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(U) Summary

Flamingo is a four-motor unmanned aerial vehicle (UAV) developed at the Norwegian Defence Research Establishment (FFI) primarily for use in research on cooperating autonomous systems. The drone is designed with a focus on achieving long flight times, easy integration of different payloads and robustness against normal weather conditions. The Flamingo UAV is based on an open-source flight controller with the Nvidia Jetson TX2 as a companion computer. A highly capable companion computer makes it possible to achieve advanced autonomy behaviour and perform scene analysis independent of a radio link to the ground station.

The construction concept is based on simple production techniques like 3D printing and carved carbon plates, making prototyping efficient compared to traditional machining and casting techniques. The total weight of the UAV varies from 2.2 kg to 2.8 kg depending on configuration, but the maximum take off weight (MTOW) is close to 4 kg with a limited flight time. Normal flight times are between 30 to 45 minutes, and weather robustness against wind and rain has been demonstrated with the standard configuration.

The UAV has been demonstrated in several swarm experiments as a part of the Valkyrie system, an autonomous swarm system delevoped at FFI with the goal of operating several electronic sensors simultaneously in an efficient way with a minimal use of human resources. This report presents the design and development of Flamingo.

(U) Sammendrag

Flamingo er et firemotors ubemannet luftfartøy (UAV) utviklet ved Forsvarets forskningsinstitutt (FFI) primært for bruk i forskning på ubemannede enheter i sverm. Farkosten er designet med fokus på lang operasjonstid, lettvint integrering av forskjellige nyttelaster og værrobusthet. UAV-en er bygget rundt en open-source flight controller med en Nvidia Jetson TX2 companion computer som muliggjør en høy grad av autonomi og sceneanalyse ombord i plattformen uavhengig av bakkestasjon og radiolink.

Byggekonseptet baserer seg på enkle produksjonsmetoder ved hjelp av 3D-printede komponenter og utskårede plater av karbonfiber, noe som gjør at prototyping og forskning med nye komponenter går raskere enn tradisjonelle maskinerings- og støpeteknikker. Plattformen har en totalvekt mellom 2,2 kg og 2,8 kg avhengig av konfigurasjon, men med en maks take-off-vekt opp mot 4 kg på bekostning av flytid. Vanlig operasjonstid på 30-45 minutter samt en værrobusthet mot normale vind- og regnforhold er demonstrert i standard konfigurasjon.

Farkosten er demonstrert i flere svermeksperimenter som en del av Valkyrie, et større autonomisystem for UAV-er med en målsetting om å utnytte flere elektroniske sensorer samtidig på en effektiv måte med liten bruk av menneskelige ressurser. Denne rapporten presenterer designet og utviklingen av Flamingo.

Contents

1 Introduction

Swarm research is one of the activities in the Autonomy research project at Norwegian Defence Research Establishment (FFI). The objective is to explore fundamental research on cooperative agents and verifying hypotheses through field experimentation. Most of the research is conducted on unmanned aerial systems, with a focus on Intelligence, Surveillance, and Reconnaissance (ISR), as one of the main applications.

The autonomy on the unmanned aerial vehicles (UAVs) are controlled by the Hybrid Autonomy Layer (HAL), an autonomy decision module developed at FFI to provide unmanned vehicles with the capability to perform advanced autonomous tasks. HAL has been implemented on several different platforms like unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs) and autonomous underwater vehicles (AUVs) in addition to UAVs. The main goal is to enable the platform to perform its mission on its own, reliving the operator from detailed control of the platform, including situations in which the platform in unable to communicated with the operator.

Valkyrie is a swarm system developed at FFI. Valkyrie implements the necessary components for coordinating multiple autonomous agents such as protocols for inter-agent communication, a multi-agent Ground Control Station (GCS) and a swarm-specific implementation of HAL. This allows a single operator to control several drones at the same time, reducing the need for human resources. By using multiple autonomous vehicles in a swarm-ISR application, better situational awareness can be obtained compared to using a single UAV.

FFI's research on autonomy has, in recent years, evolved to a level that makes it possible to conduct advanced UAV swarm-experiments. The autonomy has matured to a level that requires a capable platform with longer flight time, better weather resistance and more computational power to demonstrate the full capability of a UAV-swarm system.

This report presents the hardware development for the UAV platform Flamingo. Flamingo is a UAV developed mainly for autonomy experiments with an integrated companion computer capable of sensor processing and autonomous decision making. Flamingo is also developed for generic UAV experiments, with a design that makes it easy to integrate different payloads and make modifications to the platform without having to rebuild the system. The platform relies mostly on 3D-printed components fastened to a frame consisting of carbon fiber plates around a foam core. This solution makes it easy to build a small number of platforms without the need for a larger specialized production facility, at the same time as being a robust and light construction.

With a new and more capable platform in the swarm research activity, more complex experiments testing different sensors, links, and autonomy are possible.

2 Design

A need for an in-house developed UAV for autonomy experiments have increased as the autonomy research has matured from small-scale experiments to operations that are more complex. Earlier experiments have been based on modified Commercial-off-the-shelf (COTS)-systems. By using a robust and well-tested commercial platform the need for hardware development can be kept to a minimum. However, the main issue with the COTS-hardware is that it severely limits the adaptability of the overall system.

2.1 Requirements

The COTS UAV that the project has most experience with is the 3DR Solo [1]. This is a light consumer UAV weighing approximately 1.6 kg without payload. The UAV has a Flight Controller (FC) based on the Pixhawk Cube running the open source flight-stack Ardupilot [8], making the 3DR Solo a good platform for UAV swarm-experiments. This UAV has been used for several swarm-experiments [4, 3]. The Solo originally had a flight time up to 20 minutes without payload, but with an on-board Odroid C2 companion computer, a radio, and sometimes a camera, the flight time dropped below 10 minutes. Combined with lacking weather-resistance and the manufacturers built in limitation to access the FC, this had a large impact on what kinds of experiments it was possible to conduct.

Based on the experience from the 3DR Solo, a set of requirements for a new platform were made:

Flight Time When flying several platforms at once, the flight time is considered to be a critical factor. Most of the time it isn't practical to launch and land all the UAVs at the same time, meaning that the first airborne UAV has to wait for the rest of the drones to take off before a larger cooperative experiment can be performed. Without the ability to land all the drones at the same time, the battery margin has to be increased in case there is an unexpected delay in the landing sequence. A goal of practical flight time over 30 minutes was then set.

maximum take off weight (MTOW) The 3DR Solo has a maximum weight of around 2 kg. The current UAV-flight regulations are divided into different categories depending on weight and operation type. Most of the experiments conducted by the research-group is flown under the RO1-regulations. This means that the total weight of the system has to be below 2.5 kg and all the flights have to be in Line of Sight (LOS) with a maximum altitude of 120m in uncontrolled airspace. More complex experiments that exceed one or more of these criteria have to be conducted under military regulations. These kinds of experiments are achievable but demands much more planning and administration. Keeping the total weight of a new platform below 2.5 kg with payload would make the experiments much easier to conduct, but was not an irreversible requirement. This requirement would also depend on the payload configuration. The platform should have the ability to carry a larger payload with a total weight of about 800g, but then with limited flight time and an All Up Weight (AUW) exceeding 2.5 kg.

Weather resistance When planning a larger experiment, the weather is always uncertain. With a system that lacks the ability to operate in varying weather, it is always a risk that the experiment must cancel due to rain. With that in mind, the goal of designing a UAV that can handle normal varying Norwegian weather was set. This includes rain and wind to a certain extent, but it was not supposed to handle icing conditions or other extreme weather scenarios.

Payload In most UAV-experiments, there is the need of carrying some kind of payload. The current swarm-research is using a sensor payload consisting of a thermal camera, a daylight camera or both, preferably in a gimbal configuration. This payload needs power input from the drone and has to be controlled from the companion computer. The platform should not be limited to this payload and needs a general mounting option for different kinds of payloads. The integration of a new payload should need little to none modification to the platform, depending on the complexity of the payload.

Production and modification The UAV should be suitable for a small scale in-house production, from 1 to 5 in each batch.

Companion computer HAL is running on the companion computer. Earlier platforms have used an Odroid as a companion computer for the autonomy module, but with the limited processing power, the scene analysis and image processing have been restricted to a minimum. The need for more processing power, but still with a strict weight budget, an alternative to the Odroid is needed.

Flight controller The FC is the UAV's low-level control system, controlling the motor output based on information from the onboard sensors. The FC processes outputs from the autonomy module in the companion computer, like GPS-setpoints or attitude setpoints, and is returning sensor data to the companion computer while controlling the UAV to the given setpoint. Even though the 3DR Solo is based on an open source FC, there are some limitations to the system. The ability to fly the original radio controller e.g. is not possible. A FC with an open interface and the ability to take commands from the companion computer is needed. A FC should have the ability to work as a stand-alone unit and have fail safe mechanisms in case the autonomy module fails.

3 Flamingo

In this chapter, an overview of the Flamingo UAV from a top-down approach will be presented. The UAV is an in-house designed and built research platform with the capability of carrying varying payloads for different kinds of experiments. It is not supposed to have one final design, but is evolving along with the autonomy research, adapting to the current needs of the project. Fig 3.1 shows three Flamingos in the autonomy experiment LandX20 conducted by FFI in September 2020 on Rena.

3.1 General specifications

Fig 3.2 shows the Flamingo in its operational mode with a camera payload. This configuration is equipped with a thermal camera in a gimbal, but other cameras are possible to mount in the same gimbal. The cover on top of the frame is 3D-printed and is protecting the battery and electronics from rain and other external factors. Fig 3.4 shows Flamingo from different sides and the battery placement. Depending on configuration, the total weight is ranging from about 2.2 kg empty to 2.8 kg with the thermal camera payload and a 5.8GHz Mesh radio for swarm-experiments.

The standard 200 Wh battery gives a total flight time of approximately 45 minutes with an AUW of 2.5 kg, verifying the estimation in section 2. Flight times over 70 minutes have been demonstrated with a light configuration. The theoretical MTOW of the system is close to 4 kg, still maintaining a 2:1 thrust to weight ratio. The standard configuration for ISR-swarm experiments with an AUW of 2.8 kg gives an operational flight time of 35 minutes with a 20% battery margin.

Fig 3.5 shows Flamingo in transportation and storage mode. Here the arms are folded in the same direction, and the landing gear is folded up. It is also possible to remove the payload, making the system even more practical for transportation. The folding mechanism is based on snap-fit joints, and requires no tools for folding and unfolding. Setup time is less than 30 seconds. Fig 3.7 shows a detailed view of the snap fit lock used to hold the arm in its open position.

The battery placement is shown in Fig 3.4. The cover is removable, revealing the battery, which is secured to the frame using Velcro straps. The cover utilizes a convenient slide-lock mechanism and is not significant for the structural integrity of the platform.

3.2 Frame

Electronic components are hidden and protected inside the frame, and extra space allows component change and modification to some degree without having to redesign the platform. Fig 3.6 shows the inside of the frame with the main components and the bottom of the UAV with the integrated heat sink. The heat sink is 3D-printed in aluminum and customized for the Jetson TX2. This solution protects the companion computer by mounting it in the center of the frame, and at the same time, it transports the produced heat out of the platform. Taking advantage of the natural airflow around an airborne system, it was possible to make the custom heat sink smaller and lighter, weighing only 30g compared to the original 75g. The figure also shows pre-installed M3 clinch nuts in the carbon fiber, four in the center for the camera payload and four along the sides for future use. This makes the integration of custom payloads easy for future experiments.

Figure 3.1 Three Flamingos on a joint mission.

Figure 3.2 Flamingo with a mesh-radio and thermal camera.

Figure 3.3 CAD-model of Flamingo.

Figure 3.4 Flamingo viewed from different sides. Battery in yellow showed under cover.

Figure 3.5 *Flamingo with arms folded in transportation mode, and corresponding four Flamingos in a transportation case.*

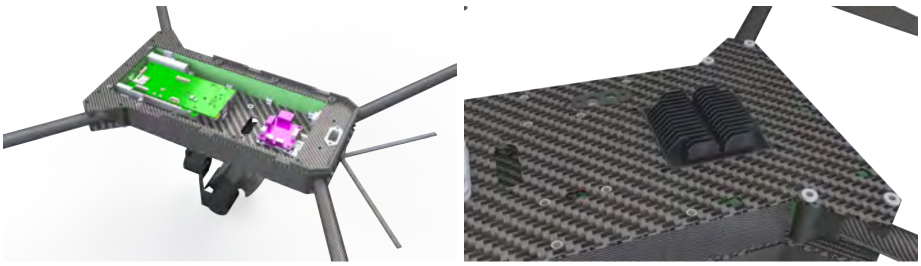


Figure 3.6 *Integrated companion computer and flight controller to the left. Right side shows the heat sink for the companion computer.*

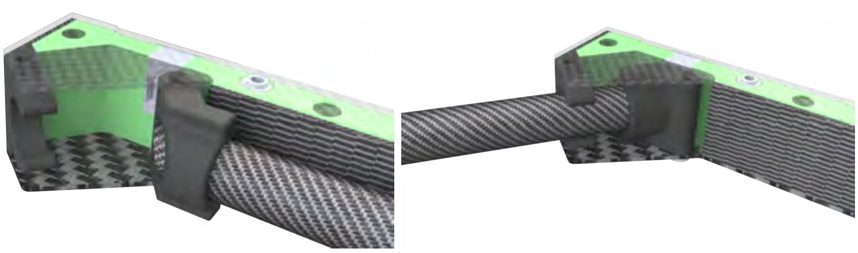


Figure 3.7 Snap-fit mechanism of the arms illustrated in open and folded position.

3.3 System architecture

The Flamingo UAV has a system architecture based on modularization of the different main components. This makes it possible to replace components and reuse solutions on other platforms, for different applications, and in future research. The UAV's system architecture can be split into four categories, illustrated in fig 3.8:

Propulsion system The propulsion system consists of four motors with propellers. The UAV's maneuvering capability, speed, and flight time is determined mainly by characteristics of this setup. The process of choosing the correct setup is described in section 3.5.

Control system The low-level control system is based on the open source software suite Ardupilot [2] running on a Pixracer from mRobotics [7]. This FC, combined with a GNSS-module and a RC-controller, is enough to perform a manual flight without the companion computer. The FC and the different flight modes is described in section 3.4

Autonomy The companion computer is running the autonomy module HAL and has a dedicated radio link to the ground station for commands and feedback. This companion computer is a Nvidia Jetson TX2 with a high performance given its low size and weight, making it possible to apply advanced high level autonomy and on-board sensor processing.

Payload The drone has a payload that in the standard configuration consists of a sensor and high-bandwidth radio link used for video and sensor feedback to the ground station. The payload is described in section 3.6.

3.4 Control system

The Pixracer is a highly capable FC, using the on-board sensors needed for a Global Navigation Satellite System (GNSS)-guided flight. By having a robust FC for the low-level control, it is possible to use the UAV as a stand-alone unit using a direct RC-link with manual control-input from a pilot on the ground, even though the UAV is designed primarily for autonomous flights. The FC has several different flight modes, and the most important ones are:

Guided This flight mode is used when the UAV operates with control input from the companion computer, normally a velocity vector. This type of control requires that the GNSS-module is operational. The system is also capable of exchanging attitude setpoints, meaning that the HAL-module running on the companion computer has direct control over roll and pitch setpoint on the drone and therefore has the ability to control the drone without a GNSS-signal.

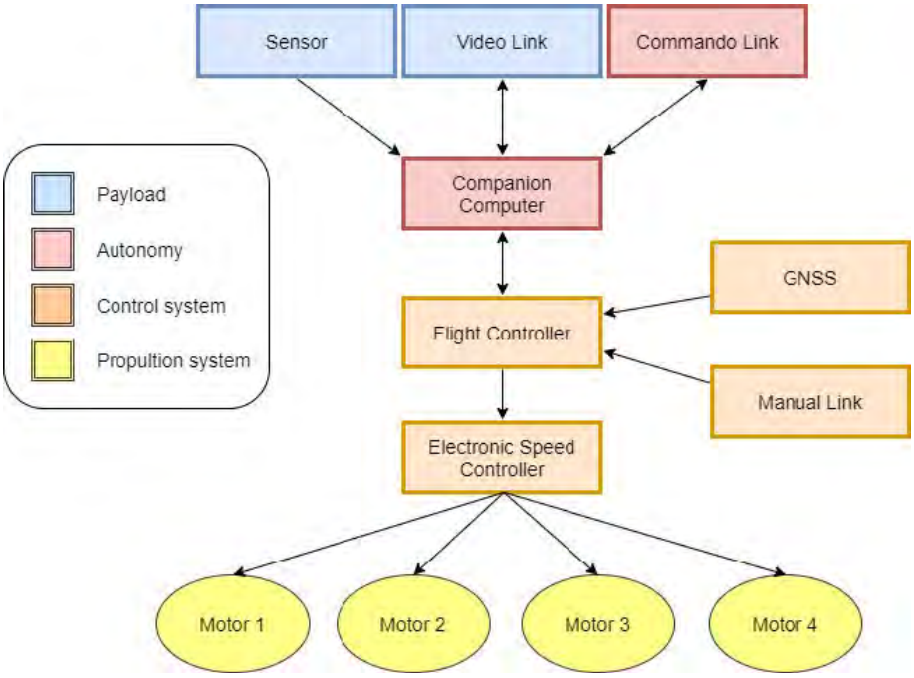


Figure 3.8 System architecture

Without position feedback from the GNSS-module, an alternative navigation system is required.

Loiter This flight mode is the manual flight mode where the UAV is controlled by a pilot with a RC-controller. This flight mode is primarily as a back-up for the autonomy module, even though it makes it possible to use this UAV as a stand-alone unit only operated by a RC-controller.

Return-To-Launch (RTL) This flight mode takes the UAV home to the take off position in the shortest route. The flight path is controlled by the FC and is used only as a safety feature. *RTL* can be initialized from the back-up link or by the autonomy module itself.

Both *Loiter* and *RTL* flight modes will always have the possibility to override the autonomous control, working as safety features when experimenting with new and unproven autonomy behavior. *RTL* is also used as a loss of link safety behavior, activated if the back-up link loses connection to the drone.

3.5 Propulsion system

In order to decide the best configuration for this UAV, different motors and propellers from T-motor have been tested in a rig that measures thrust and power consumption at different voltage levels. This makes it possible to choose the most beneficial setup in terms of optimizing flight time given a weight and battery size. Due to the initial design choice of a four motor quadcopter-configuration and a take off weight of approximately 2. 5kg, it is possible to estimate a flight time with different battery sizes. Calculations and measurements indicates that the AG4006 motor is the best fit for this kind of setup. This is a small motor weighing only 68g, but still able to deliver over 2 kg of

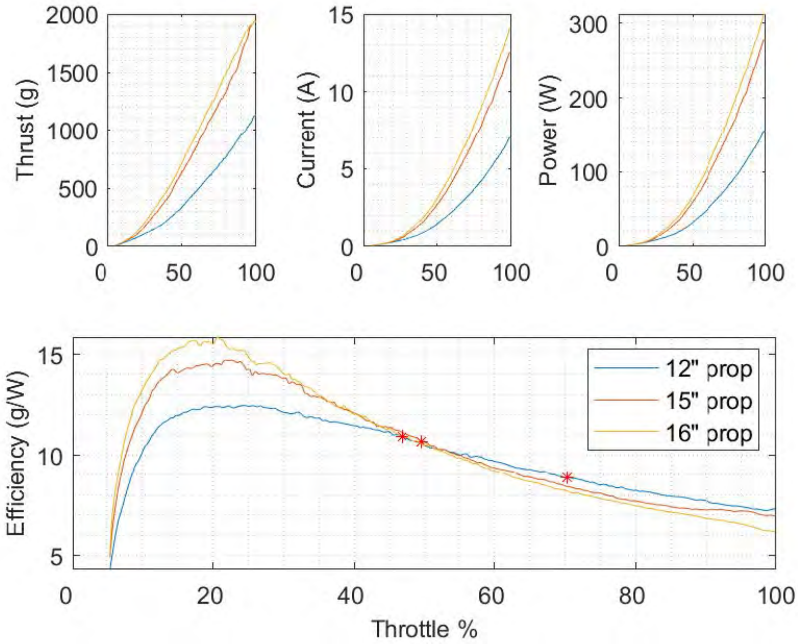


Figure 3.9 This graph shows the result of three different propellers on the same motor from 0 to 100% throttle. The throttle setting that gives 600g thrust is marked on the plot with a red dot, indicating that a 12" propeller has generally lower efficiency and needs 70% throttle to generate the same thrust as a 15" prop gives on 50%

thrust with a relative high efficiency.

This AG4006 was tested with five different size carbon fiber propellers at two different voltage settings, corresponding to a total of 10 unique configurations. The propellers spanned from size 12" to 16" both static and folding, with a voltage configuration of 14.8V and 21.1V. The two different voltage settings are corresponding to a 4 cell and 6 cell Lithium battery setup, a common configuration for UAVs in this category. The test revealed a non-significant performance difference between the folding and the static propellers of the same size. The 14,8V setup showed a small difference in terms of efficiency, but the total thrust generated due too the lower voltage was to low for this configuration. Figure 3.9 shows the summary of the performance of the AG4006 with a 22.1V power supply and three different size propellers.

Fig 3.10 shows the estimated flight time based on a quadcopter configuration with the AG4006 motor with a total weight of 1400g + battery. The calculations are done with a simulated battery with an energy density of 200 Wh/kg ranging from 0 to 2600g in steps of 100g. The plot ends when the thrust to weight ratio reaches 2:1, illustrating that a 12" propeller can handle an MTOW of 2200g while a 16" propeller has an MTOW at 3800g. The lower subplot shows the extra flight time gained per step when adding an extra 100 g/20Wh worth of battery. Due to the lower efficiency at higher thrust shown in fig 3.9, the flight time gained from adding extra batteries is almost totally absorbed by the extra weight when the battery gets large enough. The flight time increases from 38.1 minutes to 55.9 minutes when going from a 500g battery to a 1000g battery, an increase of almost 18 minutes. In contrast, a battery increase from 1.4 kg to 2.4 kg results in less than 3 minutes

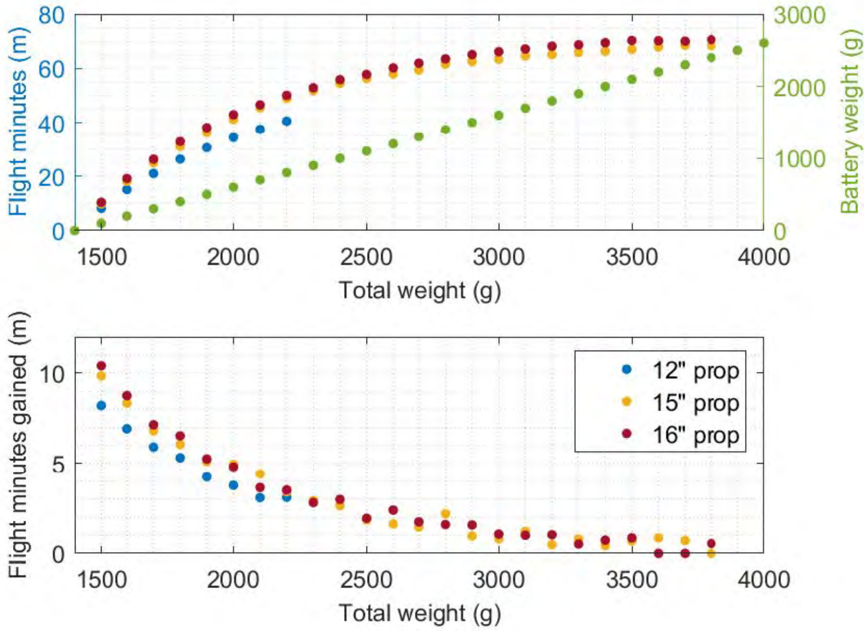


Figure 3.10 The top graph shows the calculated flight time based on increasing battery size. The lower graph shows the extra flight time gained pr extra battery cell.

extra. In summary, the plot shows that flight times over 70 minutes is possible with a large battery over 2 kg, but that a battery around 1 kg is more beneficial, still giving over 50 minutes of flight time with a light payload.

Fig 3.11 shows the estimated flight time with fixed battery size and a variable payload. The configuration is the same as in fig 3.10, but with a empty weight of 2 kg and a 1000 g battery with a capacity of 200 Wh. This figure shows an estimated flight time of 64 minutes with zero payload and 16” prop, and that the 12” prop gives 51 minutes of flight time with the same configuration. The 12” prop gives an MTOW of 2250g with a flight time of 44 minutes. A normal configuration with 500g payload and an MTOW of 2.5 kg should give approximately 47 minutes flight time with a 16” propeller, well withing the criteria defined in section 2. A 16” propeller would allow for an MTOW of 3.8 kg, giving this platform the ability to carry large payloads.

A quadcopter configuration with the T-motor AG4006 motor with a 16” propeller and a 6 cell lithium battery with the capacity of 200 Wh seems to be a good configuration for this kind of platform. The calculated flight times are of course an estimation, and factors like battery health and temperature, wind and turbulence will affect the result. Since the motors and propellers have been tested in a controlled indoor environment, the results will only be valid for a hovering flight in windless conditions. Due to the effective translation lift, there is expected to be a higher efficiency when moving through the air, but this effect has to be measured on a working prototype.

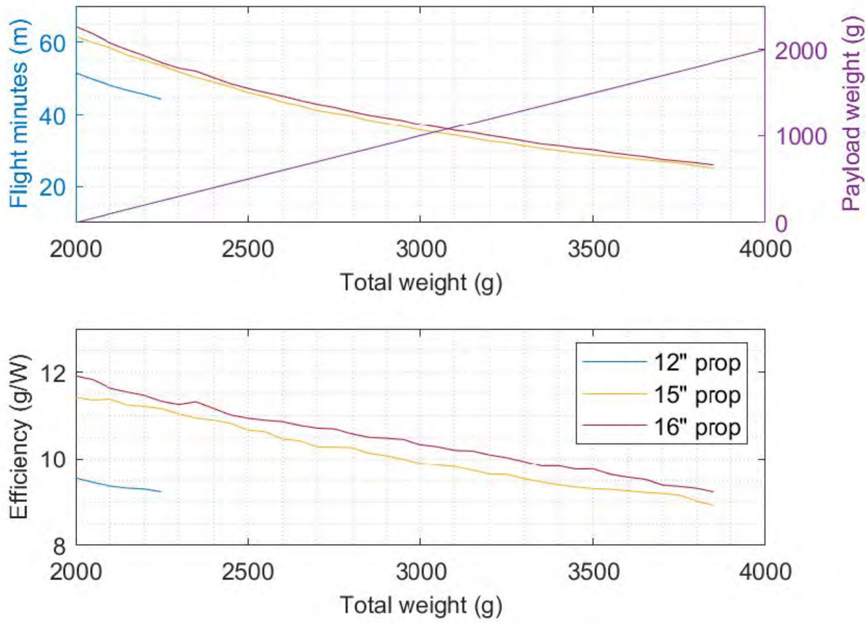


Figure 3.11 Estimated flight time based on fixed battery size and a variable payload with the corresponding efficiency at different weights.

Figure 3.12 Thermal picture of cars and people

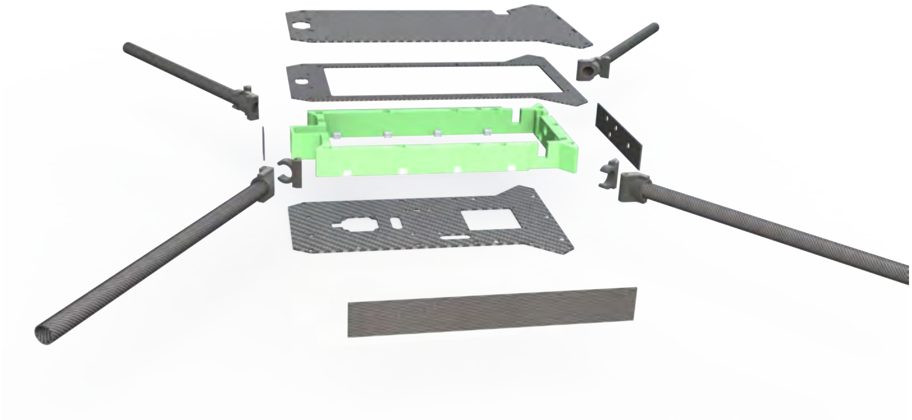


Figure 3.13 Exploded view of the frame

3.6 Payload

The Flamingo UAV is developed for easy integration of different payloads. The standard ISR-configuration of the Flamingo is a FLIR Boson 640x512 thermal camera [5] in a gimbal configuration along with a 5.8Ghz Mesh radio used for streaming video to the ground station. The thermal camera is a versatile sensor with capability to survey an area under most circumstances both in daylight and complete darkness. Figure 3.12 shows an example of a picture from the Boson camera. The mesh radio makes it possible for several drones to communicate with each other as a true distributed swarm system independent of a ground station. Using a mesh radio, a longer range can be achieved by using drones as radio-relay between the swarm and the ground station. A picture of the Flamingo with the thermal camera and mesh radio is showed in fig 3.2.

3.7 Building technique

Fig 3.13 shows an exploded view of the main components in the frame. The frame consists of 1.5mm thick carbon fiber plates glued with epoxy to a PVC-foam core. Ordering pre-cut carbon fiber based on drawings generated from the CAD-model is a convenient way to acquire materials for building. The assembly is relatively easy and requires no special tools, making this an easy technique for a small batch production. Fig 3.14 shows a detailed view of the different components in the frame. The top pictures show the foam core and the belonging carbon fiber plate. The core is made from a PVC-foam with a density of 80kg/m^3, making it a rigid and light core for this kind of sandwich construction. The bottom left picture shows a detailed view of the clinch nuts inserted into the carbon fiber, while the last picture shows a frame fully assembled before the motors and electronics are mounted.

The UAV consists of several 3D-printed components. This makes it possible to maintain a rapid prototyping process and easy accessibility to spare parts. Continuous Fiber Reinforcement technology from Markforged prints with Onyx and carbon fiber as reinforcement [6]. Onyx is the base material for the 3D-printer and is made from a mix of nylon and chopped carbon fiber. The

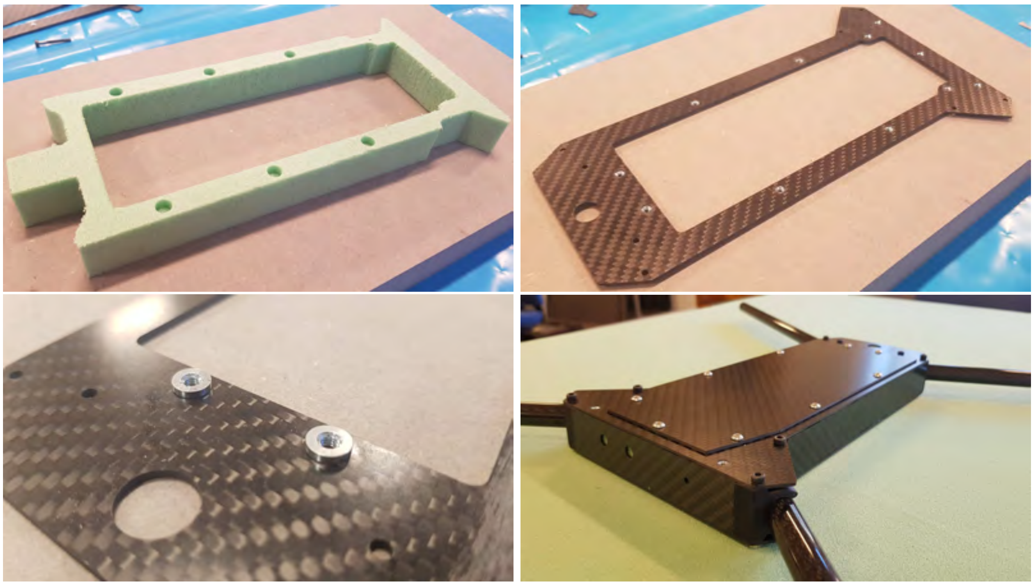


Figure 3.14 Frame parts

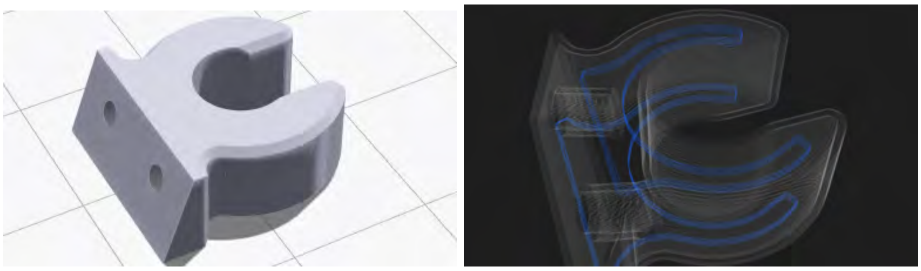


Figure 3.15 3D printed snap fit part. Internal view with continuous carbon fiber illustrated in blue

continuous fiber reinforcement creates a durable part which is fully functional without the need of post-processing. Fig 3.15 shows a part from the landing gear on the UAV both the outside view of the part and the internal view where the path for the continuous fiber string is illustrated with blue lines.

4 Experiments

The Flamingo UAV has been involved in several experiments, both as a single UAV, in a swarm, and in cooperation with other sensor systems. Many of these experiments shows the flexibility of the system.

4.1 Autonomy

Valkyrie is the swarm system developed for autonomy research at FFI, where Flamingo is the main UAV used. The Valkyrie system consists of several drones and a GCS that is capable of controlling the drones, as well as visualize sensor information and flight statistics. The ground station has the possibility to redirect sensor data to other systems and receive commands that can be used to control the swarm. The default configuration for the system is four drones and a ground station, but the system is scalable from one to many drones. A snapshot of the GCS is showed in fig 4.1, where four drones are surveying two different locations.

4.2 Flight times

The initial goal was a practical flight time of 30 minutes. A 72 minutes flight have been demonstrated without payload, but the practical duration is between 30 to 45 minutes, depending on payload. Initial tests indicate that higher efficiency is obtained when the UAV is moving compared to a hovering flight. Plot of the flight efficiency is showed in Fig 4.2. This test indicates a difference of approximately 15% or 7 minutes when moving at $5m/s$ compared to a hovering flight. There will also exist an airspeed where the efficiency is most optimal in regards of pure flight duration and an airspeed that gives the longest distance covered in one battery. More thorough experiments must be conducted to gain more precise knowledge about these numbers.

4.3 LandX 2020

The capability of the Valkyrie system and the Flamingo UAV was demonstrated on the LandX experiment in September 2020. LandX was an experiment were sensor data from different autonomous platforms and stand-alone systems were fused in a common Graphical User Interface (GUI) for better situational awareness. Over 40 hours of autonomous flight were demonstrated during this experiment, and the project gained a lot of useful knowledge about swarm operation in varying scenarios and weather conditions.

4.4 Weather resistance

During the LandX experiment, the UAVs were thoroughly tested in a typical Norwegian autumn climate with both rain and windy conditions. The Flamingos conducted swarm experiments for several hours with wind speed above 9 m/s with gusts between 15 and 18 m/s. Fig 4.3 shows the wind conditions measured by the Norwegian Meteorological Institute at Landsørkje airstrip, nearby the location of the LandX experiment. Evaluation from this week concluded that the UAV is capable of handling most normal weather in terms of wind and rain. The UAV has less testing

Figure 4.1 Snapshot of control station showing four drones covering two axes from different angles

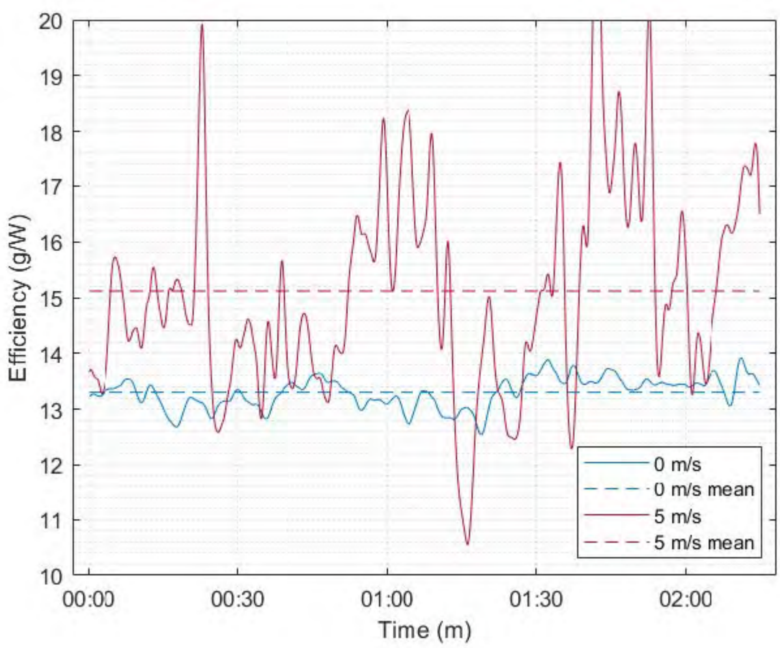


Figure 4.2 Flight efficiency at 5m/s and 0m/s

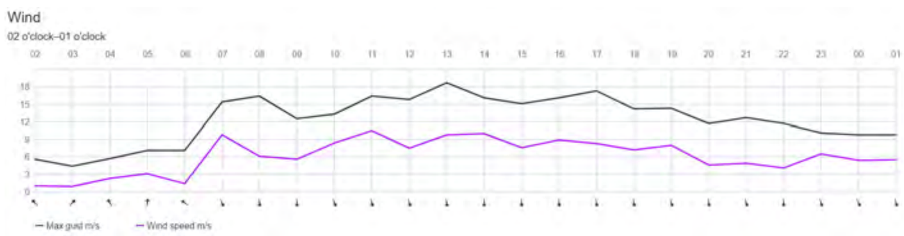


Figure 4.3 Wind conditions on Rena 16.09.20

Figure 4.4 Flamingo equipped with a CRE2-144-LW from Radionor

in winter conditions, but initial experiments from early prototypes indicates that the UAV should handle these conditions as well.

4.5 Communication link

Several different radios have been tested on the Flamingo. Since the control system is separated from the autonomy module, illustrated in fig 3.8, changing the radio required only minor changes in software and a easy integration in hardware. Fig 4.4 shows a picture of the UAV with the long range radio CRE2-144-LW from Radionor integrated on the platform. This radio uses a phased array technology with electronic beam-steering to provide a robust communication link with long range in a small form factor. This experiment was conducted as a part of an cooperation between multiple projects on FFI for evaluation of the radio.

5 Discussion and further work

At the time of writing this report, four Flamingos are built and used for autonomy research as part of the Valkyrie system in the Autonomy project at FFI. The research group has learned a lot from this process, from the initial design phase to developing and flying several drones at the same time in swarm experiments. As earlier mentioned, the Flamingo UAV is not supposed to have a final design, and improvements from current version are already implemented in the updated design. The next iteration of Flamingos are currently being made with integrated radios, upgraded companion computer and a new battery with a higher energy density.

Because of the adaptability and flexibility of the Valkyrie system, several other projects at FFI and people from outside the organization have gained interested in the Valkyrie system. There is currently an ongoing process of certifying the Flamingo and the Valkyrie system for operational use in the Norwegian Armed Forces. If an air-worthiness certification of the system turns out to be successful, this opens for new and more extensive swarm-research and operations in real-world settings.

The UAV is still in an early stage in terms of robustness and durability testing, but the main goal of developing a flexible platform for autonomy research is fulfilled. Further flight tests and more demanding experiments will define the future development of the system and where the focus on hardware development should be.

The Flamingo, along with the rest of the Valkyrie system, has made a foundation that makes it easy to conduct swarm experiments in more complex scenarios, pushing the limits of UAV swarm-research. Having a in-house designed and built UAV makes it possible to design experiments that were impossible on previous platforms due to the lack of integration possibilities. This in turn making experimenting with new kinds of payloads much more uncomplicated.

Abbreviations

FFI	Norwegian Defence Research Establishment
GCS	Ground Control Station
GNSS	Global Navigation Satellite System
HAL	the Hybrid Autonomy Layer
LOS	Line of Sight
FC	Flight Controller
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
AUV	Autonomous Underwater Vehicle
MTOW	maximum take off weight
AUW	All Up Weight
GUI	Graphical User Interface
COTS	Commercial-off-the-shelf

References

[1] 3DR. About 3DR Solo. https://www.3dr.com/company/about-3dr/solo/, 2020. [Online; accessed 25-September-2020].

[2] Ardupilot. Documentation. https://ardupilot.org/ardupilot/. [Online; accessed 30-September-2020].

[3] S. Engebraten, K. Glette, and O. Yakimenko. Networking-Enabling Enhancement for a Swarm of COTS Drones. *IEEE International Conference on Control and Automation, ICCA*, 2018-June: 562–569, 2018. ISSN 19483457. doi: 10.1109/ICCA.2018.8444274.

[4] S. Engebraten, K. Glette, and O. Yakimenko. Field-Testing of High-Level Decentralized Controllers for a Multi-Function Drone Swarm. *IEEE International Conference on Control and Automation, ICCA*, 2018-June:379–386, 2018. ISSN 19483457. doi: 10.1109/ICCA.2018.8444354.

[5] FLIR. Boson. https://www.flir.com/products/boson/. [Online; accessed 22-Januar-2021].

[6] Markforged. Mark Two. https://markforged.com/3d-printers/mark-two. [Online; accessed 30-September-2020].

[7] Mrobotics. Pixracer. https://store.mrobotics.io/mRo-PixRacer-R15-Official-p/auav-pxrcr-r15-mr.htm. [Online; accessed 28-September-2020].

[8] Px4 Docs. Pixhawk Cube. https://docs.px4.io/master/en/flight_controller/pixhawk-2.html. [Online; accessed 25-September-2020].

About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's MISSION

FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's VISION

FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

Creative, daring, broad-minded and responsible.

Om FFI

Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

FFIs FORMÅL

Forsvarets forskningsinstitutt er Forsvarets sentrale forskningsinstitusjon og har som formål å drive forskning og utvikling for Forsvarets behov. Videre er FFI rådgiver overfor Forsvarets strategiske ledelse. Spesielt skal instituttet følge opp trekk ved vitenskapelig og militærteknisk utvikling som kan påvirke forutsetningene for sikkerhetspolitikken eller forsvarsplanleggingen.

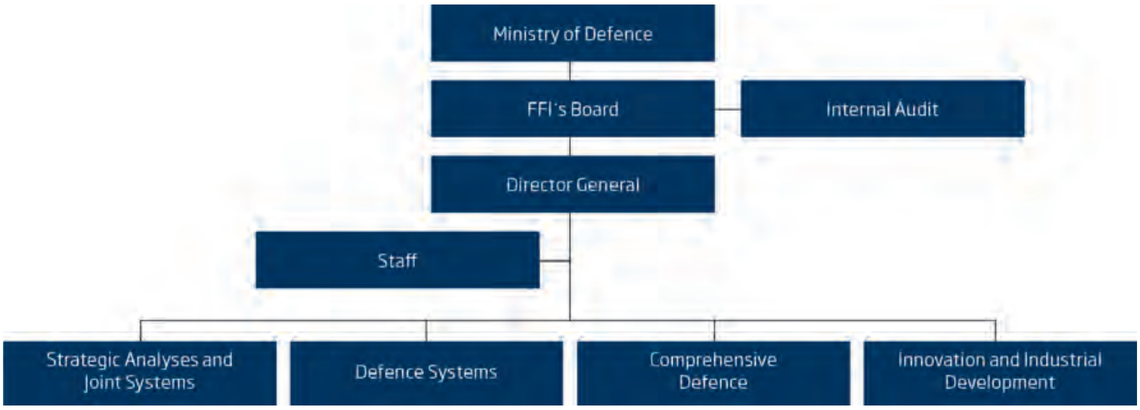
FFIs VISJON

FFI gjør kunnskap og ideer til et effektivt forsvar.

FFIs VERDIER

Skapende, drivende, vidsynt og ansvarlig.

FFI's organisation



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