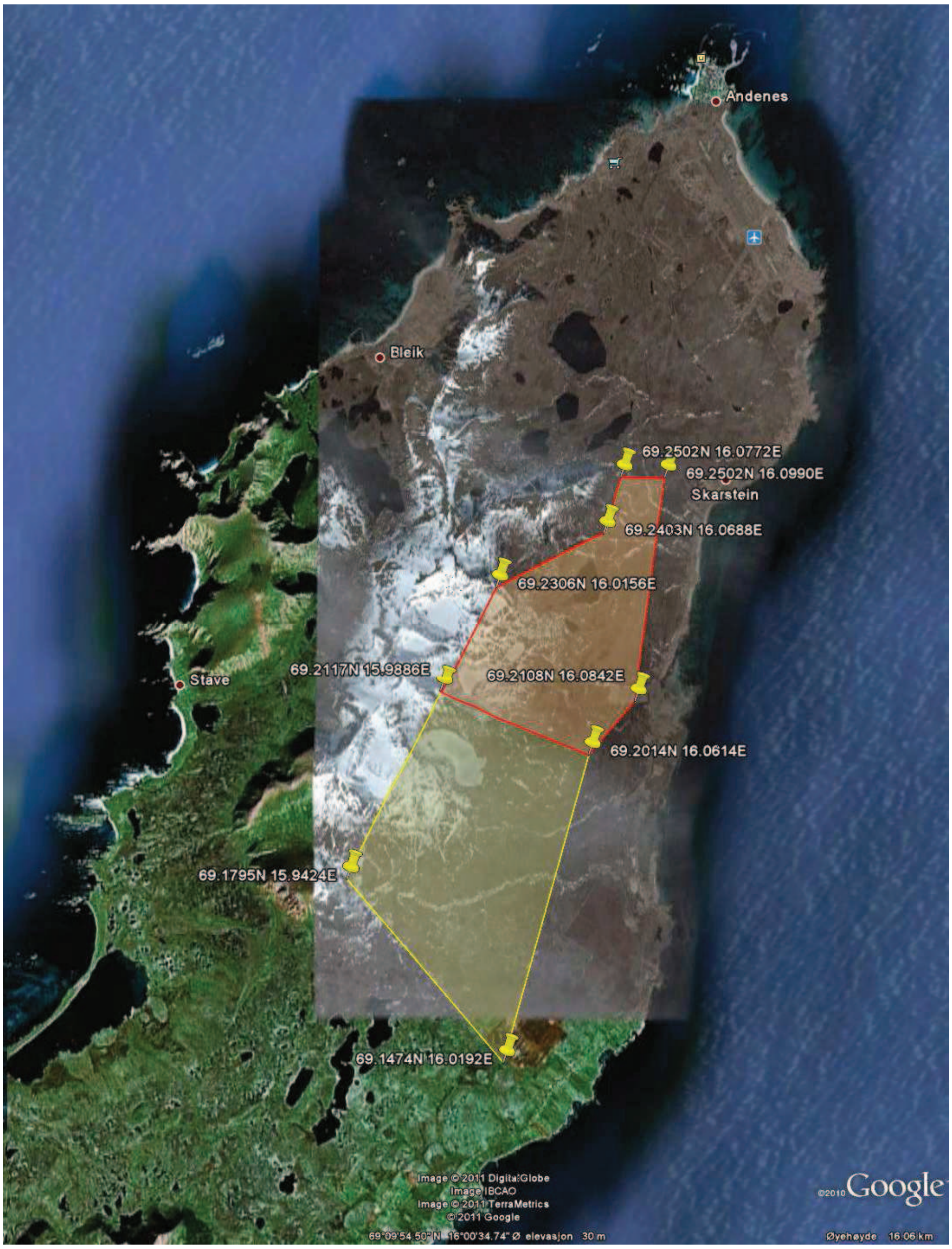
Navn på flymodell:	Skywalker EPO
Flytype:	Høyvinget monoplan med skyvepropell
Vingespenn:	1,68 m
Estimert maksimal flyvekt:	2,5 kg
Byggemateriale:	EPO styrofoam
Framdrift:	Elektromotor, børsteløs.
Estimert flygehastighet:	30-80 km/t
Estimert maksimal flytid	30-50 min

Operasjon av NAROM UAS:

Personell under start/landing:	To personer: En pilot og en operatør.
Personell under flyging:	1 person.
Flyging:	Autonom, men under konstant overvåking og kontroll fra bakken
Bakkestasjon:	PC med 2.4GHz radiomodem og toveis kommunikasjon. RC radiosender (35Mhz) for manuell take-off og landing. Radiosender fungerer samtidig som en sikkerhetslink.

Appendiks 2:

Opptegning av flyområdet i Google Earth



Figur 1: Det røde feltet illustrerer flyområdet beskrevet av koordinatene fra denne søknaden. Det gule feltet utgjør sammen med det røde feltet flyområdet Aranica tidligere har benyttet til UAS operasjoner.

C.2 Flight Authorization

Hei!

I henhold til informasjoner mottatt gjennom søknad og samtaler pr telefon, anser jeg kravene i AIC N 25/09 for oppfylt og flyging kan gjennomføres forutsatt at følgende vilkår kan følges:

1. Operasjonene foregår i henhold til de muntlige og i søknaden beskrevne retningslinjer og prosedyrer.
2. Operasjonene foregår i sin helhet under 400 fot over bakken, og innenfor synsrekkevidde, dvs. slik at pilot til enhver tid kan se, kontrollere flyet og unngå sammenstøt med hindringer i lufta og på bakken.
3. Operasjoner må ikke foregå i nærmere enn 5 km fra flyplasser uten at lokal lufttrafikktjeneste enhet (LTT) er informert. LTT kan i så tilfelle sette vilkår for flygingene.

Tillatelsen gjelder til 20. mai 2011.

Søknaden har fått Doculive saksnummer 200902205-30, og denne tillatelsen 200902205-31.

Vi noterer at LTT på Andøya vil bli kontaktet ifm operasjonene, og at operasjonsområdet har følgende koordinater:

1. 69.2502N 16.0772E
2. 69.2502N 16.0772E
3. 69.2403N 16.0688E
4. 69.2306N 16.0156E
5. 69.2117N 15.9886E
6. 69.2014N 16.0614E
7. 69.2108N 16.0842E

Vi gjør oppmerksom på at dette området utgjør deler av det publiserte fareområdet til Aranica, og det tillatte UAS operasjonsområdet slutter minimum 1 NM fra linjen mellom disse punktene.

Luftfartstilsynet ønsker deg lykke til med masteroppgaven!

Mvh

Morten Raustein
Flyoperativ inspektør
Operativ avdeling/Allmenfly/UAS
Luftfartstilsynet
www.luftfartstilsynet.no
Tel +4798261665
mra@caa.no

Appendix D

Payload System: Coding

This chapter lists the code for the the payload system.

```
///////////////////////////////////////////////////////
//     C-code for the NAROM UAS payload system       //
// GPS, pressure, temperature and humidity readings //
//              Arve Tokheim, May 2011               //
///////////////////////////////////////////////////////


#include <SoftwareSerial.h>

#define rxPin           11
#define txPin           12
#define ledPin           8
#define GPS_BUFFER_SIZE 82

int counter = 1; //frame counter

SoftwareSerial mySerial = SoftwareSerial(rxPin, txPin);


//Function printing GPGGA-format GPS data
void get_gps() {
  char string[GPS_BUFFER_SIZE];
  char a;
  int ctr;

  try_again:
  ctr = 0;

  //gps stream starts with $ symbol
  while((a = mySerial.read()) != '$');
```

```
while((string[ctr++] = mySerial.read()) != '\n');

string[ctr-1] = 0x20;
string[ctr-2] = 0x20;
string[ctr] = 0;

//Perform if GPS data is valid
if((ctr = strncmp(string,"GPGGA",5)) == 0)

  //Receiver logs upon reading "S"
  Serial.print("S ");

  //Printing Latitude data
  Serial.print(string[27]);
  Serial.print(string[17]);
  Serial.print(string[18]);
  Serial.print(" ");
  Serial.print(string[19]);
  Serial.print(string[20]);
  Serial.print(".");
  Serial.print(string[22]);
  Serial.print(string[23]);
  Serial.print(string[24]);
  Serial.print(string[25]);

  //Colons for text delimitation
  Serial.print(" : ");

  //Printing Longitude
  Serial.print(string[40]);
  Serial.print(string[30]);
  Serial.print(string[31]);
  Serial.print(" ");
  Serial.print(string[32]);
  Serial.print(string[33]);
  Serial.print(".");
  Serial.print(string[35]);
  Serial.print(string[36]);
  Serial.print(string[37]);
  Serial.print(string[38]);

  Serial.print(" : ");

  //Altitude above MSL [m]
  Serial.print(string[51]);
  Serial.print(string[52]);
  Serial.print(string[53]);
  Serial.print(string[54]);
```

```
      Serial.print(string[55]);

      Serial.print(" : ");

      //Satellite count
      Serial.print(string[44]);
      Serial.print(string[45]);

      Serial.print(" : ");
    }

    //If received GPS data was not valid
    else{goto try_again;
  }

}

//Initialization
void setup() {
  Serial.begin(38400);        //Sets serial port baud
  pinMode(ledPin,OUTPUT);     //Config LED portD
  pinMode(rxPin,INPUT);       //Config GPS input
  pinMode(txPin,OUTPUT);      //Config GPS output
  mySerial.begin(4800);       //Sets GPS serial port
  delay(1000);                //Delay after power up
  Serial.println("F8D1D1"); //Sets frequency to 433.500MHz
  delay(500);
  Serial.println("CSTBNC7");//Sets the call sign
  delay(200);
}

//Main function running in loop
void loop() {
  int pressure;
  int temperature;
  int humidity;

  get_gps();

  //Reading sensors
  pressure = analogRead(0);
  temperature = analogRead(1);
  humidity = analogRead(2);

  //Printing sensor data
  Serial.print(pressure);
  Serial.print(" : ");
  Serial.print(temperature);
  Serial.print(" : ");
```

```
  Serial.print(humidity);
  Serial.print(" : ");

  Serial.print(counter);
  Serial.println("");

  //Flashing LED to indicate operation
  digitalWrite(8, LOW);
  delay(100);
  digitalWrite(8, HIGH);
  delay(400);
  counter++;
}
```

Appendix E

Flight Log

This chapter includes the flight log for the NAROM UAV. The log was written both as part of the project, as well as by request from Luftfartsverket, and intends to provide a summary of each flight.

E.1 Initial Skywalker EPO Test: 29 March, 2011

The first flights were intended to test and provide experience with the airplane part of UAS. These flights were performed without the ArduPilot Mega (APM) autopilot, operating the UAV as an ordinary RC airplane. The weather condition in Breivika was excellent for the maiden flight, offering clear skies and calm air. The flight period began at 14:15 when permission was granted by the Andenes air traffic control, and ended at 15:50. Arve Tokheim piloted the airplane, and the effective flight time totaled an estimated 20 minutes. Jøran Grande and Torstein Wang from NAROM assisted in the flights.

Flight #1

The first flight lasted approximately 8 minutes and 30 seconds. Prior to flight the CG had been located to 8 cm behind the leading edge, and the airplane seemed well balanced in the air. For level flights the elevator rudder needed some trimming, but flight controls were otherwise excellent and the UAV displayed good stability. The motor offered ample power, enabling cruising at 35% throttle, and steady inclined climbs of 45°.

Flight #2

The second flight lasted approximately 6 minutes and 30 seconds. The purpose of this flight was to provide extra landing practice, but the airplane behaved so well that only one such practice flight was deemed necessary. The UAV offers excellent handling in airspeeds even as low as 20 km/h, and was relatively easy to land.

Flight #3

The third flight tested the UAV payload capability. A simulated payload of 550 kg was loaded into the airplane around the CG. As there was no head wind the airplane showed signs of being a bit heavy as it was launched; however, when the airplane picked up speed it still handled very well. Only a slight throttle increase from 35 to 45% was needed to maintain cruise speed. The motor still supplied ample power, and the UAV can probably tolerate larger payloads.

During the landing approach a signal glitch shortened the flight, causing a hard landing. The rough landing caused no damage, and the first flights were still regarded a total success. For future flights the RC receiver will be replaced by a more robust dual conversion receiver.

E.2 Stabilize Test Mode: 23 April, 2011

The purpose of today's flight was to test the NAROM UAV using the APM (ArduPilot Mega) *Stabilize* flight mode. The APM software used was version 1.02. The airspeed sensor was connected, but the Xbee radiolink was not needed for this flight. The flight conditions were nice with clear skies and little to no wind. The flight period began at 19:40, and lasted to 20:15. The total flight time was only 1 minute and 30 seconds due to serious radio issues. Arve Tokheim piloted the airplane, and Thomas Gansmoe (a student at HiN and feature employee of NAROM) assisted in the flight.

Flight #4

Even though the *Stabilize* system had been well tested on ground, strange issues emerged when powering the APM before flight. Following IMU initialization, the aileron, rudder and elevator control were suddenly found to have been reversed (both with the transmitter toggle switch in *Manual* and *Stabilize* mode). The APM was then rebooted and the rudder and elevator servos were suddenly back to normal operation. However, the ailerons suddenly displayed an extremely slow response in *Stabilize* mode, and after a second reboot the ailerons were back to normal but the same issue repeated with the elevator rudder. Following a third reboot the APM was functioning normally, and no reason for this unpredictable behavior was found nor experienced again. In any case, these issues emphasize the importance of thorough ground checks prior to flight, while also displaying how unstable this kind of experimental equipment may be.

As the autopilot was back to normal operation, the flight tower communicated the flight permit and Gansmoe launched the UAV. Shortly into the flight the transmitter signal was lost again, this time leaving the airplane hurling towards the ground. Luckily the glitch was temporary, and the UAV was recovered and immediately brought down for further inspections. Both this and last time the airplane had passed the range check. The APM had not been activated, and was not believed to have caused these problems.

During this flight the new dual conversion receiver was used in addition to a new pair of crystals for the receiver and transmitter. The repeated issue of signal loss raises suspicion to the RC transmitter and battery that are both 12-15 years old. Because the RC transmitter is in private ownership and funds for a new transmitter has been budgeted, a new transmitter will be purchased. The age of the transmitter system should not possess an issue in itself, but replacing the transmitter may in any case eliminate this issue.

E.3 Fly-by-Wire Test Mode: 1 May, 2011

The next flight was intended as a follow-up to the failed flight on April 23rd. The main objective was to verify operation of both the *Stabilize* and *Fly-by-Wire* modes, as well as testing the new Futaba RC transmitter. The APM software was updated to beta version 2.012. Flight time totaled 20 minutes starting 14:30, and ending at 15:30. Weather conditions were all right, with clear skies and wind speeds of $4-5$ m/s at ground level. Arve Tokheim piloted the UAV through the majority of the flight, with Jostein Sveen (from ARR Aranica) performing the landing.

Flight #5

The first five minutes were with manual control to test wind handling. Switching to *Stabilize* mode was very smooth, and the UAV leveled out as soon as the sticks were released, maintaining a horizontal flight heading. Switching to and from *Fly-by-Wire* mode was also completely smooth, and the default PID parameters for the Skywalker EPO autopilot controller appeared right. Some minor radio glitches were experienced at long range, but radio signal transmission was definitely improved. This flight was highly successful, and allows the test program to continue onto the next stage.

E.4 Return-to-Launch Test Mode: 12 May, 2011

The next flight tested the APM GPS navigation performance by activating the Return-to-Launch (RTL) mode in-flight. APM version 2.012 was used in combination with the airspeed sensor, and prior to flight extra efforts were made to evade radio noise. Any excess wiring between the RC receiver, APM, and servos was cut off and new "berghus" connectors produced and installed, and ferrite cores were mounted onto all four servo wires. This fix appeared to have worked well, and no signal glitch was experienced even at longer range.

Flight conditions were excellent, with no wind and clear skies. Flight time totaled 25 minutes, and with the exception of a few minutes flight by Torstein Wang (NAROM) Arve Tokheim piloted the UAV. These three flights were however only regarded a partial success because major problems were experienced with APM throttle control, requiring the test to be repeated. Nevertheless, excellent GPS data from all three flights was logged, and is included on the DVD in appendix F.

Flight #6

Following a five minute flight in *Manual* and *Stabilize* mode, the RTL command was transmitted to the UAV using the toggle switch on the transmitter. The UAV was then expected to turn towards the designated home area and circumnavigate this point at a preprogrammed radius of 60 m at 100 m AGL. When RTL was activated, the UAV increased motor power and turned around towards the home area. However as the UAV reached this area, the APM caused the motor to throttle back on and off in intervals, repeating at every 3-4 seconds. This forced the UAV into a steep climb followed by a stall. This pattern repeated while the airplane gained altitude. Because no improvement was observed the UAV was quickly put back into *Manual* mode. Both a second and third trial demonstrated this strange (although undramatic) behavior to repeat, and the UAV was eventually brought down for landing. Flight #6 lasted 9 minutes and 40 seconds, and a distance of 5.35 km was covered according to the APM log.

Flight #7

Flight #6 had demonstrated that the UAV could navigate by GPS data and find its way home despite the throttle issue. This is an important result, and it was decided to attempt a fully autonomous flight. This test could potentially reveal if the throttle issue was related to the RTL flight mode or airspeed sensor, isolating the problem. A preprogrammed flight plan was uploaded from a laptop and the transmitter toggle switch was reset to *Manual-Stabilize-Auto* mode.

When activating *Auto* mode the UAV showed no sign of following the waypoints, and the strange behavior repeated. It is assumed that the throttle issue causing sudden climbs and stalls caused the UAV to lose its navigational ability. The flight was then aborted, and the UAV landed after only 4 minutes and 20 seconds, covering a distance of 2.33 km. Because UAV behavior otherwise seems to work well in *Stabilize* mode, this flight concludes that either the airspeed sensor or throttle parameters are not working.

Flight #8

A third flight was carried out to provide some extra flight practice despite the reported APM problems. Only *Manual* and *Stabilize* mode were activated on this flight, but the complete flight was logged by the APM. Total flight time was 9 minutes, covering a distance of 5.87 km. The radio noise issue does now seem to have completely disappeared.

E.5 Autonomous Test Mode: 14 May, 2011

For this next flight the UAV and APM setup was kept the same with the exception of the airspeed sensor being disconnected. Flight conditions were once more excellent with no discernible wind and clear skies. The flight period began at 19:30, and lasted till 20:15. Total flight time was 25 minutes, and GPS and IMU data was collected on all three flights. Arve Tokheim piloted and monitored the UAV for the first two flights, with Jostein Sveen (ARR Aranica) monitoring and landing the UAV on the last flight.

Flight #9

A short and compact first mission[1] had been preprogrammed into the APM for the first flight. Following two minutes of manual flight, *Auto* mode was

[1] Flight plan 1, consisting of 10 waypoints with a total distance of 728 m.

activated while heading towards the first waypoint. APM successfully took control and navigated the UAV smoothly through all 10 waypoints before returning to launch. Total flight time was 6 minutes and 40 seconds, covering a distance of 5.65 km according to the APM log.

Despite the apparent success some difficulties were observed. The UAV showed signs of missing several waypoints only to turn around and pass through a second time. During these flights the waypoint radius had been generously preset to 30 m. It was concluded that the flight plan probably had been too compact, preventing the airplane from hitting all the waypoints on the first try.

Flight #10

Because flight plan 1 and 2 were both fairly compact it was decided to move directly to flight plan 3. Flight plan 3 consists of 16 waypoints, resembling the flight paths used for horizontal mapping. Total distance of flight plan 3 is 4.34 km, and the UAV will also be changing altitude throughout the flight.

Immediately after launch APM was set to *Auto* mode, and the APM autopilot guided the UAV through all 16 waypoints. After completing the flight plan the UAV returned to and circumnavigated the designated home area, and was then taken down by manual control. This time the UAV apparently missed only two waypoints, and showed no problems with hitting the waypoints on the second try without much interference with the original flight plan. Total flight time was 8 minutes and 50 seconds, covering a distance of 6.34 km.

Flight #11

It was decided to repeat flight plan 3 to compare performance and reproduceability, as well as to record the flight on video. On this flight the UAV interestingly missed the same waypoints, but performed well otherwise. Total flight time was 9 minutes, covering a total distance of 8.31 km.

Overcautious planning combined with the VLOS restrictions resulted in the planning of these compact flight plans. The waypoint miss is still expected to relate to the sharp turns on flight plan 1 and 3, and is not expected to become an issue. Today's flight test is regarded a great success and milestone in testing the NAROM UAV.

Appendix F

DVD

This DVD includes flight data, pictures, videos and software for the NAROM UAS.

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