Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Development of Fixed-Wing Unmanned Aerial Vehicle for Autonomous Cargo Delivery

Master's Final Degree Project

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Supervisor

Kaunas, 2026

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Mechatronics (6211EX017)

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Task of the Master's Final Degree Project

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1. Title of the Project

Development of Fixed-Wing Unmanned Aerial Vehicle for Autonomous Cargo Delivery

(In English)

Fiksuoto sparno nepilotuojamo orlaivio, skirto autonominiam krovinių pristatymui, kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to develop a fixed-wing unmanned aircraft that has a cargo compartment and can be applied for autonomous cargo delivery

Tasks:

1. to design a cargo compartment and perform_aerodynamic analysis;
2. to choose components and calibrate the fixed-wing UAV;
3. to design an autonomous dropping system and test it;
4. to evaluate delivery accuracy.

3. Main Requirements and Conditions

The developed fixed-wing UAV system must autonomously release the payload using an automatic dropping mechanism under stable weather conditions. The payload must be delivered while flying at an altitude lower than 40 m above ground level with a delivery accuracy of up to 5 m from the target. The research must evaluate the reliability of the autonomous payload release system through experimental tests.

4. Additional Requirements for the Project, Report and its Annexes

Not applicable

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	(Name, Surname)	*(Signature)*	*(Date)*
Supervisor	Valdas Grigaliūnas		02-03-2026
	(Name, Surname)	*(Signature)*	*(Date)*
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	(Name, Surname)	*(Signature)*	*(Date)*

Justas Pirinauskas. Development of Fixed-Wing Unmanned Aerial Vehicle for Autonomous Cargo Delivery. Master's Final Degree Project, supervisor Researcher Dr. Valdas Grigaliūnas; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: fixed-wing UAV; delivery; computer vision; aerodynamics; digital twin; additive manufacturing.

Kaunas, 2026. 61 p.

Summary

The objective of this work is to develop and test a fixed-wing unmanned aerial vehicle (UAV) which would autonomously drop items in the intended spot by capturing a QR code with on board camera, analysing it in real-time and making decisions with an integrated artificial intelligence algorithm. The literature review part of the thesis introduces the different UAV designs, their strengths and weaknesses, 3D scanning overview, modelling and aerodynamics analysis importance and principles. Further, it discusses 3D printing materials, processes, and the importance of parameters for this project. Also, sensors and artificial intelligence integration in drones and autonomous object detection. Lastly, real-life testing and delivery accuracy are important in such a project. In this project, a fixed-wing UAV is scanned with a HandySCAN 700 3D scanner and a digital twin of the drone's structure is created for the best possible cargo compartment modelling. After that, components are picked for the intended task of delivering a small parcel in a visual line-of-sight flight. The cargo bay is modelled with an integrated Sony 8MP 77° IMX219 autofocus camera module and servo motor for the autonomous dropping of the cargo. Camera is connected to the Raspberry Pi Zero 2 W computer for AI-Based QR code detection from computer vision libraries to autonmously drop cargo without a pilot intervention. Lastly, everything is tested to evaluate the delivery accuracy and limitations of the proof-of-concept fixed-wing UAV system. During real-life testing it was identified that out of ten flights, four of them identified the target and initiated the payload dropping sequence. With a used 35.5 x 35.5 cm ArUco QR code on the ground and 2-3 m flight height, when the code was detected, delivery accuracy varied from 4.13 m to 5.64 m when measured from the centre of the QR code.

Justas Pirinauskas. Fiksuoto sparno nepilotuojamo orlaivio, skirto autonominiam krovinių pristatymui, kūrimas. Magistro baigiamasis projektas, vadovas m.d. dr. Valdas Grigaliūnas; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: fiksuoto sparno BO; pristatymas; kompiuterinis regėjimas; aerodinamika; skaitmeninis dvynys; 3D spausdinimas.

Kaunas, 2026. 61 p.

Santrauka

Šio projekto tikslas – sukurti ir išbandyti fiksuoto sparno bepilotį orlaivį, kuris autonomiškai išmestų krovinį numatytoje vietoje, identifikuodamas vietą QR kodo skenavimu bepiločiame orlaivyje esančia kamera, kuri realiu laiku analizuoja aplinką ir priima sprendimą su integruotu dirbtinio intelekto algoritmu. Literatūros apžvalgoje buvo pristatyti skirtingi bepiločių orlaivių tipai, jų privalumai ir trūkumai, taip pat 3D skenavimo procesas, modeliavimas ir aerodinaminės analizės svarba bei pagrindiniai principai. Taip pat aprašytos 3D spausdinimo medžiagos, procesai ir skirtingų nustatymų svarba šiame projekte. Papildomai buvo aptarti sensoriai, dirbtinio intelekto integracija į bepiločius orlaivius bei autonominis objektų aptikimas. Pabaigoje aptarti realių sąlygų testavimo ir pristatymo tikslumo svarbos šiame projekte aspektai. Šiame projekte fiksuoto sparno bepilotis orlaivis skenuotas su HandySCAN 700 3D skeneriu ir jo pagalba buvo sukurtas skaitmeninis drono dvynys. Jis padėjo atliekant krovinio skyriaus modeliavimą. Po to visi komponentai, skirti išpildyti projekto užduotį – pristatyti 100 g krovinį vizualiai matomoje teritorijoje – buvo pasirinkti. Krovinio skyrius buvo modeliuojamas su integruota vieta Sony 8MP 77° IMX219 kameros moduliui ir servo motorui, kurie skirti autonomiškam krovinio išmetimui. Kamera sujungta su Raspberry Pi Zero 2 W kompiuteriu, kuris atsakingas už dirbtinio intelekto QR kodo aptikimą naudojant kompiuterinės regos biblioteką. Šis procesas reikalingas autonominiam krovinio išmetimui be piloto intervencijos. Visi komponentai šiame fiksuoto sparno bepiločio orlaivio projekte ištestuoti ir įvertinti. Įvertintas pristatymo tikslumas ir sistemos ribinės sąlygos šios koncepcijos kūrimo projekte. Po atliktų testų paaiškėjo, kad iš dešimt atrinktų skrydžių virš QR kodo tik per keturis iš jų buvo išmestas krovinys. Su naudotu 35.5 × 35.5 cm ArUco QR kodu ant žemės ir skrendant 2–3 metrų aukštyje, kai kodas buvo aptiktas ir buvo inicijuotas krovinio išmetimas, krovinio pristatymo tikslumas siekė nuo 4.13 m iki 5.64 m, matuojant nuo QR kodo centro.

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Abbreviations:

UAV – Unmanned Aerial Vehicle
VTOL – Vertical Take-Off and Landing
CFD – Computational Fluid Dynamics
CAD – Computer-Aided Design
DT – Digital Twin
GNSS – Global Navigation Satellite System
RTK – Real-Time Kinematics
AI – Artificial Intelligence
CNN – Convolutional Neural Network
ESC – Electronic Speed Controller
Li-Po – Lithium Polymer Battery
RGB – Red, Green, Blue (camera)

Introduction

Unmanned Aerial Vehicles (UAVs) in the last few years have become one of the most evolving engineering and technological spheres. Huge attention is for the autonomous and manual flights which can take pictures or videos, deliver objects, spray and seed in agricultural fields, help in rescue and search operations, infrastructure inspection and military operations tasks. The biggest benefits when comparing to other solutions are usually the price, simplicity, efficiency, and ease of use. In all these spheres, delivery of medications and even heavy cargo loads is rapidly evolving. UAVs are integrated as an alternative for planes, helicopters, cars and bikes for the delivery of goods in difficult terrain, urban environment, or to simply reduce costs or deliver items more quickly. Although multirotor drones are easier to take off and land because they have the ability to do so vertically for the delivery operations, fixed-wing designs offer better aerodynamic efficiency and longer flight time, which is crucial for cargo delivery. Fixed-wing design is best suited due to the generation of lift force in horizontal flight without any requirement for much energy, although lift off and landing could be more complex due to the requirement of the initial speed for flight and inability to hover. On the other hand, a combination of these two technologies exists, and it is called vertical take-off and landing (VTOL) drones. These UAVs combine a fixed-wing design because it has wings to generate lift, but also have additional motors and propellers and have the possibility to take off and land vertically. Despite this benefit and longer flight than compared to multirotors, these drones are more expensive and harder to operate.

The modern creation of UAV systems requires an engineering perspective. It combines aerodynamic analysis for the best performance for the intended wingspan, speed and drone weight. Structural modelling which would ensure safety and reliability in most weather and flight conditions with the required factor of safety. A control algorithm which would ensure UAVs safety in urban areas or during beyond visual line of sight flights. An artificial intelligence application which would help to make flight paths more efficient, detect objects or avoid obstacles with the help of sensors. Lastly, experimental validation, which is crucial for all engineering projects. All these processes combined ensure stable, safe, reliable and efficient drone flight in any delivery operations. Based on the desired task drone can be from a multirotor to a fixed wing, from manually operated to fully autonomous, and this versatility allows the use of drones in many different scenarios and cargo operations, which will be discussed in this project.

This project's proof-of-concept project could further be validated by different tests to ensure that this type of UAV can autonomously deliver items and fly for long distances, which would contribute to further drone integration in our everyday life.

Aim: to develop a fixed-wing unmanned aerial vehicle for autonomous cargo delivery
Tasks:

1. to design a cargo compartment and perform_aerodynamic analysis;
2. to choose components and calibrate the fixed-wing UAV;
3. to design an autonomous dropping system and test it;
4. to evaluate delivery accuracy.

Hypothesis: Aerodinamical optimized fixed wing UAV with autonomous QR code detection can accurately deliver items without pilot intervention.

1. Unmanned Aerial Vehicles snd Their Components

Unmanned Aerial Vehicles (UAVs) during the last two decades have become one of the most evolving technological aeronautical and mechatronics fields in the world. During the first evolving period of the drones, they were mostly used in military and surveillance operations, but with the rapid improvement of electronics, batteries, sensors, navigation control algorithms and artificial intelligence, their application fields have significantly expanded. During the last few years, UAVs have been used in infrastructure inspection, agriculture, surveillance, taking pictures or videos, search and rescue operations and autonomous delivery systems.

In the made analysis, authors state that the operation of the modern drone must be viewed as a complex and efficient cyber-physical system which ensures that aerodynamics, mechanics and digital processes operate at the same time [1]. This system integration allows the drone to do autonomous tasks with very minimal human involvement, which is piloted by the UAV. With the evolution of drone autonomy, safety, stability, and reliability become more and more important as UAVs can fly for longer and reach further distances where a pilot can not see the drone.

1.1. Classification of UAV Platforms

In the scientific literature, drones are usually classified based on their aerodynamic characteristics and the principle of lift force generation. Main UAV categories are: multirotors, fixed-wing and hybrid vertical take off and landing (VTOL) UAVs.

Multirotors are known for their versatility and ability to fly in tight spaces and lift heavy loads. They have the ability to land and take of verticaly and hover in the same place. This is made possible by motors and propellers, which are the only source of lift in this type of drone. These types of drones are usually known as quadcopters (with four propellers) but have many other configurations, such as hexacopters and octocopters. More propellers can generate more thrust, thus more lift power, more stability, and safety because if one motor or propeller fails, the other can compensate and the drone can at least land safely without risking the drone and the attached cargo or equipment. That is why these drones are used for operations where precise positioning and smooth movement are required. However, as shown in the aerodynamics analysis, these types of drones are the most inefficient [2]. This type of UAV consumes a lot of energy during all phases of the flight because motors must constantly generate all of the lift, even during horizontal flight. Because of that, multirotors' range and flight time are very limited, even without a heavy load, and this really limits their application in delivery operations.

Fixed-wing UAVs work and look like a commercial aeroplane. This type of drone flies according to the principles of aviation, where lift is generated by the airflow around the wings. Air going around the aerodynamic profile creates a lower pressure zone on top of the wing and a higher pressure zone below the wing, and because of that, wings generate lift. When aerodynamic design to the multirotor drone, this type is much more complex because all aerodynamic surfaces play a huge role in flight stability and efficiency. On the other hand, calibration and electronics are usually simpler because this type of drone is usually engineered with a single motor and propeller, which only propel the drone forward and a few servos which help to manoeuvre the aircraft. A multirotor fixed-wing can fly in manual mode when the pilot controls the motor and aerosurfaces, and also in autonomous mode, where the drone maintains speed and altitude and makes turns with the help of an internal flight controller. In the study made about the fixed-wing drone designed for cargo delivery operations, it was determined that optimised fixed-wing aerodynamic flight can reduce energy usage and increase flight range [3]. In additional experiments, it was determined that when converging from vertical take-off mode to fixed-wing flight, energy consumption is reduced by more than half [4]. That shows that the development of the delivery drones shifts to more aerodynamically efficient designs. The fixed-wing drones can fly longer and keep a stable flight while using less energy, which is very important for delivering any type of items, and that is why this design is used in this project.

Hybrid vertical take-off and landing (VTOL) drones are a combination of multirotor type drone and fixed-wing type drone. It has the ability to hover, take off and land vertically like a multirotor drone, but also has the ability to fly in horizontal flight, like a fixed-wing type UAV. The most complex part of this type of flight is the transition between vertical flight and horizontal flight while taking off and from horizontal to vertical when landing. Usually this transition is done with servo motors, which tilt the motors from generating lift to forward for force or in that phase, in another concept, additional motors with propellers, which are responsible for drone propulsion, are turned on and take of and landing motors are tuned off. Alternative VTOL designs used in research projects and in small-scale deliveries include tailsitter and tandem wing designs. Tailsitter design features four mounted motors which generate propulsion in the same direction, and the steering and manoeuvring of the plane is done with differential thrust, quite similarly to how it is done in the conventional quadcopter drone [5]. Tandem wing design, listed in Fig. 1, features the capability to reach speeds up to 105 km/h and fly for long distances, but this design faces stability and mass distribution issues and complexity of control systems [6].

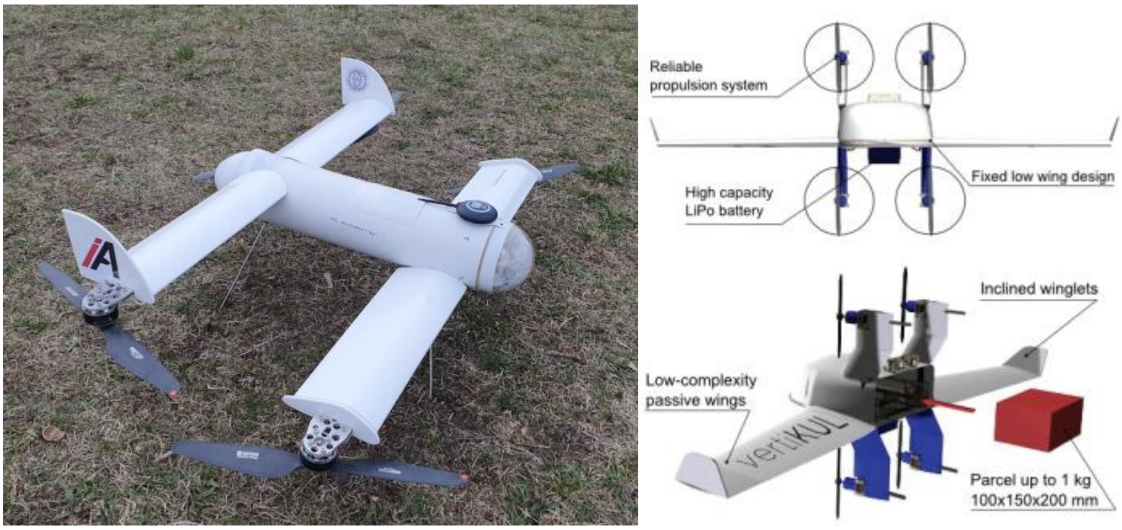

Fig. 1. Alternative VTOL designs [5,6]

In the made aerodynamics and structural analysis, it was discovered that VTOL drones with their additional motors, mechanisms, electronics and energy distribution components increase the overall weight of the UAV and make the drone more complex, which reduces the reliability, ability to deliver cargo for long distances and reduces aerodynamic efficiency [7]. That is why this type of drone is usually developed by big companies and not suited well for single person project. It is developed because of its ability to universally apply to many types of operations, but the structural, electronic, and mechatronic complexity results in difficult configuration setup and usually poor reliability during flight tests and during operations.

1.1.1. UAV Structural Design

The design of the unmanned aerial vehicle is made out of different mechanisms and electronic systems, which together form and create a drone for the intended task. From the simplest FPV drones to the most complex agriculture, military or delivery VTOL UAVs, every drone has aerodynamic surfaces, a motor, a source of energy and electronics.

Aerodynamic surfaces obviously vary from drone to drone. If a multicopter only relys on propellers and a structure that holds motors, battery and other components is not really important for fixed-wing drone wings, fuselage, tail and propeller is crucial for flight. Propellers are used in all types of drones, they can be as small as 1.2 inches and as big as 63 inches. They vary not only by size but also by blade number, the airfoil shape, and the tip. Every propeller is carefully picked based on spinning speed, desired power output, and flight speeds. VTOL and fixed-wing drones rely on wings in horizontal flight, and the aerodynamic profile of the wing is also very important. Wing is engineered to make as much lift as possible with the least amount of drag possible in the modelled speed and drone size. Other aerodynamic surfaces like rudder, elevators and ailerons must be made and engineered precisely because they ensure stability, manoeuvrability and control of the UAV. For the delivery operations, it is important to note that additional weight not only reduces flight time, but also affects aerodynamic parameters. In done studies, it was theoretically determined that a 500g payload increases stall speed from 11,43 m/s to 12,74 m/s when comparing the same UAV without the additional load and increases pitch rate from 2,5 degrees per second to 3,12 degrees per second [7]. Also, a poorly mounted or placed payload compared to the centre of gravity of the drone can induce instability even though the UAV flies perfectly without the payload. Obviously, experimental flights must be conducted to confirm this theoretical data, but the payload's effect on aerodynamics during UAV flight is unquestionable.

The propulsion system is one of the most important UAV components and in modern UAVs mostly equipped with electric motors. There are two types of them. Brushed and brushless. Other types of motor, like petrol or hydrogen, are also used but not that frequently, and for now mostly in military or research projects. Brushed electric motors are the older version of electric motors. They are not that efficient and are used less and less in the drone industry. The most common and most used electric motor is a brushless motor. A brushless motor uses electric switching through an electronic speed controller (ESC) without any physical contact between rotor and stator inside the motor. That ensures efficiency, durability and power. Scientific literature indicates that in the domain, this motor is usually equipped with a fixed-pitch propeller to ensure reliability, efficiency, stable and predictable thrust, and lighter weight compared to more complex solutions. Also, another important aspect is that these motors are usually outrunner type, which means that the rotor spins around the stator, which enhances torque in low revolutions per minute (RPM). This construction allows mounting the propeller directly to the rotor without any differential, which reduces weight. Also, these motors are quieter than any other motor [8]. Modeliation of UAV propulsion system is a consideration and calculation of electrical and mechanical parameters. Motor efficiency is calculated by dividing output power from input power

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\omega \cdot T}{V \cdot I}, \qquad (1)$$

where: ω – angular velocity (rad/s); T – torque (Nm); V – voltage (V); I – current (A).

After calculating the motor output parameters, the propeller can be picked. The thrust that is generated with the motor and the propeller depends on RPM, propeller thrust coefficient and existing aerodynamic forces during flight.

UAV's energy system is a vital part of drone's system. Without it, the drone system does not work. It directly influences flight time, maximum distance and ability to lift payload. Stored energy, in most cases, when talking about drones, electric energy is transferred to mechanical power through ESC and motors. Energy system modelling is a critical stage when making a drone. The battery must ensure sufficient power to the motors, low mass, low volume and stable energy during intended flight conditions. In the electrical UAVs, lithium polymer (Li-Po) batteries are usually used because of their large energy density and low weight. Battery technology differs by three specific parameters: specific energy, energy density and specific power.

Table 1. Comparison of different battery types [8]

Battery type	Energy (Wh/kg)	Energy density (Wh/L)	Power per kilogram (W/kg)
Ni-Cd	40	100	300
Ni-MH	80	300	900
Li-Po	180	300	2800
Li-S	350	350	600

The table shows that Li-Po stores the largest amount of available power per kilogram, which is why it is used the most in the drone industry. Despite these advantages, battery technology is the most limiting factor in terms of flight time in the UAV technological field.

Although batteries are the dominant source of energy, especially for the smaller UAVs, scientific studies more and more often analyse alternative energy sources. One of the most promising energy sources is hydrogen. Scientific research shows that the energy of these elements can reach 1000 Wh/kg, which is about three times more than that of to Li-Po batteries. However, this technology is still very expensive, and it is hard to extract energy efficiently. Supercondensers are usually used as an additional energy source which compensates for the battery limitations. They have the ability to extract a large amount of energy per short period of time, which is beneficial when doing dynamic manoeuvres or lifting the drone from the ground. Fixed-wing drones, because of their large surfaces, have the ability to have solar panels on top of the wing to generate additional energy from the Sun. This allows for extending flight time however, energy generation is limited and additional weight is not always effective. Due to the advantages of different energy sources, hybrid systems, which take advantage of different technologies, are used in drone technology [8]. In addition, scientific literature examines alternative energy supply technologies. One of the broadly used technologies is tethered. That means that the drone is connected to the base station on the ground by a wire and can stay in the air for an unlimited time. However, flight distance and height are very limited. Also, autonomous battery swapping systems for continuous operations are used. This technology enables longer drone operations without any human interference. A more futuristic approach to this problem solution is laser energy transfer. Energy can be transferred through a laser beam up to 5 km distance, enabling operations up to 12h. However, the drone must always fly in the direct line of sight of the laser. The laser must always be pointed at the drone, which is a difficult technological task, and a direct beam to the drone means the mission in a specific area is limited to one or a few drones [8].

1.1.2. Navigation and Control Systems

The drone navigation and control system are a crucial part in safe flight. These systems ensure that the drones fly where it is supposed to, keep a smooth trajectory and precise mission completion. Modern UAV navigation systems usually rely on a few simultaneously working technologies. These are GNSS navigation, inertial navigation, visual navigation, recognition of patterns or detection of markers and also integration of artificial intelligence in keeping the drone safe and most efficient. In today's UAVs, these systems are working simultaneously to ensure the best safety during flight and additionally help the pilot, which reduces human error. GNSS navigation is the most commonly used navigation technology in today's UAVs. It could be used not only for tracking the drone's position in real time but also to help the drone keep a stable flight, hover in the same place and execute autonomous missions based on a generated flight plan. The UAV's trajectory is generated as a list of discrete points, and control of the drone is performed using a proportional navigation algorithm during the autonomous missions. This algorithm adjusts the UAV's flight path based on the real-time angular error. Experimentally, it was determined that GNSS landing accuracy is around 1,1 m, which means that the technology on its own is not reliable for precise operations. Moreover, GNSS is known for vulnerability to jamming and spoofing, which is not ideal when there is a need to ensure safety [9]. That is why, for precise operations, technologies such as Real-time Kinematics (RTK) and synergies with other technologies are used. Also, the visual system for the recognition of obstacles or flight markers is used to assist the pilot in flight. In studies, it was determined that the visual system can not be used alone in the drone's navigation system as it suffers in poor visual conditions and can suffer from latency, which can delay the drone's pitch and roll corrections. In a done study, it was determined that the drone's visual system recognition reliability drastically decreases when the drone is further than 6-8m above the marker and a latency higher than 150 ms between recognition and control causes oscillations during landing [10]. Additionally, it was determined that faulty visual marker recognition could increase by up to 10 % in poor weather conditions [11]. That is why the integration of AI in the navigation and control systems can be so beneficial. It can reduce the need for human input when there is an error or in other scenarios when a pilot misses important details. However, even in these times when AI can do more and more pilot input and controlling of the UAV is still the main and crucial part of the manual or autonomous flight. During manual flight, every input that the pilot makes is mimicked in the drone's behaviour. During an autonomous mission, the pilot must mark the working area and desired flight parameters based on weather and area conditions, which is crucial for safe flight. A basic and most commonly used method is UAV control through radio waves. The remote controller transmits PWM signals to the drone, most commonly in 2,4 GHZ radio wave frequency. This standard has a low latency (~20–50 ms), but on the other hand, it is vulnerable to signal interference, noise and does not have the ability to control the drone through obstacles or over long distances [12]. That is why other control systems are used for higher-end missions. For missions in difficult terrain, urban environment or longer flights when the drone flies further than the visual line of sight, ground control stations (GCS) are used. GCS has the ability not only to send commands to the drone but also to receive telemetry in real time. Also, the different and additional communication channels are used, like internet-based communication and laser or fibre optic for more specialised applications [8]. These technologies ensure signal strength, connectivity with the drone in a wider range of applications, and control system stability.

1.2. Delivery Operations with Drone Technology

During the last few years, drones have become one of the most promising fields in transportation and delivery. While this field is still developing and not widely spread, it has a lot of potential and can be applied in various delivery operations with different drone technologies. In this chaper the main aspects of last-mile delivery, where drones are mostly used today and payload delivery and dropping systems are examined.

1.2.1. Last-Mile Delivery

Last-mile delivery is one of the hardest parts of the logistics industry. The scope of this delivery includes transportation from the centralised hub to the final end user or client. During this phase, the industry faces many challenges like heavy traffic, tight and poorly maintained roads and labour storage, which requires optimisation and a more technological approach. The strongest influence in this field is the expense of transportation and delivery time. Introduction of drone technology in this field can help reduce costs, labor and make faster deliveries in heavy traffic or rural areas. Newest research in this field indicates that UAV integration in the last-mile delivery can drastically reduce delivery price and also reduce carbon emissions. Scientific literature indicates that drones can reduce delivery costs by 96.5% and carbon emissions by 71% in comparison with traditional delivery methods [13]. Additional reduction in delivery costs and delivery time could be made with optimisation algorithms. For example, a drone can work in synergy with existing delivery solutions to add efficiency to current delivery applications. In scientific literature, various ideas are analized one of which is the Flying Sidekick Travelling Salesman Problem (FSTSP) modeli n which drone works together with a delivery truck. In this model drone can make a few deliveries during one flight, thus reducing the delivery time [14]. Other methods include coordination of multi-UAV delivery, where a few drones fly together in cooperation in order to deliver more parcels in a small area over the same period of time in comparison to the traditional method [14]. In addition to optimization a consideration of payload weight is essential when modelling last-mile delivery with a drone. VertiKUL UAV construction determined that this type of platform can carry up to 1 kg of payload [5]. Moreover, in other hybrid VTOL UAV designs can carry up to 500 g of weight [7]. Additionaly the current drone delivery systems, which are operated all around the world by companies like Zipline and Wing, show similar results. Payload weight does not exceed 3,6 kg, which is relevant to the numbers in scientific literature. This is largely limited by current battery technology and the ability to store wanted energy, and the cost of weight for that energy. Fixed-wing designs can carry a payload for a longer period of time, but are rarely used due to the need of runway for takeoff and landing. These limiting factors, for now, are the main obstacles in further development of UAVs in this field.

1.2.2. Payload Delivery and Dropping Systems

Payload delivery mechanism in drones is a complex system which combines aerodynamics, mechanics and control mechanisms. Payload delivery to the desired area or place is the final stage of the payload delivery operation. After that, only the flight home is left. This stage is crucial as it determines the accuracy of the delivery and the safety of the parcel. In the scientific literature, drone delivery is determined as a sequence of operations. It consists of some kind of payload loading, which can be done manually by a human or automatically using autonomous loading mechanisms, then stable flight and final delivery, which could be done by landing, by lowering the cargo with a cable or dropping it from the air [15]. The final decision in terms of which of these solutions should be used depends on the area, payload, energy consumption, flight efficiency and UAV construction. Different delivery mechanisms requirements and specifications are listed in the table below.

Table 2. Comparison of different mechanisms vs. drop-box mechanism [16]

Mechanism Type	Automated Parcel Drop	Requires UAV to land	Parcel storing	Requires a dedicated parcel holder
Retractable Tether	Yes	No	Exposed	Yes
Gripper Arms	No	Yes	Enclosed	Yes
Payload Basket	No	No	Exposed	No
Storage Pod	No	Yes	Enclosed	No
Parachute	No	No	Exposed	No
Drop-box	Yes	No	Enclosed	No

Dropping systems configurations are categorised by their working principles and integration in the drone and delivery system structure. One of the usual solutions is lever or gear motion transition systems. These mechanisms open the box or directly release the payload in certain angle in order to deliver payload as accurately as possible and minimize flight dynamics influence to delivery accuracy. These mechanisms can be made with cardan or rotary joints with specific damping mechanisms, such as coil or Sarrus-type shock absorbers if it is required to deliver a fragile or expensive payload not only accurately but also gently [17]. Moreover, control of such mechanisms is very important in order to accurately synchronise dropping system initiation, dropping start time and efficient force to open or release all type of payloads. Correct control algorithm, together with hydraulic or electromechanical actuators, can ensure resistance to vibrations and micro-shifts in the centre of gravity during flight [3,18]. Drop system realisation depends on drone, mission requirements and deployment conditions. Although lever and hinge-based systems are the most popular because of their simplicity and reliability in some configurations gear control or hydraulic control could be made in order to have higher control accuracy, reliability and longevity. The most important modelling stage is to evaluate how each mechanism can influence energy usage, system weight, because these parameters will have a huge influence during the flight mission [16,19].

1.3. 3D scanning, virtual prototyping and testing

In this chapter, technologies which help test and improve models in a virtual environment are discussed. Moreover, how the synergy of each technology can improve compliment each other and contribute to more efficient drone flight and reduce testing costs.

1.3.1. Digital Twin

Digital twin is a crucial design stage when adding features or improving existing structure or machinery. DT represents a physical object virtually with the ability to update, join with ojer real life objects or place in the desired space without the need to do it physically. Also, it allows to do strength, aerodynamic testing in a virtual environment without the need to do it physicaly wich requires a lot of resources [20]. In addition virtual model allows for a larger variety of testing in various conditions, which in some cases cannot be met physically or would require a lot of risk for example, during drone flight, during adverse weather conditions [21].

One of the most popular digital twin creation tools for complex parts or structures is 3D scanning. Simple parts could be measured and modelled based on measurements, but complex structures require detailed information. That is why 3D scanners allow uploading DT to the CAD environment for testing, improving or implementing in other systems. 3D scanning provides data on the topography, surface textures, and microgeometry of real-world surfaces, which are essential for precise modelling and testing. Scanners could be photogrammetric or laser-based. Data is usually a point cloud, which is represented in 3D space in any CAD software in compatible formats [22].

Hardware and working principles of scanning technologies differ and have their own strength and weaknesses. While photogrammetry is cheaper and faster, laser-based scanning is much more accurate. Fotogrametric scanning uses standard RGB pictures from all around the object, and with the help of software, these photos are combined in 3D model or point cloud through the use of structural reconstruction algorithms, such as bundle adjustment and point cloud registration [23]. The working principle of laser-based scanning technology uses projected light patterns (fringe patterns) with cameras that capture the distorted light lines. The typical compact light scanner shown in Fig. 2.

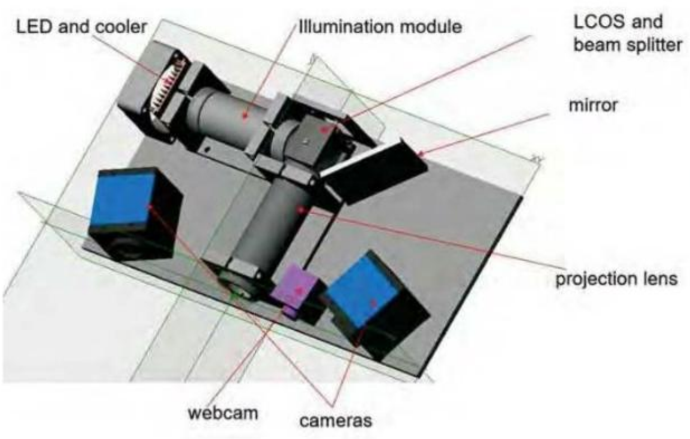

Fig. 2. Schematic of a typical compact structured light scanner with two cameras (webcam only for alignment) [23]

The system uses the triangulation principle, which determines the relative geometric relationship between the projector's output (light beam or strip) and the coordinates of the input point measured by the camera. According to the scientific literature, several profiling methods can be used, including phase-measuring profilometry (Phase Measuring Profilometry, PMP). This is considered one of the most accurate structured light methods because of its ability to achieve high precision and good colour texture. This also helps effectively avoid specular reflections from surface textures [22,24]. These technologies help to ensure high scanning speed and accuracy, which is crucial in digital twin creation. These technologies and scanning methods are often combined — photogrammetric data is supplemented with laser data to improve surface texture, provide a more accurate coordinate reference for the computational workflow, and reduce local artefacts [23].

Construction modelling is an essential part in new geometry creation as this ensures reliable structural integration between loads, existing structure, and the control architecture. Modelling is based on modular component conception. Components such as the body frame, joints, lightweighting elements, and force transmission points are integrated into a unified structure that can be analysed using CFD and FEA. Virtual modelling ensures the ability to change, modify or replace each and every part if intended conditions are not met. The scientific literature draws attention to the importance of CAD integration for accelerating the prototyping process [21]. Moreover, construction modelling requires constant interaction with a digital twin, in which CAD data, material properties, and load analyses are integrated into a single live product model for testing and improving. For intended analysis, the physical part or structure must be accurately recreated and modelled as it is in the real world to ensure correlation for strength, aerodynamic, or vibration analysis. Main CAD platforms, such as SOLIDWORKS, CATIA, and Siemens NX, allow users to create modular section models, add connection points, route electrical/power cables and model everything from zero or on top of an existing part or digital twin [25].

1.3.2. Computational Fluid Dynamics (CFD) Analysis

CFD analysis is one of the fundamental parts of modern system modelling. It can be used to test any object in most of the fluids on Earth. It allows for getting the understanding and values on how fluid interface with the object, what forces develop and which adjustments and improvements have to be made in order to make the part more efficient. Aerodinamical characteristic like lift and drag are closely related to the shape of the body, the texture of the surface, and the flow characteristics that vary depending on mission conditions. CFD starts with the preparation of geometry and the creation of a mesh. Geometry must be recreated accurately by a mesh to ensure the most accurate analysis results. Then designated testing area is created around the object. The whole mesh for CFD analysis must cover both boundary regions and large volumes that generate accurate cross-flows. Scientific literature sources emphasise that a properly selected grid and a proper solution method are essential for a reliable assessment of the main forces which affect the object [26]. After that, models and testing parameters are picked to test the desired object in the desired conditions, which will replicate real-life conditions. The most popular and most often used are Reynolds-Averaged Navier–Stokes (RANS) equations with k-ε or k-ω SST turbulence models, which provide fast and reliable estimates [27]. The mian parameter when modelling a planes dropping system and payload carrying bay is drag. Reduction of drag is important in order to make the plane more efficient which will help to fly longer with the same amount of energy. Drag coefficient which will show the difference between different geometries, is calculated with Eq. 2.

$$C_d = \frac{F_D}{\frac{1}{2}\rho U_{\infty}^2 A} \quad , \tag{2}$$

where: F_D is the drag force (N); ρ is the fluid density (kg/m³); U_∞ is the free stream velocity (m/s); A is the projected area of the object (m²).

In analyzed researches, similar geometries for the intended payload bay were analysed and shown in Figure 3. Forms of the bay can differ from a simple box, which is not aerodynamic and most aerodynamic shape on earth – the tear drop shape. While modelling such a part, it is important to understand the sacrifices made to make the shape as aerodynamic as possible. Usually, it is not possible to make the best shape possible, as components inside the part must fit. Components like servo motors, batteries, computers, as well as the carried payload, must fit accordingly to fulfil the desired operation requirements. That is why this research was picked because it analyses possible shapes which are aerodynamic but at the same time give the possibility to fit components inside with a small aerodynamic drag impact on the plane. This is crucial in any flight operations, and understanding of shapes is crucial for this project's success.

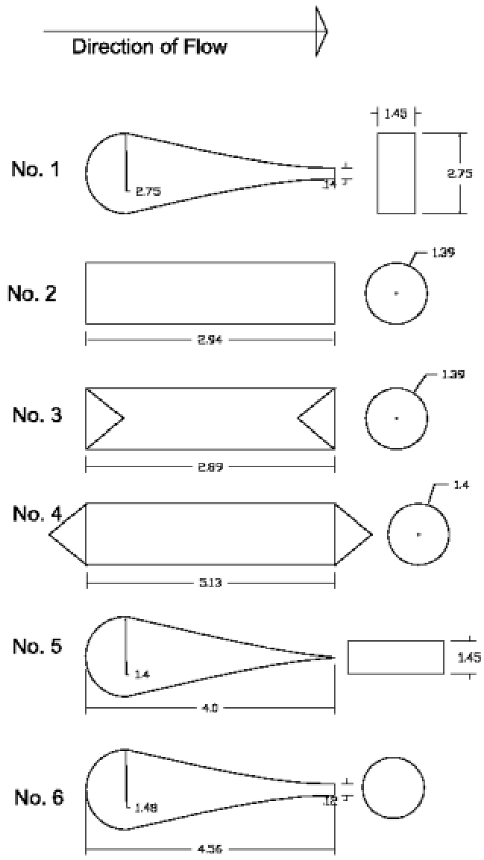

Fig. 3. In a scientific paper tested objects and dimensions in inches [28]

In the analysed data, it is seen that objects which have larger and more cornered projected area are generating more drag. It was found that shape no. 1 generated nearly twice as much drag as shape no. 6. Based on that information modeled payload bay will follow this shape in order to save energy and make the UAV more efficient.

1.4. Additive Manufacturing in UAV Constructions

Additive manufacturing is beneficial in making any complex geometry. In drone technology, it is used for frame covers, custom manufacturing for individual complex parts and especially for testing and demo units creation. For any custom manufacturing and individual tasks, this is an accessible and widely spread technology which give aces to test theories practically. In addition, this technology can save weight in the final product.

1.4.1. Additive Manufacturing

Firstly, this is the process which takes a created CAD design file and then, with the help of software converted to a stereolithography (STL) file. After that, the drawing made in the CAD software is approximated by triangles and sliced, containing the information of each layer for the printer [29]. Additive manufacturing (AM) ensures flexibility when implementing multi-composite or polymer-based solutions, which allows the implementation of wires, sensors, antenas and any other hardware in the part structure or without the need for additional fasteners, which saves weight and reduces assembly complexity. AM integration into manufacturing processes raises three main concerns when deciding which solution to use. It must be decided which materials will be used, process mechanics for the specific parts or mechanisms, final finish requirements, and postprocessing availability. From these three main technological solutions are picked. These are stereolithography (SLA), fused deposition modelling (FDM) and Laser Engineered Net Shaping (LENS). The fundamental principle of SLA involves the polymerisation of photopolymer materials using ultraviolet (UV) light in a layer-by-layer process. This method provides high surface quality and precision, but it restricts material selection and limits resistance to elevated temperatures. Consequently, SLA is primarily employed for prototyping and the production of small batches requiring precise geometry [30]. The FDM technique shown in Fig. 4 makes use of a thermoplastic extruder that extrudes plastic rods or filaments in layers, thereby achieving thickness, lines, and further integrations. FDM is more cost-effective, accessible, and suitable for projects that demand more dimensional flexibility; however, it has a greater influence on surface quality, smoothness, and accuracy in comparison to the conventional SLA technique. FDM allows for faster prototyping and thermo-mechanical stress resistance, especially with the addition of further planar segments [29,30].

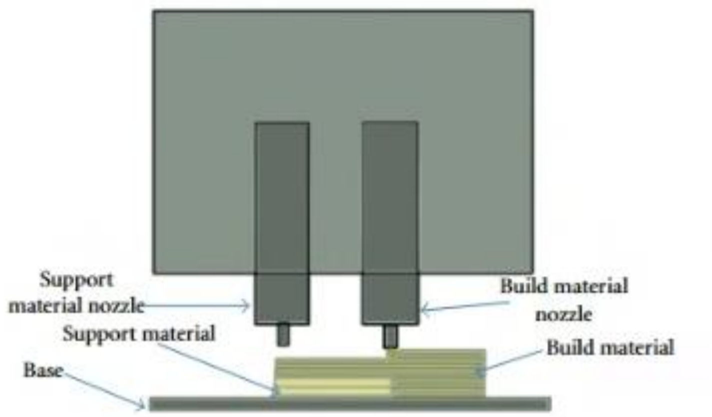

Fig. 4. Fused deposition modelling

LENS, or Laser Engineered Net Shaping, is a variant of laser technology which is very sophisticated. It uses a laser beam to shape a metal or composite structure, thus offering high precision, dense microstructure, and high strength. These aspects are very important for a complex component. LENS allows for the production of components that are subjected to tensile stress, offering a strong structure without the need for machining on the surface, a factor that is of great importance in aerospace components and lightweight metals. Taking into account UAV structure and flight conditions, AM is also incorporated into topological optimisation and modular solutions, which allows to make the structure lighter without the need of reducing overal strenth of the structure. In integration with DT and CFD, additive manufacturing proceses providesan oportunity to immediately change geometrical parameters and material properties directly from the virtual models. This encourages faster prototyping with faster and more accurate calibration based on experimental test data.

1.4.2. Printing Material Properties and Weight Reduction Strategies

Material properties are the essential part of AM. The same model can perform poorly and perfectly only with a change of material. Resaerches show that with the inclusion of FDM technology and correct materials, parts can achieve the same or better strength with the same or lighter weight [31]. Not only the material but also the usage of it, printing parameters, infill and strategies can enhance wanted properties as well. Most widely used materials – ABS, PLA, LW-PLA, PETG, PC, PA and ASA are compared in the table below.

Table 3. Characteristics of raw polymeric materials [32]

Property	ABS	PLA	LW-PLA	PETG	PEI	PC	PA	ASA
Advantages	Cheap, lightweight, flexible	Biodegradable, sustainable raw materials Biodegradable, sustainable raw materials		Non-toxic, chemically resistanthigh strength	Temperature, flammability, and chemically resistant,	Temperature-resistant, high strengthand impact	High interlayer adhesion, resistant to abrasion	UV resistant, durable
Weakness	Temperature deformations, toxic gases	Low melting temperature, brittleness	Low melting temperature and modulus of elasticity	High water absorption, hardly printable	Expensive	High printing temperature, deformation instability	High water absorption, deformation instability	Deformation instability, high precision printing demands
Density (g/cm^3)	1.04–1.12	1.20–1.26	0.42–1.20	1.27–1.28	1.17–1.34	1.19–1.20	1.10–1.25	1.05–1.07
Tensile strength (MPa)	32–52	31(11) ± 71	10–43	47–50	54–104	55(19) ± 62	55–63	42–50
Elasticity modulus (GPa)	1.8–2.0	2.3–4.5	0.86–3.4	1.5–1.9	2.1–3.1	2.1–2.4	2.0–3.0	1.6–2.1
Glass transition temp (°C)	100–112	50–70	55–60	70–75	186–220	145–147	62–79	101–116
Melting temp (°C)	125–150	150–160	150–160	-	-	228–280	189–194	130–141
Shrinkage (%)	0.5–11	0.3–8.1	-5.8–7.8	0.3–12	20	0.8–1.0	0.5–8.1	0.5–0.8
Toxic gas emission	Yes	No	No	No	No	Yes	Yes	Yes
Price (€/kg)	25–33	17–60	35–43	28–30	202–273	43–85	66–71	32–35

LW-PLA (lightweight polylactic acid) is considered one of the most perspective materials for lightweight structures like drones, model aircrafts, RC components, and mold or prototype fabrication. As it is seen in the table, LW-PLA density varies from 0,42 g/cm^3 to 1,20 g/cm^3 and do not extrude toxic gases, which makes it a perfect material for fast prototyping and part development with porous or topologically optimised structures. LW-PLA in comparison with PLA is characterised by a significant reduction in weight (approximately 14% lighter), while maintaining or even improving bending strength. However, tensile strength may be slightly lower [31,32]. Additionally, it could be used with foam technologies to reduce weight even more. In the done research, it was found that weight reduction strategies are based not only on a lower filler density but also on the extrusion control. For example, if the infill density is below 30%, then the structure has weak interlayer adhesion. On the other hand, if infill density is above 60%, then the weight reduction effect reduces significantly. Printing parameters - material flow rate (Mf), wall line count (Wlc) has the highest impact on mechanical strength of the structure, thus material itself must always be combined with correct printing parameters no matter which material is used in order to achieve the intended parameters and material behaviour under load [31]. That is why LW-PLA is widely used in drone part creation. Reduction in weight in aviation is crucial because it determines flight efficiency.

1.5. Artificial Intelligence in Drone Technology Navigation

Artificial intelligence (AI) and computer vision methods are becomeing esential part of autonomous UAV navigation. Especially while detecting obstacles, making precise manoeuvres in obstructed environments and landing precisely in the desired place. Traditional navigation methods like GNSS do not asure desired accuracy, especially for delivery applications, as the deviation of this technology can reach 1-2 m. Aditionaly AI and computer vision can help navigate and keep a stable flight even in GNSS denied environment. That is why precise vision-based technologies like visual identification with AI or detection of QR code are used and researched more and more often especialy in the UAV delivery operations and autonomous navigation.

1.5.1. Computer Vision and QR Navigation in UAV Systems

Integration of computer vision methods in UAV systems involves several key stages: gathering of data and object recognition, or segmenting of data. Data acquisition could be done with a variety of sensors for different applications. The most popular and cheapest option is RGB cameras, which take pictures or film in a way that our eyes do. More complex options include NIR, thermal and infrared cameras, which capture a larger variety of reflections and can be used in more complex environments.

Table 4. Summary of done studies on UAV computer vision strategies [33]

Category **Sub-category**	**Type of Camera**	**Time for Drone Landing**	**Descriptions**	**Strength**	**Weakness**
Passive methods	A trinocular system with three visible light FireWire cameras	Daytime	Color landmarks on the UAV are deployed as key features for position estimation by a ground station using CamShift algorithm.	Good landing and positioning results; practical for real-time applications.	Feature extraction not reliable in low light; complex setup of three
	A pan-tilt unit (PTU) with stereo infrared cameras	Daytime and nighttime with various weather conditions	Several target tracking algorithms tested on quadrotor and fixed-wing aircraft.	Tracks target early using large PTU field of view; efficient and accurate.	Low accuracy in fixed-wing touchdown; affected by high temperature background.
	Two NIR camera array system with NIR laser lamp	Daytime and nighttime with different light conditions	NIR laser lamp fixed on UAV nose for detection.	Wide baseline improves calibration and localization precision.	Not practical in narrow landing area; complex dual-camera setup.
Active methods Without marker	Visible light camera	Daytime and nighttime with a guiding lamp	Image binarization and Hough transform used to extract runway border line.	Simple algorithm for runway border-line detection.	Requires guiding lamps at night; limited applicability.

Category Sub-category	Type of Camera	Time for Drone Landing	Descriptions	Strength	Weakness
	Visible light camera	Daytime	Two-stage processing to find all landing areas and select best using naive Bayesian classifier.	Drone can find landing site in emergency without marker.	Limited experimental validation; tested on laptop.
Active methods With marker	Thermal camera	Daytime and nighttime	Letter-based FIR marker used for extracting feature points and enabling safe landing.	Less affected by illumination and environment.	Expensive; not suitable for conventional drone systems.
	Visible light camera	Daytime	Marker detection via contour, circle detector or SURF-based key points.	Marker detection possible using onboard visible camera.	Detected only during daytime; not real-time onboard.
	Visible light camera	Daytime and nighttime	Real-time marker-based tracking algorithm tested on low-power onboard system.	Works both daytime and nighttime.	Requires specific marker.

With each sensor's advantages and disadvantages, scientific lieterature discuss main marker detection algorithms. Traditional recognition models are based on image binarisation, edge detection, and geometric analysis. They are characterised by high energy efficiency and stable accuracy. Especialy power consumption is crucial for marker detection during UAV flight because power is carried in the drone, and extra weight results in shorter flight.

Table 5. Comparative analysis of marker detection algorithms [34]

Algorithm	Processing Speed	Accuracy	Robustness	Power	Energy Efficiency
Traditional (ArUco)	N/A	11 cm offset	Moderate	~5W	High
CNN-based	17.5 ms/frame	95.6%	High	~15W	Medium
YOLOv5	Real-time	80.9%	High	10–30W	Low-Medium
Hierarchical	19.8 Hz	High	Excellent	~10W	Medium
Multi-stage	15.5 fps	FPR 0.7%	High	10–30W	Low

Without classical computer vision algorythim, deep learning methods are also analyzed. Models which use specialised deep learning algorythim called convolutional neural network (CNN) feature higher accuracy, can work when the camera is partially blocked, there is fog or unintended rotation. During the research, it was found that the use of various optimization algorithms (SGD, RMSprop, Adadelta, Adam) enables a classification accuracy of 92–95% that is why it is very reliable across various orientations [35]. However, these algorythims consume more evergy. Also, usage of these algorythims is limited due to high computational complexity. Due to mentioned challanges traditional methods are most widely used in UAV autonomous navigation and recognition [11,33,34,35]. However, with the development of electronics and processing algorithms, these solutions will be used more frequently in the future as it is likely that with the improvement of algorithms and electronics, these solutions will be more efficient. This will alow to use it in more projects and in more wide range of operations.

1.5.2. Real-time Data Processing Challenges

While gathering data with any kind of sensor, pilots or engineers run into challenges which can affect detection accuracy, speed or reliability. The literature highlights that marker-based navigation is highly accurate due to the precise geometrical structure, but it can be affected by the field of view, distance to the object, processing speed, image resolution, latency and weather conditions. One of the main challenges is the complexity of the recognition pipeline. In the analysed study, it was highlighted that QR detection, which could be used for various applications, covers several important stages: image acquisition, edge detection (e.g., using the Sobel operator), contour analysis, identification of geometric structures, perspective transformation, and final decoding. Complexity and poor efficiency in each stage cause a reduction in calculation speed, which can be essential for dropping or drone landing operations. CNN methods enable recognition accuracy of up to 95% for QR codes in various orientations; however, they require larger resources for calculations. In done researches it was found that to ensure stable recognition for UAV landing operations, the algorithm must ensure at least 20 FPS recognition speed so that the flight controller can efficiently react to changing drone position in space [34,35]. If the processing frequency is lower, then problems like trajectory oscillations, overshooting and inaccurate final position can occur. Additionally, recognition could be influenced by poor weather conditions. In a done study, it was determined that recognition algorithms are sensitive to changing lightning, for example, scattered clouds or shadows, noise in the camera and low object contrast. Also, experiments show that QR codes can be reliably detected at distances of up to 6–8 meters because, as the distance increases, the dispersion of the determined angular points increases significantly, which reduces the accuracy of the position estimate [11]. Obviously, height can be increased with a larger area of detection or specific zoom lence but portability of the QR code or scanning area will be decreased. Due to these problems, additional image processing methods, such as binarisation or filtering, are often used, or visual sensors are supplemented with other sensors, like infrared cameras. However, additional binarisation or filtering causes longer calculation process, and additional sensors increase the system price and overall weight of the UAV [33]. Moreover, the data transmission and processing architecture plays a vital role in the recognition system. UAV systems usually use onboard data processing because data transfer to the cloud results in higher delay. Finally, a review of the literature highlights that one of the most effective ways to ensure stable drone flight and reliability is to use sensor fusion algorithms with other onboard sensors like IMU or GNSS, which allows for maintaining stable operation even if the visual information is poor or the processing algorithms are not working as intended.

1.6. Chapter Summary

In this chapter, UAV types, construction, navigation, control algorithms, and application to cargo delivery were described. Multirotor, fixed-wing and VTOL drones were analysed, addressing their advantages and disadvantages. Determined that the fixed-wing UAV, because of its best aerodynamic efficiency and longer flight distance, is most suitable for the delivery operations. Also, 3D scanning, digital twin, CFD analysis and additive manufacturing technologies were discussed and their advantages in UAV structure creation. Lastly, artificial intelligence and computer vision technology are described with possible implementations in drone technology.

2. Theoretical Justification of the System Design and Performance Evaluation Methodology

In this section, the theoretical justification of the picked solutions and the methodology for evaluating project success are presented. Firstly, different UAV types, cargo delivery methods, control algorithms and navigation types are presented and picked for the intended delivery task, application and budget. Moreover, evaluation of project success is also presented, which is crucial part in determining project parts like aerodynamic efficiency, computer vision reliability and delivery accuracy.

2.1. Theoretical Justification of Picked Solutions

Due to rising urbanisation, growth of the E-commerce sector, rising customer expectations, and delivery urgency, modern UAV systems are more widely applied in autonomous cargo delivery operations. It can be used as an alternative method because other solutions have drawbacks in rural or heavily urbanised areas [36]. The efficiency of these systems for the desired task is determined by UAV construction and control algorithms. Each decision has its own strengths and weaknesses and can be the best decision for one or another task. In scientific literature, UAV systems are analysed as complex cyber-physical systems that integrate aerodynamic, mechanical, and digital components [1]. This approach allows for evaluating the system from different perspectives and objectively evaluating the advantages and disadvantages. In this master's degree project, a fixed-wing UAV system is tailored for autonomous delivery operation, which is why it is necessary to justify the UAV platform, control algorithm, and cargo delivery choice.

2.1.1. UAV Platform Type and Cargo Delivery Method

One of the main tasks in this master's degree project is to choose a UAV platform. This step will influence energy efficiency, working range and payload capacity. In scientific literature, three main UAV types are distinguished: multirotor, fixed wing and VTOL. Strengths and weaknesses of each platform type are described in paragraph 1.1.1. For the desired task - flight height lower than 40 m and accuracy better than 5 m from the target, and in order to reduce the project's budget and achieve the desired result, a fixed-wing drone is picked. The main platform type aspect while planning was available budget and fixed-wing design with a single motor and relatively simple design, which is the cheapest option in comparison with multirotor and VTOL UAVs. Fixed-wing design is widely used in delivery operations by companies like Zipline, which shows that this UAV design in this sphere also has a lot of potential. The ability to fly long distances and the efficiency of flight are the main advantages in delivery operations with such a UAV platform type, which will be made use of in this master's degree project [15].

There are a few main cargo delivery methods described in section 1.2.2: landing and removing the payload, retractable tether, parachute drop and drop-box. The retractable tether solution can not be used because of the picked UAV platform. Fixed-wing UAVs can not effectively use and land the payload because they must always be in the air and can not be stationary. Landing with a fixed-wing UAV type requires take off landing area without obstacles, so landing in the desired delivery destination could be complex and not available. That is why, for this project, the cargo dropped in the desired place is picked. It is the solution which enables UAV flight with minimal weight, which saves flight time and extends range. Also, enables a quick delivery without the need to circle around the delivery destination and the ability to engineer a mid-air dropping mechanism, which is done in this project.

2.1.2. Control Algorithm and Navigation

Navigation is one of the most important UAV system components. A traditional GNSS system is known for limited accuracy, which can be from 1 to 5 meters, depending on the visible satellites [9]. This accuracy is not suitable for precise delivery operations, especially in cities and obstructed environments. RTK technology could be used to get more precise accuracy (up to 2cm). It is widely used in photogrammetry drones, but for this project is too expensive and too complex. Visual navigation methods can be used to allow for greater accuracy with the QR codes used. Done research showed that marker-based navigation can ensure stable object recognition in real time, but it is limited by camera resolution and weather conditions, which will be tested in this master's degree project. Additionally, QR-based navigation features have low calculation complexity, which is suitable for low-energy real-time recognition systems.

The system control algorithm is the essential part of this project. It must ensure safe and stable flight and accurate cargo delivery to the desired place. For the flight and manoeuvring the drone over the desired place, manual control will be used. This ensures stability and reliability during VLOS flights. Obviously, it is limited by the range and precision, but more complex flying systems are not available within the desired budget. For the control of the cargo bay, a closed-loop computer vision-based algorithm is used in which the data gathering, processing and decision making are happening all the time, as shown in Figure 5.

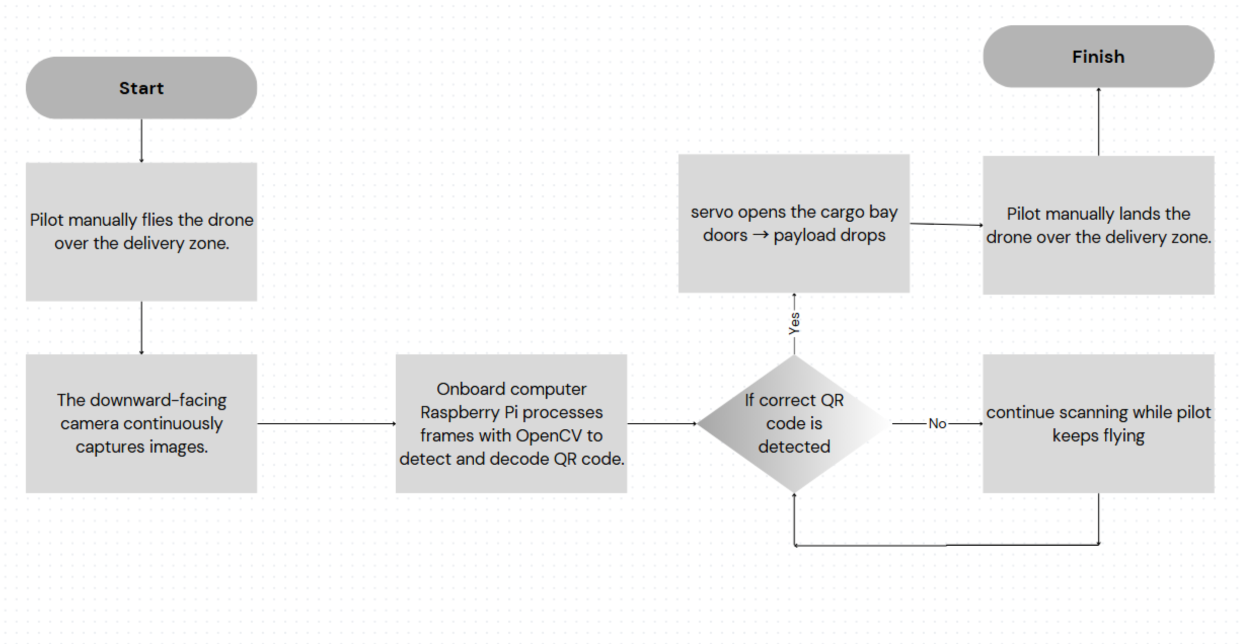

Fig. 5. System flow chart

The accuracy and precision of this system will be determined by processing speed because a large delay will make the cargo delivery inaccurate and ineffective for any operation and weather condition.

2.2. Methodology for Evaluating Project Success

In order to objectively evaluate the created UAV system performance, it is necessary to apply quantitative assessment methods which will allow to analyse system accuracy, reliability and efficiency. In scientific literature, it is emphasised that autonomous UAV system evaluation must be done not only with quantitative measures but also with statistically based indicators which allow for evaluating system stability and reproducibility [15]. In this project, an evaluation methodology was created based on several key criteria: aerodynamic efficiency, computer vision reliability, delivery accuracy and overall project success rate. This multifaceted analysis allows in deph evaluation of the system working in simulated and real-world environments.

2.2.1. Aerodynamic Efficiency

Aerodynamic efficiency in a plane sis know and lift to drag ratio. This value is a base measure of a plane's aerodynamic performance in level flight or different flight phases. The increased efficiency has a major impact on flight speed, time and range, which is crucial for delivery operations. In this project, the construction of the planes is changed only by adding an extra cargo bay, which obviously will not increase lift but will only increase drag. To keep the longer flight range, aerodynamic efficiency must be kept as high as possible. That is why minimal drag is crucial for this project [37]. To have the best possible efficiency, model cargo bays will be tested in CFD software to determine which will have the lowest drag force. The model which will hold a desired small medicament box volume inside it and generate the least amount of drag force will be picked for printing and will be used in real-world experiments. The drag force by the CFD software is calculated with Eq. 3.

$$F_D = \frac{1}{2} C_D \rho A v^2 \quad (3)$$

where: C_D is the drag coefficient; ρ is the fluid density (kg/m^3); v is the free stream velocity (m/s); A is the projected area of the object (m^2).

2.2.2. Computer Vision

In this master's degree project, computer vision and QR detection are used. Open CV (open-source computer vision library) will be used to have an efficient and trained computer vision program. It is an AI programming library. It has more than 2500 optimised algorithms, which are included with the comprehensive set of classic and state of the art computer vision and machine learning algorithms, which ensure reliability for this project [38]. It is crucial to evaluate the system's reliability and accuracy. In scientific literature, these systems are evaluated by detection accuracy, processing speed, and maximum detection range. Processing speed is expressed in frames per second (FPS). Research shows that in order to ensure a stable recognition system must reach 20 FPS processing speed because lower FPS can cause poor reliability and poor delivery accuracy [33]. Also, different weather conditions and maximum height must be evaluated in order to understand when computer vision can be used efficiently. This allows for evaluating system reliability in real-world operations. In order to understand the made computer vision system, the detection speed from QR entering the frame to the servo opening, the maximum height at which the camera will be able to detect the QR code and also, performance in different lighting conditions will be measured.

2.2.3. Delivery Accuracy

Delivery accuracy is the main parameter in this project. This measurement directly defines the system's ability to perform a desired task. During the dropping, the UAV height and speed will be measured to gain an objective understanding of dropping accuracy. Due to the nature of the test and because of the manual UAV flight repeatability, of exact values will be impossible to replicate that is why the average of all attempts will be calculated at different altitudes and speeds. In scientific literature, delivery accuracy is often defined as the distance from the desired delivery point to the actual payload dropping point [15]. The average error is calculated with Eq. 4.

$$\bar{x} = \frac{1}{n}\sum x_i \tag{4}$$

where: $\bar{x}$ is the average delivery error (m); n is the number of tests performed; x_i is the error measured during the i-th test (m).

However, during real-life testing, wind can have an influence on ballistic dropping accuracy. To account for possible deviation from the target due to wind, the real target drop error will be recalculated based on wind velocity at the release point. To calculate it, Newton‘s 2nd law will be used, assuming only air resistance and gravity are acting on the object, which leads to ballistic equations [39]:

$$\dot{x} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{v_x} \\ \dot{v_y} \\ \dot{v_z} \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \\ v_z \\ -\frac{C_D \rho A}{2m}(v_x - w_x)V_r \\ -\frac{C_D \rho A}{2m}(v_y - w_y)V_r \\ g - \frac{C_D \rho A}{2m}(v_z - w_z)V_r \end{bmatrix} \tag{5}$$

where: ; v_x v_y v_z are the velocity components of the object (m/s); w_x w_y w_z are the wind velocity components (m/s); V_r is the relative speed between the object and the air (m/s); C_D is the drag coefficient; ρ is the air density (kg/m³); A is the reference area of the object (m²); m is the mass of the object (kg); g is the acceleration due to gravity (m/s²).

The scientific literature sources emphasise the importance of multiple systems related to delivery accuracy. Robust perception, reliable timing, and synchronised flight and release mechanism determine the overall delivery accuracy, but the final result will be measured due to the determination of this project's success.

2.3. Chapter Summary

In this chapter, the theoretical justification of picked fixed wing system for this project and the performance evaluation criteria were proposed. Firstly, with the analysis of scientific literature sources and previous studies, the choice of UAV platform, dropping mechanism, navigation principles and control algorithm was justified. Secondly, the experimental and statistical evaluation methodology was determined in order to objectively evaluate the project's success. Calculation and objective determination of the main criteria of – delivery accuracy, computer vision reliability, and aerodynamic efficiency was proposed. This complex analysis of project work will allow not only to understand the working capabilities of the UAV system but also to identify the key factors that determine its accuracy and stability under actual operating conditions.

3. Project Decisions and Results (Experimental Part)

In this chapter, independent research and design work related to fixed-wing UAV modelling, analysis, additional parts and configuration is described. Applied methods, technologies in use, obtained results and performance in real-life conditions are discussed. In this project's experimental part, 3D scanning, modelling, CFD analysis and 3D printing technologies are used in order to create a functional fixed-wing UAV dropping mechanism after recognition of the place QR code with a made computer vision algorithm. This chapter describes how the physical model was reverse-engineered for additional part modelling and additional components were introduced to the already existant fixed wing UAV, and how this aeroplane was tailored for the delivery operations of a small medicine box for a proof-of-concept project task.

3.1. 3D Scanning

To recreate an accurate UAV form on the CAD platform, 3D scanning technology was used. In this chapter, the equipment, technology and necessity for this project are described. Creation of a digital twin for a physical plane model is essential due to the accurate tests in CFD and also precise modelling in CAD. Without digital twin creation, the model would be rough and not accurate to the physical plane model, which would complicate the cargo transportation bay. It reduces simplifications of complicated geometries, which are usually done in manual modeling and also ensures accurate representation of the plane. 3D scanning was done using a handheld 3D scanner, HandySCAN 700 shown in Fig. 6. It works using the laser triangulation principle, which is considered one of the most accurate methods in digital twin creation [20]. Technology uses two lasers and a camera. Based on the triangulation principle from the laser point and the reflection point to the camera, the distance from the device to the surface is measured and captured. The used device is characterised by high accuracy, which can be as accurate as 0.03 mm. That is why this device was used for this purpose, as precise plane recreation is essential for future tasks of this project. Also, to accurately measure, categorise data and allow the device to know its position in relation to the object positioning targets are used. These markers are spatial reference points that allow the scanner software to precisely determine the scanner’s position relative to the object and merge data from different scanning paths into a single coordinate system. They are made with contrast and reflective materials, with the other side covered in glue to have the ability to stick to the model. They are very important while scanning a big object, or in this project's case, changing the object's position during the scan to scan the plane from all sides.

Fig. 6. Used equipment for 3D scanning (HandySCAN 700 and position targets)

Moreover, the combination of HandySCAN 700 and positioning targets allows independent scanning from external positioning systems like fixed cameras or base stations, as the scanner uses the described dynamic marker-based tracking during the process. Firstly, before scanning, positioning targets on the plane and extra towers with positioning targets were placed to capture all the geometry. During the scanning process shown in Fig. 7, a few passes from all planes, fuselage planes and difficult geometries were done in order to reduce shadow zones. After that, the plane was flipped to capture the other side of the geometry and combining was done through placed markers as the device knew the exact position in relation to the object even after the change of position. The process combined took around one hour.

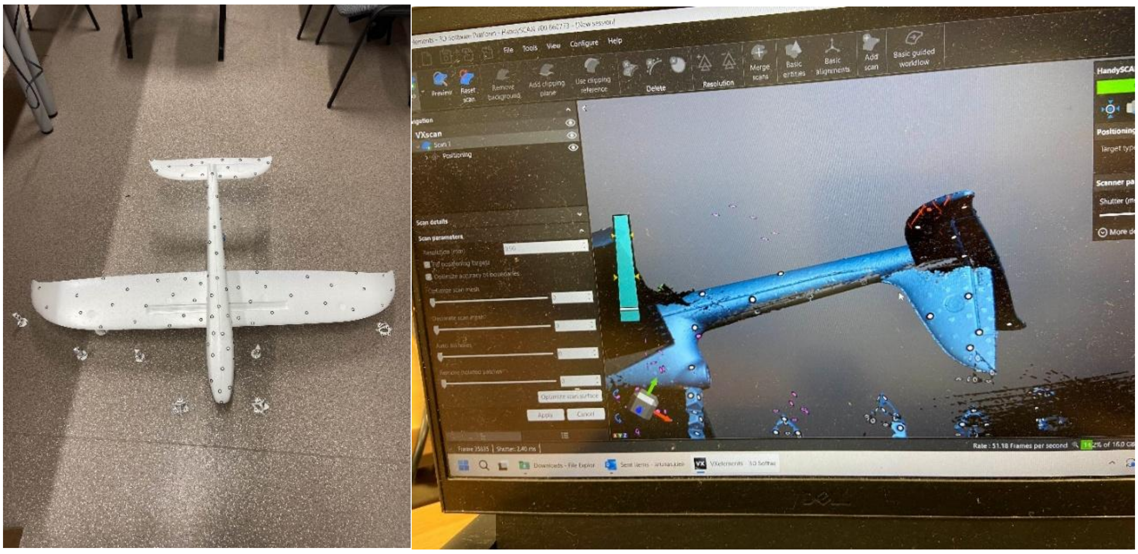

Fig. 7. 3D scanning process

After the initial scanning process, the data was processed. The process consisted of cleaning up the model from captured unwanted geometries and other noise captured around the object. After that, it was converted to the desired file format, which later could be used in CAD software. The file format is a point cloud. It is a discrete approximation of an object's surface, consisting of a large number of spatial points, each defined by coordinates (x, y, z), but there is no representative mesh or 3D model directly from the 3D scanning device. However, as it is seen in Fig. 8, the point cloud is dense, and the geometry of the plane is properly captured. Additionally, from the described advantages and used in this project, the 3D scanned model can be used for measuring different and difficult models, their surface curvature, analysis of geometric deviation can be done and also determination of structural deformations.

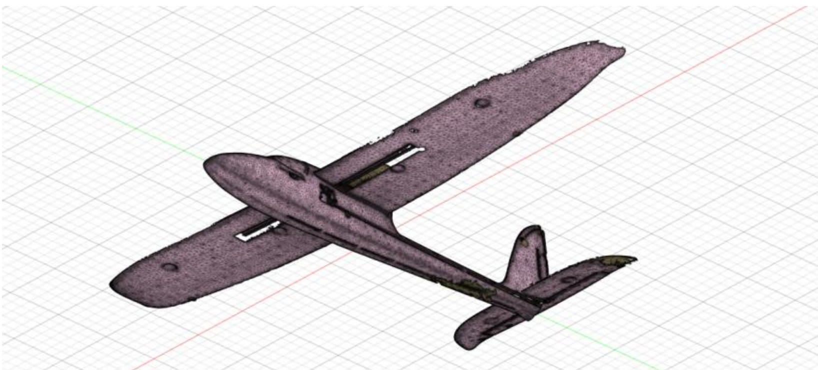

Fig. 8. Scanned plane model

Finally, the point cloud was positioned relative to coordinates axis and prepared for CAD modelling and model creation. This method allowed to get high presion UAV digital twin, which is essential for CFD analysis and cartridge modelling. In comparison with theoretical and manual modelling, this method allows a more precise representation of construction curvature, especially small geometric nuances.

3.2. Cartridge Form Modelling

Gathered, structured, and cleaned data from 3D scanning in point cloud file format had to be remodelled to suit CFD analysis requirements and surfaces and solids for the cartridge modelling process. After that, two versions of the cartridge were modelled. The main aim of this modelling was to prepare aerodynamic surfaces for CFD analysis and also to model an aerodynamic and functional cartridge model for payload carrying and dropping after QR code detection. Also, the modelled payload compartment must be integrated into the existing UAV structure to reduce the impact on flight characteristics, weight and aerodynamic distribution. Unlike when building a model from scratch in this project, the reverse engineering method was applied to have the relevant geometries, shapes and accurate surfaces for precise modelling of the UAV payload compartment. The modelling process seen in Fig. 9 started by orienting the point cloud relative to the 3D axes of the global coordinate system. Axes aligned in relation to flight direction by slicing model with required sketches and planes. This step is crucial to all further steps because inaccurate orientation affects future plane and sketch creation, which can result in an inaccurate model for the CFD analysis or an inaccurate cartridge that, after printing, would not fit the existing UAV structure. Next, point cloud projections to create planes were created, which allowed to identify fuselage shape and model nuances for model and cartridge creation. In this step, a plane model was created without a tail in order to reduce mesh in CFD analysis, as ANSYS student limits the mesh size.

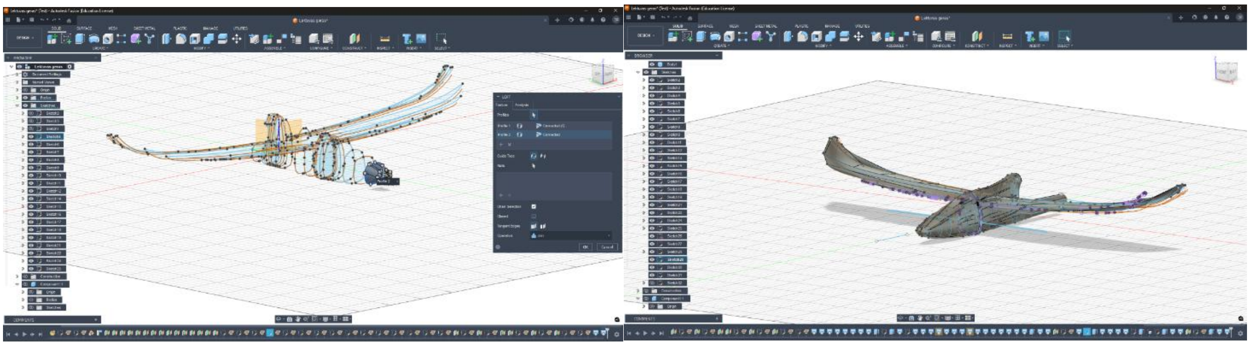

Fig. 9. UAV 3D modelling process and the modelled plane model

After the creation of a plane shape, and made transformation from point cloud to 3D solid cartridge modelling started. In the fuselage projections on planes, sketches were created for the cartridge model creation. Payload carrying and dropping bay must include a servo motor for opening the payload bay when QR code is detected, a camera mounting position for stable and reliable mounting during flight and volume inside it to fit a small medicine box for the proof of concept. An important aspect is that the cartridge was modelled as an integrated fuselage part for better airflow oppose to a separate attachment. This approach required careful consideration of all components' placement and planning, as the structure itself is compact and glued to the existing plane fuselage. In the first version seen in Fig. 10, the cartridge camera was placed at the front of the model in the non-closed mounting area with high gradient curvature at the front for easier mounting of the camera. The front of the model was made without side walls in order to save weight. Payload compartment featured an enclosed shrinking form towards the tail of the aeroplane in order to reduce wake behind the model. Also, it featured a mounting bracket to the existing holes, but in later versions, this approach was removed in order to save weight and ability to rely on glue because of the low mass of the part.

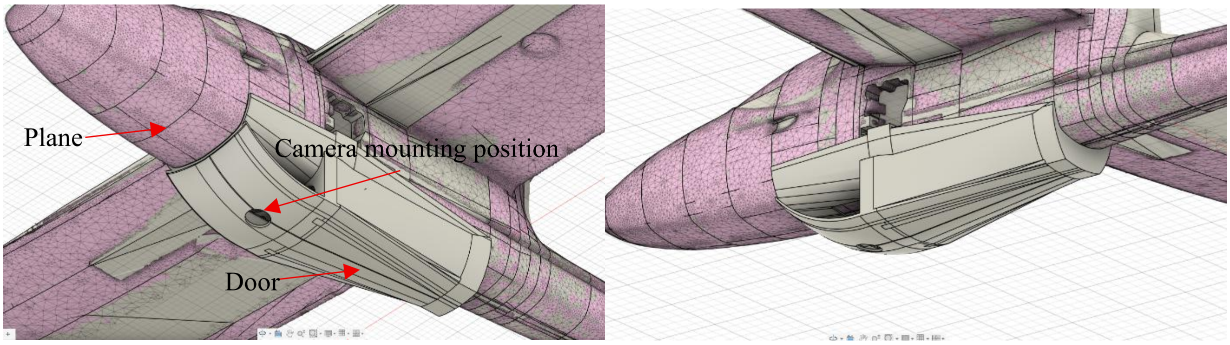

Fig. 10. Plane cartridge model version 1

Taking into account the first design approach and the need for idea validation in CFD, the second version of the cartridge was created. This design features a much more pointy front for more efficient airflow around the cartridge, and additional doors in the front for easier access to the camera mount. Also, it is completely enclosed for better airflow. The rear door design featured the same hatch and release mechanism with an integrated servo motor position in the model. The rear of the model was kept open in order to same weight and have better access to the servo motor for checking and confirming the correct movement during door opening initiation. As previously mentioned, the model was fully mounted only with glue and additional mounting brackets were removed for airflow and weight reduction purposes. Precise modelling and curvature around the fuselage is seen in Fig. 11. It confirms and displays the reverse engineering advantages in this model making and adaptation to the existing complex geometry.

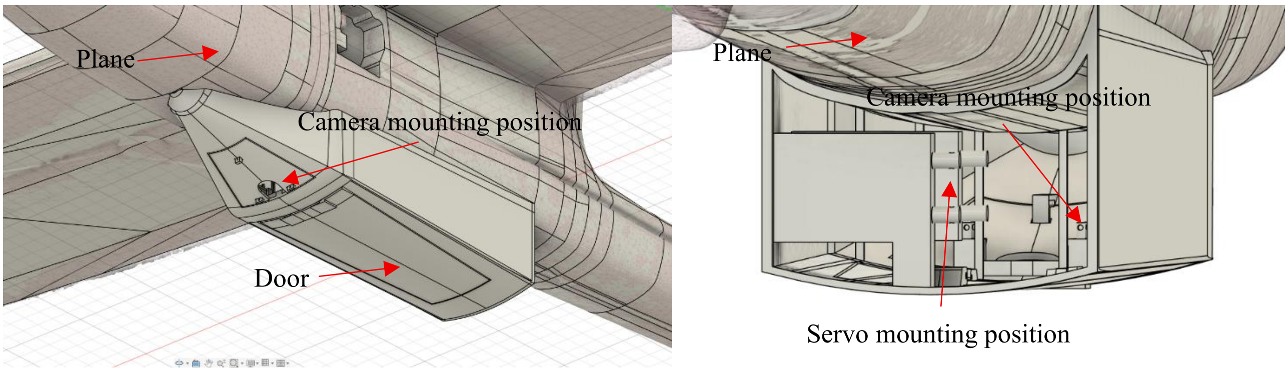

Fig. 11. Plane cartridge model version 2

The modelling process from point cloud conversion to 3D solid and cartridge modelling was done in Fusion software. Ability to import and work with point cloud and create planes and sketches in relation to existing point cloud, and the ability to change modelled part in timeline box meant that this software for this part of the project was picked. This modelling phase and creation of models, together with a physical parts model, allows construction optimisation before having the physical part. This helps to reduce costs and time in the model optimisation and consideration part of the project. Three created models were converted and exported as an STL file for CFD analysis and to the 3D printer for deposition modelling of the made parts in CAD software. The final and used model in the physical test of this project was simplified as the front doors of the version 2 were removed in order to make the shapes more easily printable for the 3D printer. However, the described 3D scanning and modelling method plays a crucial role in the precise modelling, which ensures a high degree of reliability in the results and enables well-founded engineering decisions to be made.

3.3. Aerodynamic Analysis

In this chapter, modeled fixed wing UAV model is analyzed using computational fluid dynamics (CFD) software Ansys. The analysis goal is to evaluate the additional payload carrying bay influence on the overall aerodynamics of the UAV, focusing on and comparing the drag force of different designs and plane models without the payload carrying bay. Additionally, evaluate different modelled payload carrying models and pick the one which generates the least amount of drag force. Aerodynamic analysis is curtail part of this project in determining the modelled bay influence on the UAV overall drag and picking the least amount of drag-generating model in order to have longer, more efficient UAV flight, which is crucial for delivery operations. For the analysis, a digital UAV model was used from 3D scanning and modeled in above described method in CAD modelling, ensuring the accuracy of the actual structure's geometry. Analysis was done with a plane without the payload and with two payload-carrying bay models. Analyses were done in three different flight speeds (10 m/s, 15 m/s and 20 m/s) to eliminate calculation error possibility and test in the designed flight conditions of the fixed-wing UAV. Standard environmental parameters were picked: The air density is $\rho = 1.225$ kg/m³, and the flow is assumed to be steady and incompressible, which is reasonable given the speeds under consideration. Fluid temperature 22°C. How it is seen in Fig. 12, a mesh was formed for the UAV surface and the testing environment. Mesh is one of the most important aspects in CFD analysis, but it cannot be as detailed because of the limits in the Ansys student version. Detailed mesh was used in the wings leading edge, the fuselage front, the payload compartment and flow separation zones. In these areas larges speed gradients and turbulence effects are formed, which is why a finer mesh is crucial in these areas. Also, the environment around the tested model has a large impact on the CFD analysis results. Creation of a large testing area is important because in a small compact area, the plane flow can not move freely, which can reduce the accuracy and induce unwanted behaviour of the airflow. Due to these aspects, the height of the testing area was five times the height of the aeroplane, the same area was in front of the plane and after the plane in order to simulate the drag accurately, two times larger was picked (ten times plane length). This ensures stable CFD results and clean flow movement all around the model which ensures reliable testing results. The nature of the flow was assessed using the Reynolds number:

$$Re = \frac{\rho v L}{\mu} \qquad (6)$$

where: Re is Reynolds number; v is free stream velocity (m/s); L is a length scale that characterises the scale of the flow motions of interest (m); μ is the fluid dynamic viscosity (Pa.s or N.s/m^2 or kg/m.s).

For this type of simulation, a Reynolds number of 5×10^5 was used. Which was used after made calculations from the formula above. For the analysis of the k-ω SST turbulence model was picked to accurately measure values in the inflation layer and determine flow separation zones. This model is widely used in aerydinamic researches becasue of the accuracy in evaluating surface influence on the flow [37].

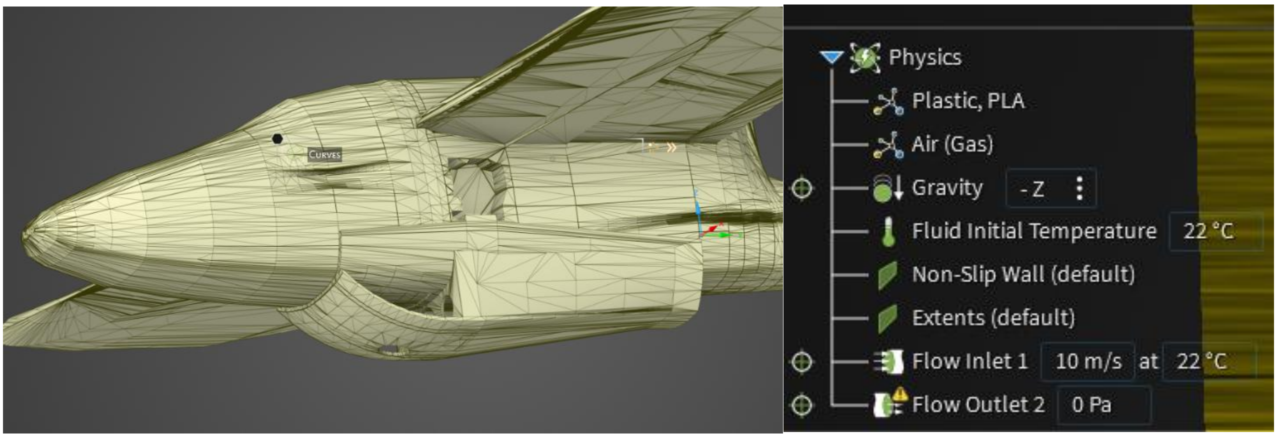

Fig. 12. Mesh for CFD analysis and the parameters used in CFD analysis

During the CFD analysis, the Y force, which is equivalent to planes darg force, was measured and compared. It is visually clearly seen that a plane without a payload bay has an even distribution of flow around the wings and fuselage, which shows that the model is well aerodynamically optimised. It is clearly seen that higher static pressure is in front of the plane and in front of the wings. At the back of the plane, the wake region is seen in Fig. 13.

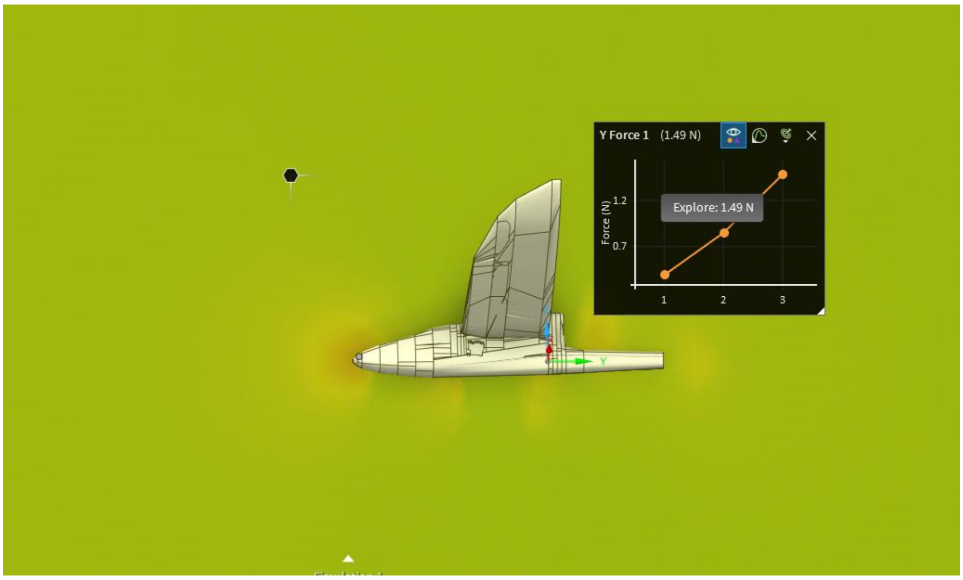

Fig. 13. Results of the plane without a cartridge

Analysing the model with a cargo compartment changes the aerodynamic characteristics and increases drag. The additional structure increases the frontal area and creates new areas of flow separation, which directly increase drag, creating a wake around the cartridge that disturbs airflow and creates uneven pressure distribution. Drag force with cartridge V1 increased on average by 46% in contrast, cartridge V2 increased drag by 13%. This large difference can be attributed to the more aerodynamic shape used in the V2 design, and also the removal of a large empty space after the initial wall in the V1 design. Together, these differences made a huge difference on average, 0.3 N less drag in comparison to V1 and V2 cartridge designs. This shows that the cartridge shape has a major influence in overall drag of the plane, which influences flight time and range of the UAV used in delivery operations. Also, the CFD analysis results shown in Fig. 14. highlighted the influence of the flight speed to the drag force. In the made analysis, it is seen that the increased speed from 10 m/s to

20 m/s is attributed to a four times higher drag force. That is why not only the shape and construction of the plane influence flight range and flight time, but flight speed must be modelled carefully to extend the operation parameters as much as possible.

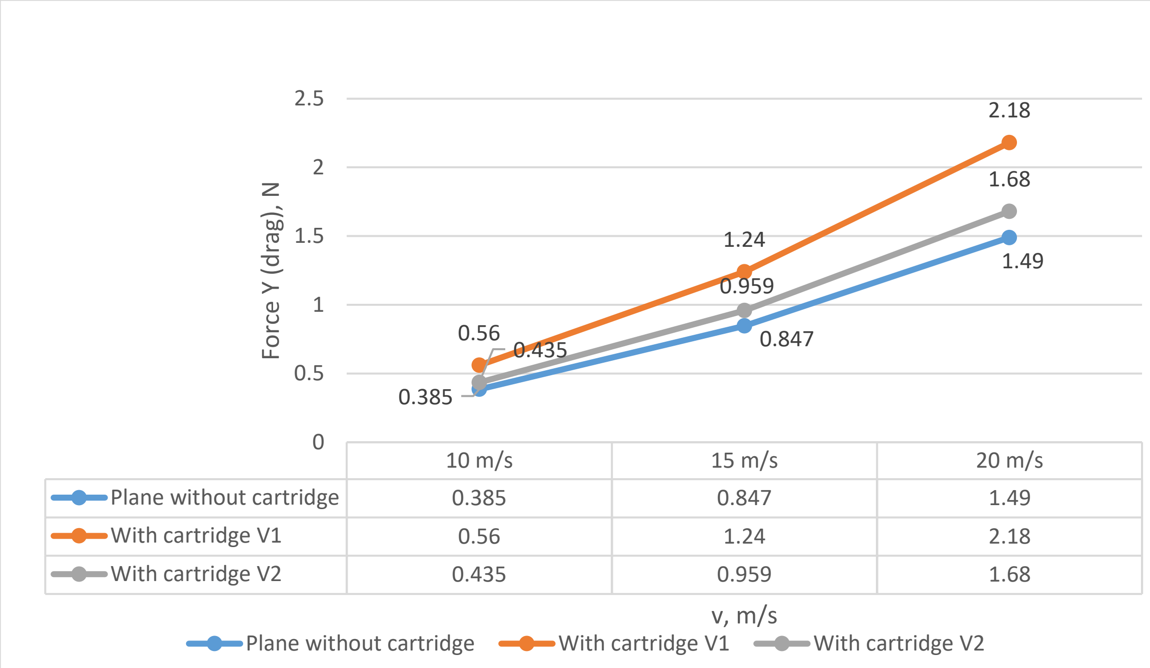

Fig. 14. Graph of drag for different configurations

Done CFD analysis allows for a few important conclusions. Firstly, payload cartridge integration inevitably increases the overall drag of the plane. However, careful modelling and aerodynamic shape can significantly reduce the impact to up to 0,3 N, which is significant for this type of light and medium-sized UAV. Secondly, energy consumption, especially in fixed-wing UAV flight, is directly related to aerodynamic efficiency. That is why even small constructional improvements can have a huge influence on the overall performance of the plane. Based on the CFD analysis, an aerodynamically optimised cargo compartment design was selected for the final prototype, which ensures minimal influence on the drone's characteristics and minimal reduction of flight efficiency.

3.4. UAV Flight Hardware Selection

In order to create a physical and flying UAV model for autonomous delivery operation, components must be selected carefully. This is a crucial step because it determines the system's stability, reliability and efficiency during delivery operations. Unlike in theoretical analysis in hardware selection, it is necessary that all components would be compatible with each other. Not only mechanical but also electrical, signal and functionality perspectives. In the scientific literature, it is emphasised that a UAV system must be evaluated as a cyberphysical system in which energy supply, control algorithms, sensors and mechanical components are working in synergy [1]. In this work, components were picked individually based on individual but also on a few general parameters: power-to-weight ratio, energy efficiency, reliability, simplicity of the design and budget. This way, a stable and well-balanced UAV system was formed for experimental analysis of this project.

Base for all components had to meet the main requirements: fixed wing platform, light, and have the ability to integrate other components and solutions onto the existing platform. For this project, the MULTIPLEX EasyStar 2 UAV platform was picked. This platform is known for high aerodynamic stability due to high-wing configurations and a positive dihedral angle, which ensures self-stabilisation in the lateral plane. This stability is very important for this project because of the additional components and surface integration on the plane's body for payload carrying operations. Also, this simplifies control algorithm complexity and allows for compensating external disturbances. Moreover, the structure is made from light Elapor-type foam, which ensures a small UAV structure mass and can deform and not instantly break during an accident, which is crucial for testing operations. Large internal space seen in Fig. 15 allows integration of additional components like a microcomputer for visual data processing without disturbance of airflow and UAV design. Because of these features, this UAV platform is widely used in the development of UAV prototypes, and it is used in this project.

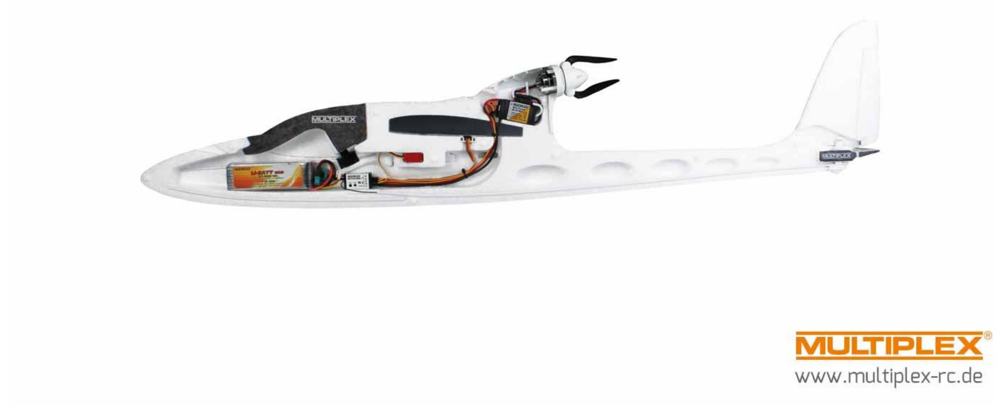

Fig. 15. Used Multiplex EasyStar 2 UAV model

The UAV propulsion system is an essential component of UAV flight. It must provide stable and reliable power to the propeller and, together, ensure the desired propulsion of the drone. The UAV propulsion system consists of a brushless motor ROXXY BL Outrunner 2834/08 and the electronic speed controller (ESC) ROXXY BL-Control 720 S-BEC. Outrunner type motors are characterised by higher torque at lower RPMs, which allows to effectively use of larger diameter propellers. This is very important for this project as a fixed-wing UAV will be thrown by hand with additional equipment inside the plane, which means that it will be heavier than inicialy design. The picked motor has a brushless construction. Design features electrical commutation in comparison with mechanical commutation used in brushed motors. In a motor, a stator's magnetic fields are generated, which interact with the rotor's permanent magnets to generate torque. This ensures larger efficiency, smaller heat generation and better reliability in comparison with older brushed motor designs. One of the most important parameters of any electrical motor is the KV coefficient (RPM/V). It defines the engine's rotational speed at a voltage of one volt. This allows us to determine the optimal propeller-motor combination, because larger KV means higher rotational speed, however smaller torque. For fixed-wing UAV, usually the 900-1200 RPM/V KV is used, which is why a motor with 1120 KV is picked for this project. Compatibility with the used ESC ensures reliable use of this motor in the project. ESC ensures stable and precise motor RPM control with the input of pulse-width modulation (PWM) signals, which are transmitted by the control system and generated three pahse voltage which is necessary for BLDC motor rotation. Integrated S-BEC function allows powering other electric components, most usually the receiver, as it is used in this project. This allows powering other components like servos without any additional wires and powering up to a used battery.

For the UAV's power supply, ROXXY EVO LiPo 3-2200M 20C; 24,4 Wh is used. Lithium-polymer (LiPo) batteries are known for high energy density and low weight, which is why they are widely used in UAV systems. 20C discharge coefficient allows to provide a large amount of energy, which is necessary for motor work during large load operations and scenarios. Also, it ensures a stable UAV motor and all powered systems are working as it is, reducing the possibility of sudden voltage drops, which could influence the propulsion and control system of the UAV. The picked battery and capacity of 2200 mAh will allow for performing flights up to 20 minutes, which is more than enough for testing UAV capability in autonomous operations with manual UAV flight. Battery capacity can not be increased drastically because it has a big influence on the UAV mass, and also, the position of the battery limits its size of it inside the UAV.

For the control and communication in the UAV, the SPEKTRUM AR410 DSMX 4-channel sport receiver is used together with the SPEKTRUM DX6i remote controller (RC). The used receiver ensures stable communication with the RC and UAV system. The used DSMX technology uses adaptive frequency hopping, which allows for reducing the possibility of signal loss and improves redundancy to electromagnetic interference. Stable communication is crucial for manual flights used in this project as loss of control means that the UAV is likely to crash. To control aerodynamic surfaces in the tail of the drone, servos MS-12020 MG are used. These servos use metal gears, which ensure longevity and better reliability in comparison with plastic ones. Larger actuating force (1.5 / 2.0 kg · cm) allows reliable control of aerodynamic surface in all flight conditions. Fast servo response is crucial in order to accurately and precisely manoeuvre the drone during manual flight. Precise control of the plane directly correlates with delivery acuracy that is why they are very important.

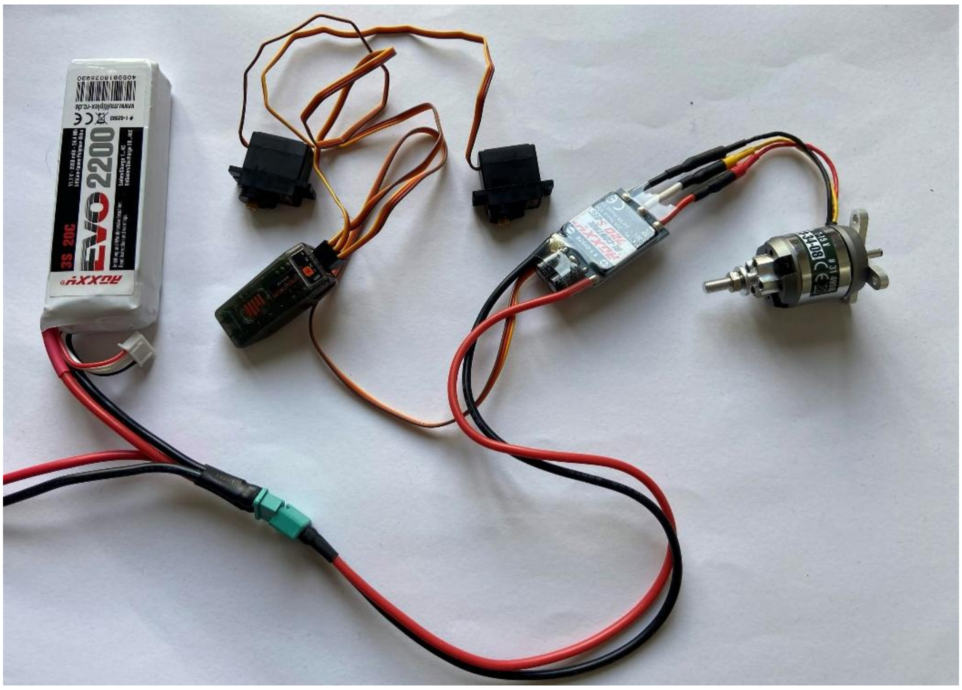

Fig. 16. Connected UAV parts used in flying a fixed-wing UAV

All picked components form a UAV system used for manoeuvring the drone in the air, as seen in Fig. 16. The system combines energy supply, propulsion, control and mechanical elements which ensure stable, safe and precise flight of the UAV during payload dropping testing.

3.5. Payload Release Mechanism and Processing Algorithm

One of the main tasks on this project is to engineer a functional payload release mechanism and autonomous processing and initiation algorithm. The system is created with integration of mechatronics and digital subsystems, combining a sensor, a computer which does calculations and is responsible for computer vision and a motor which is responsible for payload dropping initiation. Payload dropping and identification of precise area system realised using a single-core entry-level computer – Raspberry Pi Zero 2, which was picked because of the low mass, low volume, low energy consumption and comparatively low costs. This platform allows integration of a camera and servo motor without additional heavy and complicated subsystems, which is very beneficial in aviation for extending flight range. To gather visual real-time data and provide it to the Raspberry Pi Zero 2 Sony camera IMX219, which was picked with a field of view (FOV) of 77° and seen in Fig. 17. This camera was picked due to its compact size, ability to integrate it with the picked computer and also relatively low energy consumption, low mass and good quality. 77° FOV allows a wide range of detection below the aeroplane in a wide range of heights, which is necessary for manual flight, in which precise flight height can not be reached consistently. Connected servo motor MS-12020 MG after detection of the QR code on the ground opens the cartridge. Motor ensures a stable and precise turning radius for picked weight of the payload and the door. The servo is controlled via a PWM signal from the Raspberry Pi computer, which is directly connected via a wire. This system allows for precision and minimal reaction time from detection to servo initiation, which is critical during the flight of the UAV. System is powered by the onboard ROXXY EVO LiPo 3-2200M 20C; 24,4 Wh battery, which provides power to the UAV flight components and detection system. Together with it, the ASSAN 8A UBEC voltage regulator is used for providing precise voltage to the Raspberry Pi computer, ensuring stable detection and working of the dropping mechanism.

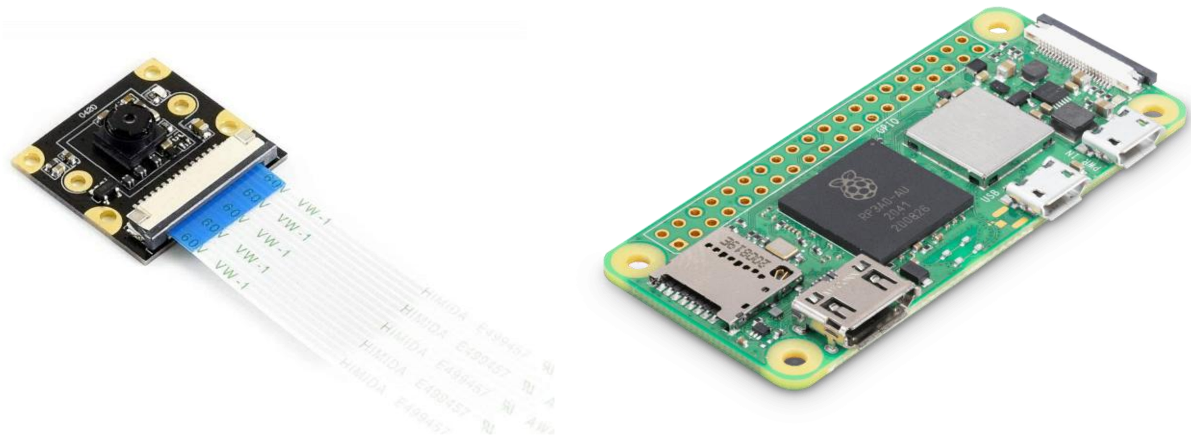

Fig. 17. Used computer RASPBERRY Pi Zero 2 and a camera SONY 8MP IMX219 77°

Autonomous payload dropping is this project is based on visual navigation using marker based approuach. For the precise area identification ArUco type markers were picked, which have a clear geometric structure and are easily detected by using computer vision algorithms. The existing library is picked in order to have the best recognition possible in all conditions without the need to train the algorithm. Alogorythim realized in the Python programming language with the use of OpenCV library of ArUco QR codes. The system is working in a continuous loop in which below described main steps are being carried out. Firstly, the algorithm starts by initiating the SONY 8MP IMX219 camera and defining the required resolution (1280x960), which enables enough detail. However, it may be reduced in order to reduce reconstruction and scanning time. Then, every detected pixel is converted to grayscale format in order to reduce processing time and complexity, and make the processing algorithm work faster. After that, ArUco detector is used, which analyses the picture and looks for specific shapes coded in the QR codes. After identifying any of the shapes in the library system, it identifies the QR code ID and displays information about QR code detection. It allows not only to detect QR codes but also to determine if the desired zone is reached, and different tasks can be programmed depending on the different QR IDs. After that, the servo motor movement is initiated to open the payload compartment. An important aspect is that the control algorithm would work in real time without delay of more than 1,5 s, which would make the dropping mechanism unusable because the UAV would fly over the QR code without the ability to detect it in the modelled flight heights. Moreover, weather conditions like lightning, shadows and camera frame rate play a vital role in reliable control algorithm work for the desired task. Because of that, testing and fine-tuning are done in Chapter 3.7.

The payload dropping system is the essential part of the UAV project. It enables an autonomous delivery function with an integrated visual processing algorithm and mechanical executor, which ensures fully autonomous work during the last and most precise required flight phase. This solution is modular, which means that it is future-proof and can be modified and improved with the change of camera or computer for faster or a wider range of detection. In this way, this system provides a foundation for further research works and also the application of UAV autonomy.

3.6. 3D Printing and Final Assembly

Applying additive manufacturing methods allowed the transfer of modelled parts in CAD software to physical items. Final integration to the UAV structure and integration of desired components depend on printing quality, material and settings of the process described in this chapter.

For the making of physical parts of modelled items for real-life testing, fusion deposition modelling (FDM) technology was used, which is one of the most widely used technologies in small batch UAV components manufacturing. The technology principle is based on filament melting and the deposition of its layers based on a pre-generated digital model and the path of the nozzle. The printing process was prepared using slicing software, which converts a CAD software-generated STL file to the G-code format, which is used in the 3D printer. In this software, printing parameters like layer height, infill density, wall thickness, extrusion temperature and printing speed are set. Accurate and precise calibration of the parameters to the desired task is critical for the best technology use. They have an impact on the mechanical properties of the printed part, surface quality and mass of the final product. While analysing printing process data in Fig. 18. determined that the majority of the printing time is spent on forming the outer walls and generating the support structures. Support structures are essential for this part printing, as this ensures reliable shape recreation even in hanging parts of the model. Due to the complex aerodynamic shape of the plane part overhang angles occur in many different parts. When in these zones the angle exceeds 45°, additional supports must be placed in order to avoid deformation and layer shift during the printing process and in the final part. Also, a large amount of support not only extends printing time but also requires a larger amount of material and additional postprocessing in terms of removing supports from the made part. These aspects are important and, if possible, should be avoided in order to save resources and time. However, for this project, with the intent to save as much mass as possible and to fit the plane as best as possible for best aerodynamic performance, a complex structure was kept, even though it meant that a large number of supports had to be placed in the printing process. Additionally, orientation of the part inside the printer plays a crucial part in the part strength because FDM technology produces an anisotropic structure, which means that the strength between layers is lower than the strength within the plane of the layer. The printing process was executed with Elegoo Centauri Carbon 3D printer, which is characterised by a robust mechanical design and sufficient precision for the prototyping of engineering components. This printer is designed for 3D printing professionals, featuring CoreXY heated chamber kinematics and with maximum nozzle temperature of 320 °C.

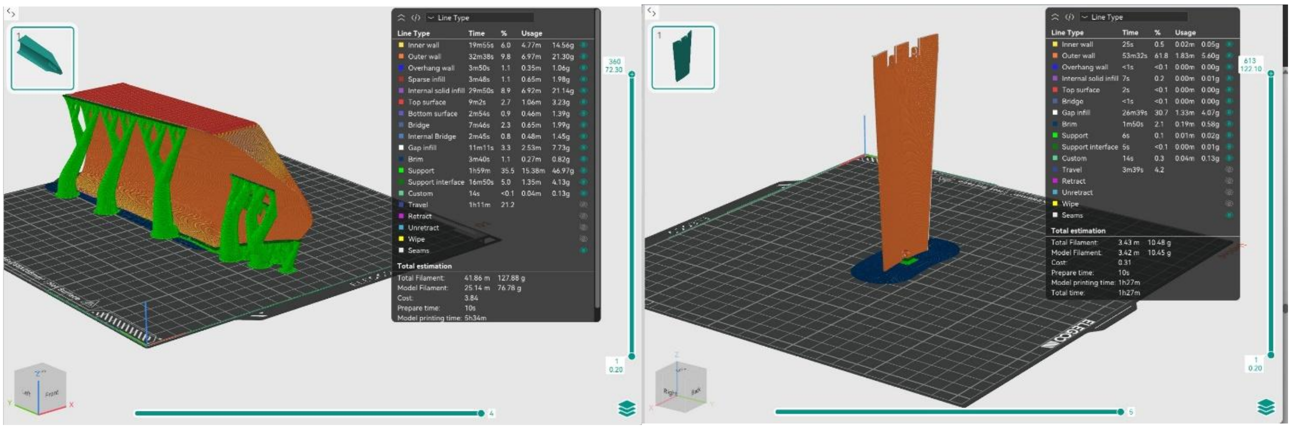

Fig. 18. 3D printing settings and time for separate pieces

One of the most important steps in printing was the choice of the material. Although the theoretical analysis considered the use of lightweight PLA (LW-PLA), the practical test identified this material's weaknesses. It requires very specific printing parameters and can print in a very narrow window in terms of nozzle, printing bed and air temperature. LW -PLA exhibits a foaming effect, which reduces the overall mass of the part but makes it really hard to work with. Poor configuration and parameters result in geometric inaccuracies, surface defects and uneven density. For these reasons, in this project, stable and reliable PETG material was used, which has better mechanical properties, better impact resistance and layer adhesion, which is beneficial while printing such complex aerodynamic structures. PETG is also less fragile, which is good for physical testing of the UAV. Evaluation of the mass aspect of LW-PLA helps to reduce the overall mass of the printed part. In direct comparison, it could reduce the structure mass by 10-20%, depending on the process parameters [40]. This means that the printed part is around 120 g mass could be reduced to 103 g, which means reducing the printed part mass by 17 g. Although this difference in UAV flight is not negligible and can have an impact on flight time and range, in this project step, reliability and construction strength were a priority.

First prototype of the cartridge model featuring two doors for easy access to the camera and servo motor was not successful, as in the made part, structural defects became apparent. How it is seen in Fig 19. printed part dimensions and holes were not as modelled in CAD software. Some holes were fully clogged, and the dimensions of the door holding hinge were larger than modelled and required additional sanding. Also, doors for easy camera access were mounted on too-fine tabs, which were not sturdy enough for holding the door in place. These defects occurred due to thin modelled items and details which 3D printer nozzle could not replicate. Also, because of the poor tolerance and the too-small-diameter holes.

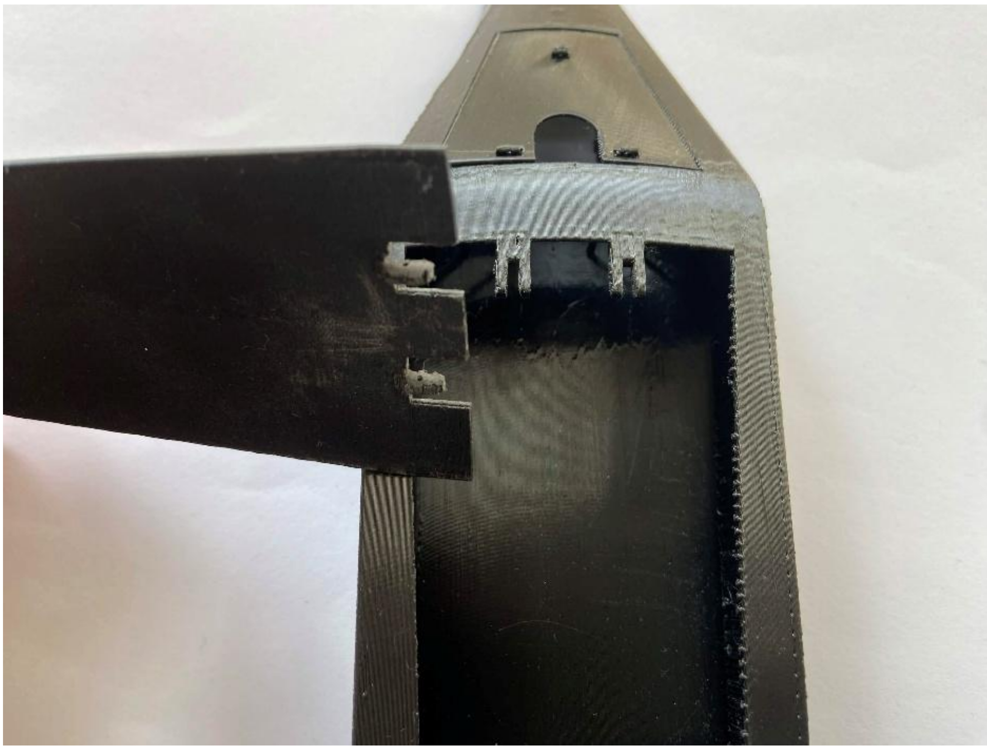

Fig. 19. First 3D print iteration of plane cartridge model version 2

Based on the results of the first prototype, a second CAD model was made. In this, a few structural corrections were made. Wall thickness was increased, tiny and complex intems were remodelled, simplified, and size was increased. Also, holes were aligned with better tolerance and increased in diameter in order to avoid clogging, like in the first prototype. Moreover, the front door for camera acses where removed and a solid structure was picked due to the simplicity and more reliable printing process seen in Fig. 20. These changes allowed for improved printing quality, reduced the number of defects in the final part and ensured model functionality in real-world tests. This iterative process allowed gradual conversion from a theoretical model in CAD software to a physical and functional model in the real-world environment.

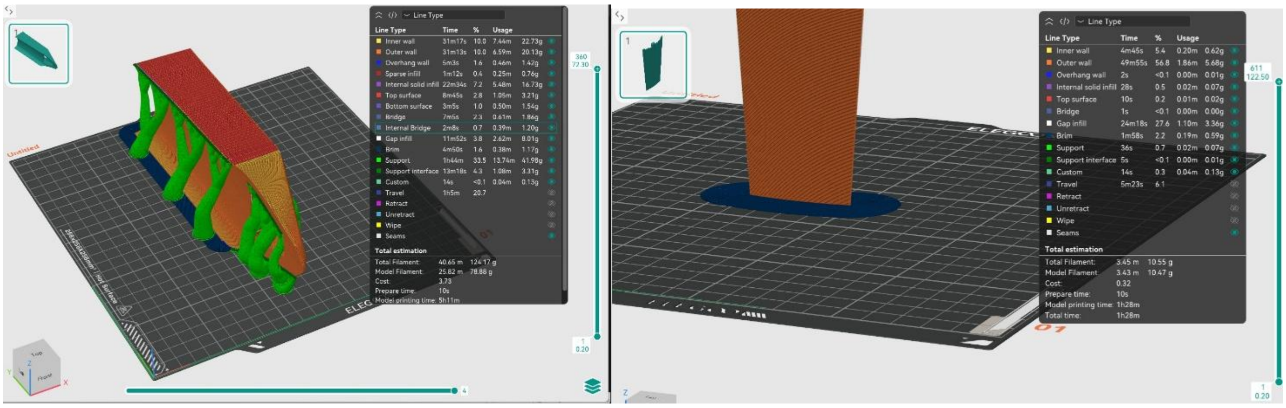

Fig. 20. 3D printing settings and time for separate pieces of the second and final prototype

After successfully printing the second and final prototype, the final assembly of the components and their integration into the fixed-wing UAV was done. The payload compartment was mounted as the structural part of the UAV with the help of glue in order to keep structural integrity and reduce drag as much as possible. Glueing in the part without additional mounting brackets or components allows for reducing the weight and reducing any mechanical part number which could fail during the printing or testing process. During the integration process, special attention was paid to the mass centre position because a shift in it can have a significant impact on the stability and manoeuvrability of the drone. Also, the structure of the plane was modified in order to transfer wires between the camera and the onboard computer Raspberry Pi, which is mounted inside the plane's fuselage, as seen in Fig. 21. The placement of the motor with motor mount is seen at the top, ESC is mounted at the middle of the fuselage in a separate compartment with UBEC for Raspberry Pi. This helps to safe space at the front of the plane for the battery, Raspberry Pi and wiring. In the payload compartment, the servo motor and camera are fitted in the desired positions for QR code detection and door opening. The picture is done with half of the fuselage. After all components are in place, the fuselage is merged into one piece, glued together and prepared for flight.

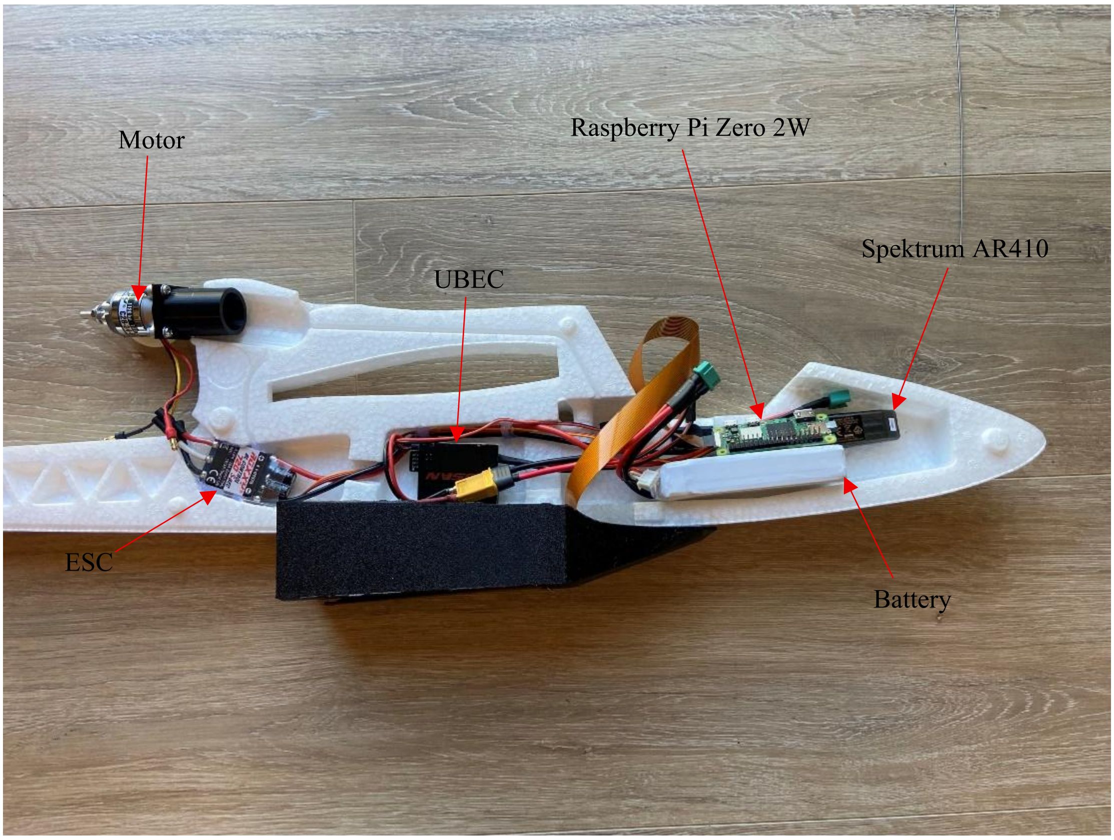

Fig. 21. Half esambled fixed wing UAV with components and their position in the fuselage displayed

It can be said that additive manufacturing and FDM enabled effective production of a component with complex geometry, but required an iterative approach to the final part making and understanding of technological limitations. Choice of the PETG material ensured a reliable and structurally rigid part with the best possible CAD model fulfilment.

In the final step, all components are wired together. The wiring diagram in Fig. 22 shows every component and physical or wave connections. The power flows from top to bottom, from the battery to the ESC and UBEC 5V regulator, and later to all necessary components for flight and also autonomous cargo delivery. Usage of a single power source ensures minimal mass of the aeroplane, which is essential for UAV delivery operations, and also better packaging capabilities inside the aeroplane. UBEC 5V output regulator is needed to ensure Raspberry Pi Zero 2W works during flight, as various factors like voltage noise, shared ground loops can result in computer shutdown, SD card corruption or poor performance due to the inability to provide precisely 5V from UAV battery.

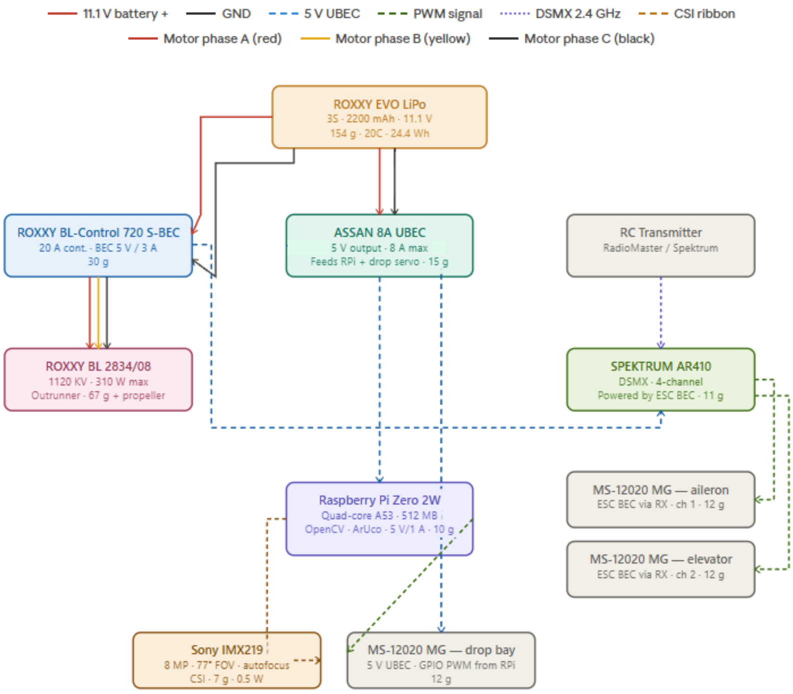

Fig. 22. Autonomous delivery UAV wiring diagram

After wiring and assembling everything together, the system was tested in real-life testing described below.

3.7. Computer Vision Limiting Factors and Experimental Measures

The computer vision system was used due to compatibility, light weight, low power consumption and availability in terms of budget. Used computer Raspberry Pi Zero 2W features a quad-core 64-bit ARM Cortex-A53 processor clocked at 1GHz and 512MB of SDRAM. That means that Zero 2 is up to five times faster than the original Raspberry Pi Zero. However, due to the complexity of this system, the camera can not be used in full resolution as it would result in lower than needed detection speed. The experiment identified the system's weakness and allowed to pick the best possible resolution for this project, flight and cruising speed of 8 m/s.

Table 6. Computer vision detection speed and used resolutions

Resolution	Frame time (ms)	Frames per second (FPS)
1280x960	500-670	1,5-2
1024x768	380-400	2,5-2,63
800x600	250-300	3,33-4
640x480	210-240	4,17-4,76

Frames per second identified that high resolutions with this setup can not be used, as it would result in a flyover without detection. However, lower resolutions require a larger QR code due to a lower number of pixels and the need for usability during drone flight. With each deduction in resolutions, flight height is reduced if the same QR code size is used, so the compromise has to be made in flight height due to the limitations of the used system. A larger QR code was made to compensate for the reduction in resolution in order to have higher FPS, which is essential for detection during drone cruising speeds.

To further analyse the limitations of the computer vision system, especially the 8MP IMX219 77° camera used in the project flights, experiments were conducted in different lighting and at different heights. Performance in different lighting is crucial for delivery operations because lighting can not be perfect all the time and can drastically influence system performance and delivery accuracy. Different shadows, clouds or adverse weather conditions can influence the visibility of the QR code on the ground, and the determination of working conditions for this type of system is crucial. Knowing possible weather conditions can help make deliveries more efficient, as well as understand malfunctions during delivery flights. To understand the performance of the system, tests were performed at a stable 1m height above the QR code printed on A4 paper. Its size 18,5 x 18,5 cm. Testing of the system was done 15 minutes apart in the evening, and the lightning was measured with the help of a mobile phone application, Lux Light Meter Pro. In done studies, it was found that this measuring method can have up to 15% deviation with the used mobile phone, but it is okay for a rough estimate used in this part of the project [41].

Table 7. QR code detection during different times of day and different lightning intensities

Day time	Lightning (lux)	QR code detected
19:02	2423	Yes
19:18	1250	Yes
19:33	1868	Yes
19:48	967	Yes
20:03	956	Yes
20:19	611	Yes
20:34	364	Yes
20:49	222	Yes
21:04	82	No

The experiment showed that the system could detect QR code in lightning 222 lux and better, which was detected at the end of the sunset when the Sun was nearly below the horizon. However, during testing, two false detections and the detection time increased. Even if detection is possible in 222 lux, it can not be used efficiently as detection would take too long, and the drone would fly past the QR code so the current setup could be used efficiently up to 500 lux.

Another important measure for test flights is height. To determine the possible flight and detection height of the QR code quadcopter drone, the XAG P100 PRO was used to precisely lift the camera to the desired height. The camera was mounted pointing directly to the ground, as in a fixed-wing UAV used in the project. Recognition speed was measured in 0,5; 1; 1,5; 2; 2,5; 3; 3,5 meters in perfect lightning conditions (above 1000 lux), and at the same time, to narrow down possible detection errors due to lightning. To compensate for the reduction in resolution due to previously described reasons, two QR code sizes were evaluated: 18,5 x 18,5 cm and 35,5 x 35,5 cm. An exact resolution number of 1024x768 was picked for future tests and flight due to the best compromise between detection speed and detection resolution. The test helped to evaluate possible flight scenarios for the test flights.

Table 8. QR code detection height using different QR code sizes

Height (m)	Detection of 18,5 x 18,5 cm QR code	Detection of 35,5 x 35,5 cm QR code
0,5	Yes	Yes
1	Yes	Yes
1,5	Yes	Yes
2	No	Yes
2,5	No	Yes
3	No	Yes
3,5	No	No

Overall, after conducting experiments with a computer vision system in can be said that system efficiency and reliability are reliant on a few different aspects: lighting, flight altitude, marker size, and computing capabilities. Optimisation of each and every component can have significant results for the overall functionality of the system. Proper lighting is crucial for RGB camera as it relys on sunlight reflection from the ground and the QR code. Reduced flight altitude helps to identify codes with lower resolution, increased marker size can help fly faster and higher with the same system, and increased computing power can significantly improve detection reliability and give access to all available camera resolution. However, due to a limited budget, some sacrifices were made in this project to have a functional proof-of-concept flyable fixed-wing UAV with a functional computer vision system.

3.8. UAV Flight Range and Time Calculations

With the additional mass and power consumption, the UAV will have a shorter flight range and shorter time in the sky. To calculate this, distinct system configurations are evaluated: the base fixed-wing UAV without additional components, a drone equipped with a cargo bay and hardware necessary for QR detection and door opening and a full configuration with an additional 100g payload, which represents a small medicine box.

Different power consumption in calculated cruising speed (8 m/s) for brushless motor ROXXY BL 2834/08 is listed in three numbers because with the increase in weight, the power consumption which is necessary to achieve cruising speed also changes. It is calculated by calculating lift coefficient, the induced drag coefficient, the total drag coefficient, the dynamic pressure, the drag force, the aerodynamic shaft power, the electrical motor power and the battery current draw from the motor. Values from CFD analysis can not be used in these calculations, as the model in CFD was created without the tail to reduce complexity and have a better mesh due to the software limitations.

$$C_L = \frac{2mg}{\rho v^2 S} \quad (7)$$

where: C_L is lift coefficient; m is UAV mass (g) ; g is gravity (m/s^2); ρ is air density (kg/m^3); v is cruise speed (m/s); S is wing area (m^2).

$$C_{Di} = \frac{{C_L}^2}{\pi ARe} \quad (8)$$

where: C_{Di} is the induced drag coefficient; AR is the aspect ratio (wing); e is the Oswald efficiency factor.

$$C_D = C_{D0} + C_{Di} \quad (9)$$

where: C_D is the total drag coefficient; C_{D0} is the parasitic drag coefficient; C_{Di} is the induced drag coefficient.

$$q = \frac{1}{2}\rho v^2 \quad (10)$$

where: q is the dynamic pressure (Pa); ρ is air density (kg/m^3); v is cruise speed (m/s).

$$F_{Drag} = qSC_D \quad (11)$$

where: F_{Drag} is drag force (N); S is wing area (m^2); C_D is the total drag coefficient.

$$P_{shaft} = F_{Drag}v \quad (12)$$

where: P_{shaft} is aerodynamic shaft power (W); F_{Drag} is drag force (N); v is cruise speed (m/s).

$$P_{motor} = \frac{P_{shaft}}{\eta_{prop}\eta_{motor}} \quad (13)$$

where: P_{motor} is electrical motor power (W); P_{shaft} is aerodynamic shaft power (W); η_{prop} is the propeller efficiency coefficient; η_{motor} is the motor efficiency coefficient.

$$I_{motor} = \frac{P_{motor}}{U_{battery}} \quad (14)$$

where: I_{motor} is the battery current draw from the motor (A); P_{motor} is the is electrical motor power (W); $U_{battery}$ is the battery voltage (V).

These calculations help to evaluate the different plane parameters during different flight conditions, including speed and weight, which is crucial in the calculations. The table below represents all components in evaluated configurations with their mass and power consumption, which are used in the calculations.

Table 9. Information about each component used in the configurations

Component	**Mass (g)**	**Power consumption (W)**	**Configuration**	**Notes**
Multiplex EasyStar 2 airframe	290	-	Base	Elapor foam structure, wing panels, tail, fuselage halves
ROXXY BL 2834/08 brushless motor	67	6,5; 8,8; 9,9	Base	1120 KV, 310 W max, 14-pole outrunner
ROXXY BL-Control 720 S-BEC (ESC)	30	-	Base	20 A cont. / 30 A peak, switching BEC 5 V / 3 A
ROXXY EVO LiPo 3S 2200 mAh 20C	154	-	Base	11.1 V nominal, 24.4 Wh, 154 × 35 × 21 mm
SPEKTRUM AR410 DSMX receiver	11	0,1	Base	4-channel, DSMX adaptive freq. hopping
MS-12020 MG servos × 2 (flight)	24	0,1	Base	Metal gear, 1.5 / 2.0 kg·cm torque

Component	Mass (g)	Power consumption (W)	Configuration	Notes
Propeller + wiring	20	-	Base	7″ × 6″ folding prop included with EasyStar 2
Raspberry Pi Zero 2W	10	1	Payload system	Quad-core ARM Cortex-A53 @ 1 GHz, 512 MB RAM
Sony IMX219 camera (8 MP, 77°)	7	0,5	Payload system	FOV 77°, autofocus, connected via CSI
MS-12020 MG servo (drop bay)	12	-	Payload system	PWM-controlled cargo door actuator
PETG cartridge V2 (3D-printed)	120	-	Payload system	Aerodynamic drop-box; V2 adds only +13% drag vs. bare fuselage
ASSAN 8A UBEC	15	0.3	Payload system	5 V regulated output for Raspberry Pi
Cargo (medicine box)	100	-	Cargo only	Proof-of-concept payload

With an increase in mass and energy consumption, and after the evaluation of all parameters in stable cruising speed, flight time and range are calculated. This helps to evaluate the possible performance and theoretical reduction in flight parameters with additional hardware tested and used in this project.

$$T = \frac{E_{batery}\eta_{usable}}{P_{total}} \tag{15}$$

where: T is the flight time (h); E_{batery} is battery stored energy (Wh); η_{usable} is usable energy from the battery (%); P_{total} is the total power drawn from the battery (W).

$$R = vT \tag{16}$$

where: R is flight range (m); v is speed (m/s); T is the flight time (s).

For the calculations, usable energy of 80% was used in order to realistically consider battery saving and flight safety measures. After doing calculations with the listed formulas and values, the results are put in the graphs seen in Fig. 23 and 24 and the table, identifying the main results.

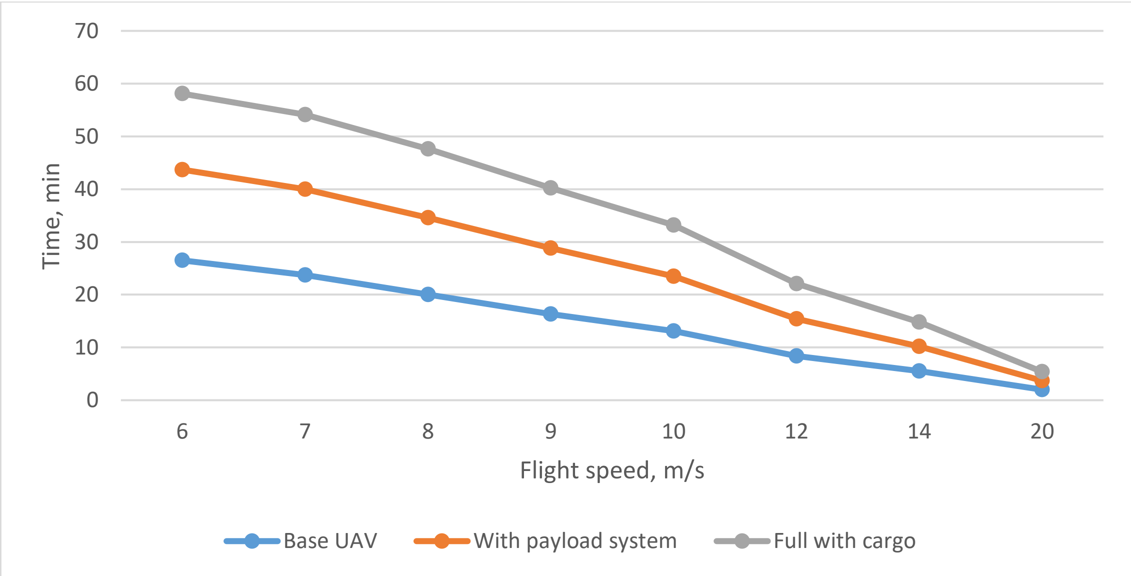

Fig. 23. Theoretical flight time performance of different configurations

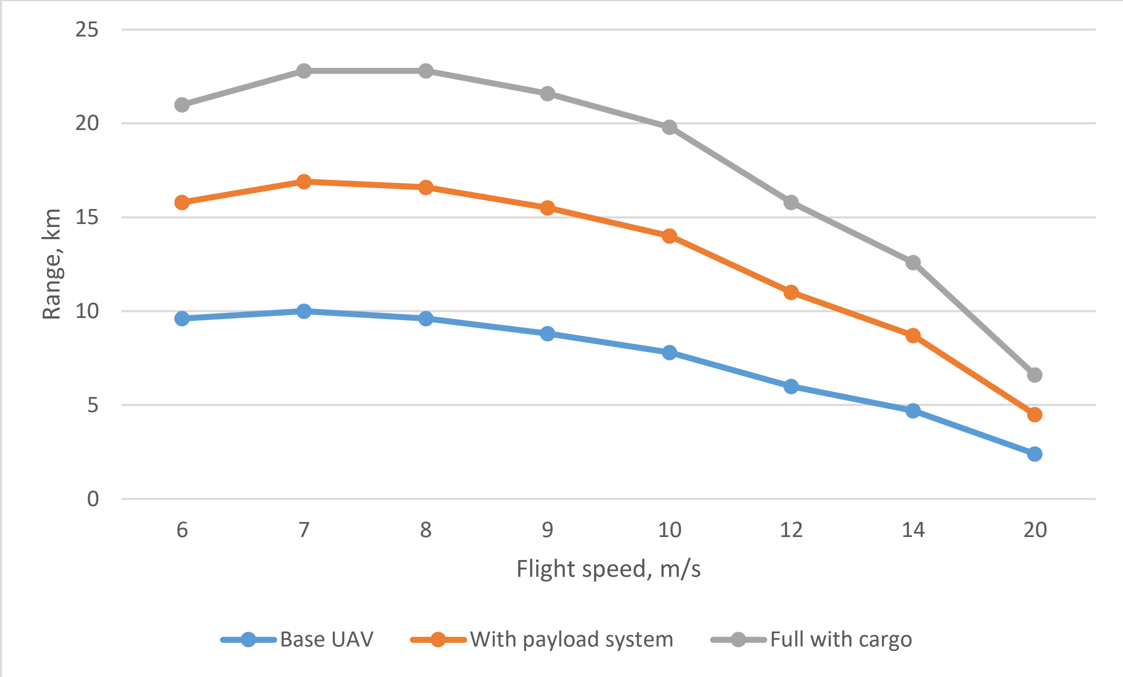

Fig. 24. Theoretical flight range performance of different configurations

Table 10. Theoretical performance summary

Speed (m/s)	Base UAV Time (min)	With Payload Time (min)	Full Cargo Time (min)	Base UAV Range (km)	With Payload Range (km)	Full Cargo Range (km)
8 m/s	20.0	14.6	13.0	9.6	7.0	6.2
10 m/s	13.1	10.4	9.7	7.8	6.2	5.8
14 m/s	5.5	4.7	4.6	4.7	4.0	3.9

After adding the complete autonomous payload system with Raspberry Pi Zero 2, servo motor, UBEC output regulator, Sony camera and the cartridge structure, the mass increased by 184 g (31%) and a continuous electronic power draw of 1.8 W was added. The payload, which is carried in the structure and is delivered with this system, also adds 100 g. Addition of the payload and the cargo reduced flight time from 20 minutes to 14.6 minutes without the payload inside and to 13 minutes with the payload inside the cartridge. When comparing the reachable flight range numbers of cruise speed, which is 8 m/s reduced from 9,6 km to 7 km and 6.2 km in configurations without and with payload inside the payload system. The speed chart reveals that maximum range is achieved at 7-8 m/s, which is the best speed for delivery operations. Faster speeds increase parasitic drag rapidly and have a significant impact on the flight time and thus range of the UAV. The payload system and its power consumption relate to 15% of the overall power consumption during cruising speed flight. This is power efficient choise when comparing to other solutions, which allow autonomous payload delivery.

3.9. Experimental Measurements of Delivery Accuracy

In order to evaluate autonomous payload delivery systems capabilities, real-life testing was done. During computer vision system testing seen in Fig. 25, the plane was held above the targets in a real-life environment to once more determine detection capabilities.

Fig. 25. Real-life computer vision testing and a picture from the onboard camera tests

In a flight test seen in Fig. 26, the plane was flown 2-3 meters above the QR code and the delivery accuracy was evaluated. Ten flights were used for the evaluation of the system, which were in the most stable flight, where the camera pointed directly at the QR code. During the manual flight, it is not easy to ensure exactly similar conditions for the test, which is why other flyovers were eliminated due to poor flight performance. Poor flight performances include too high or too low speed, poor positioning of the camera due to the tilt of the plane, inaccurate height due to the gust of the wing or inaccurate interpretation of the flight by the pilot. This human factor limited the stable and accurate testing measures during real life testing.

Fig. 26. Real-life flight tests

However, from the picked ten flyovers where the flight was the most stable and in the desired parameters range, only four times QR code was detected. Additionally, delivery accuracy from such a low height was also lower than expected (seen in Fig. 27), measuring from 4.21 m to 5.7 m from QR code centre.

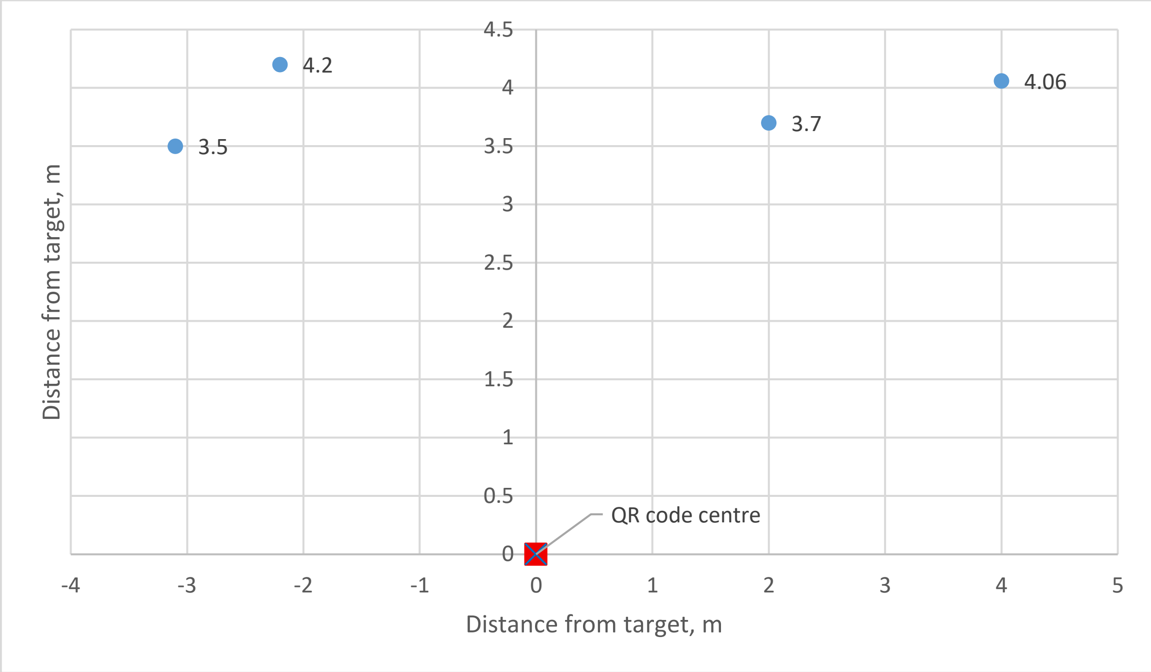

Fig. 27. Delivery points in comparison with QR code centre

Landing position was evaluated based on the done studies in ballistic payload delivery [39]. With formulas listed in chapter 2.2.3 and with a wind of 2 m/s headwind during testing, a medicine box of 100 g and flight speed of approximately 5 m/s (hard to know during manual flight), the wind had an influence of 0.09 m. The box approximately drops around 0.73 s, which is low enough that the wind would not have a big influence. Balistic drop when the medicine box is released directly above QR code listed in the Fig. 28 below.

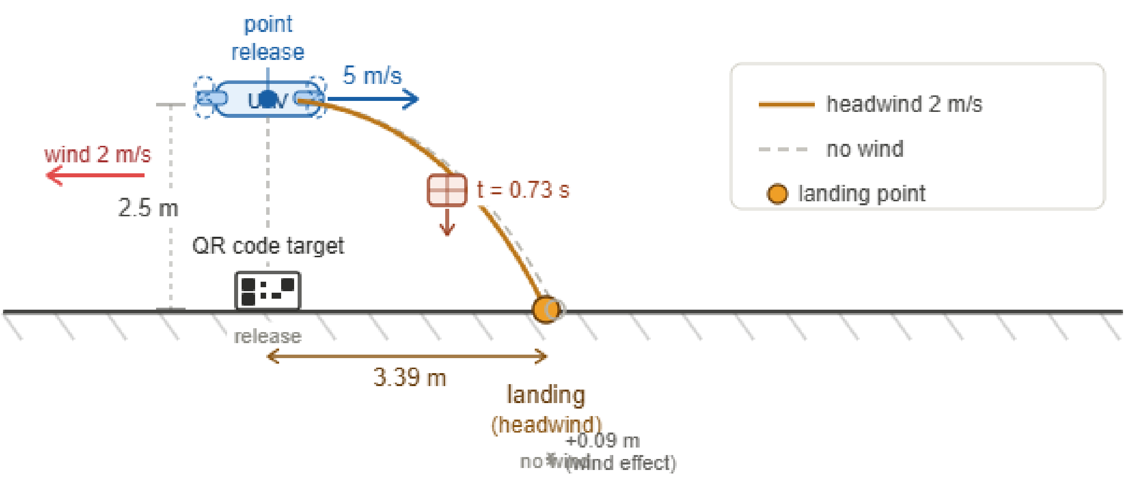

Fig. 28. Balistic medicine box drop from 2.5 m in 5 m/s drone flight

With the adjustment of wind delivery accuracy adjusted from 4.21 m to 5.7 m from QR code centre to 4.13 m and 5.64 m. A real-life test was conducted and showed that the real bottleneck of this system is real-time visual computing power and reaction time between the QR code in the frame and the servo opening. This could happen due to poor camera performance, poor QR code quality or most likely an incapable computer for this task, Raspberry Pi Zero 2W. Pi Zero 2W CPU can only process 2-3 frames per second, which is too low for UAV flight. If the camera is not precisely pointed downwards or the flight speed is higher, the system has only 1-2 frames to detect the QR code, which is very unlikely, as real-life tests identified. Insufficient processing power forced to use a lower resolution, which is not ideal for QR detection, as flight height must be reduced. Also, a camera with a narrower FOV would fit better for such an application and would allow a higher flight height. Moreover, the algorithm used in this project and listed in Appendix 1 had to be made without confirmation of the QR code, which means that false triggers appear during flights when the QR code is not even in frame.

3.10. Chapter Summary

The chapter described practical project decisions and experimental results. With used 3D scanned model UAV digital twin was created, which was used for cartridge modelling. UAV components for flying and autonomous payload dropping were picked and tested in real-life testing. Apart from identified weaknesses, the system works and can detect and deliver payload autonomously at a very narrow parameter range, with a likelihood of delivery at 4.13 m to 5.64 m accuracy of around 40 %, which must be improved in future system development.

4. Project Managerial and Economic Analysis

The task of this project was to make a fixed-wing UAV with an autonomous delivery system with a limited budget for a proof-of-concept drone design. Components were picked to best suit project requirements with the intention of building a functional and effective UAV for the desired task. In this chapter projects environmental impact, socio-economic constraints and projects impact is presented.

4.1. Project Components Economic Analysis

When picking the best suitable components for this projects few main constraints must be met. Firstly, all parts must work with each other, which means that they must be compatible with each other. During the assembly proses few problems occurred in compatibility when the receiver did not work with the used remote controller, and after that, another receiver had to be purchased. These small details add up to the total project costs, but it is a part of a research and development project. Secondly, all the parts must meet the required budget. As a student's project budget was limited, parts were picked according to that. Lastly, from an aviation perspective, parts must be lightweight, compact and most efficient as possible for their price to best fulfil the project. In table below all components and their prices are listed.

Table 11. Price of each component used in the configurations

Component	Price (Eu)	Configuration	Notes
Multiplex EasyStar 2 airframe	120	Base	Elapor foam structure, wing panels, tail, fuselage halves
ROXXY BL 2834/08 brushless motor	35	Base	1120 KV, 310 W max, 14-pole outrunner
ROXXY BL-Control 720 S-BEC (ESC)	30	Base	20 A cont. / 30 A peak, switching BEC 5 V / 3 A
ROXXY EVO LiPo 3S 2200 mAh 20C	25	Base	11.1 V nominal, 24.4 Wh, 154 × 35 × 21 mm
SPEKTRUM AR410 DSMX receiver	35	Base	4-channel, DSMX adaptive freq. hopping
MS-12020 MG servos × 2 (flight)	32	Base	Metal gear, 1.5 / 2.0 kg·cm torque
Propeller + wiring	10	Base	7″ × 6″ folding prop included with EasyStar 2
Raspberry Pi Zero 2W	18	Payload system	Quad-core ARM Cortex-A53 @ 1 GHz, 512 MB RAM
Sony IMX219 camera (8 MP, 77°)	15	Payload system	FOV 77°, autofocus, connected via CSI
MS-12020 MG servo (drop bay)	16	Payload system	PWM-controlled cargo door actuator
PETG cartridge V2 (3D-printed)	12	Payload system	Aerodynamic drop-box; V2 adds only +13% drag vs. bare fuselage
ASSAN 8A UBEC	10	Payload system	5 V regulated output for Raspberry Pi
Cargo (medicine box)	0	Cargo only	Proof-of-concept payload
Total	358	Combined	

The project's total expenses are 358 euros without the inclusion of HandySCAN 700 used for 3D scanning from the KTU laboratory, CAD Fusion software, which was used in the student version and also CFD software ANSYS, which was also used in the student version. In comparison with similar solutions in the market, project costs are much lower (about 5x -10x), but the project UAV is not fully functional as it was found in real-life testing. Apart from that projects result features manual flying for 13 minutes with full cargo and autonomous payload dropping.

4.2. Project's Environmental Impact

Project result – UAV with autonomous payload dropping is fully electric. This means that it is zero carbon emissions during flight, and if charged from renewable energy sources. However, if the battery is charged and used for one flight (19,5 Wh) and charged at home Lithuanians electric circuit emission factor is 0,185 kg CO_2/kWh from 2024 data. Which means that to charge one battery and make one delivery mission, it would emit 0,0037 kg CO_2 it to the atmosphere. In comparison, diesel-powered delivery transport can emit around 271 g CO_2/km which means that for a 4.2 km mission, which a UAV could make, it would result in 1,14 kg CO_2, which is a 308 times larger amount in comparison with the project-developed solution. Even when taking into consideration the emissions from electricity generation, scientific literature sources state that UAV technology can reduce carbon emissions by 71% in the transport sector in comparison with traditional trucks and cars [13]. Also, fixed-wing UAV construction is much more efficient and aerodynamically effective, which allows for reducing carbon emissions much more that quadracopter or other copter drones.

Fixed-wing UAV construction is made from “Elapor” foam, which is recyclable but hardly processed. Payload cartridge is made from PETG, which is in contrast to ABS during 3D printing, does not emit toxic fumes which are harmful to humans. 3D is a beneficial manufacturing technology because parts are made without any waste, which means that all the used material is directly used in the part. This helps to save resources. Also, CAD modelling and consideration of different parts and fittings reduces the need for many testing parts, reduces the possibility of inaccurate measurements and helps to further reduce waste during the manufacturing process. A battery is one of the most significant parts in terms of environmental impact. Lithium polymer batteries are dangerous waste and can be recycled only in specialised recycling places. Thus, considering the impact on the environment and difficult to recycle battery does the biggest impact on the environment in this project.

4.3. Project's Social Impact

Project conception – medical supplements delivery, which can be expanded with a bigger UAV. This directly correlates with drone delivery expansion in this field. With various drone models and gaps in the delivery chain, drones are used more and more for small-package delivery. For example, the project “Zipline” with a fixed-wing delivery system helped to reduce vaccine shortages in Rwanda by 60% an dincreased medicaments supplying to the medical centres by 10% [42]. Although the project's prototype is not a commercial solution, the project's conceptual model demonstrates the technical feasibility of such systems in a low-budget environment in places where conventional transport can not access or access is limited.

Delivery costs of any goods are an important part of the transportation sector. Delivery by heavy ships or trailers, which are travelling for long distances with a large amount of goods, can not be changed with drone technology as of today, but last-mile delivery in heavily crowded cities in hard-to-reach places can benefit from the existing UAV technologies. For example, in comparison to drone delivery with conventional transport, which runs on diesel power, it can reduce costs substantially [13]. Also, delivery times can be reduced substantially as a drone can manoeuvre freely without needing to wait for other traffic to pass or wait in traffic jams. Also, it can fly a shorter distance from point A to point B without the need for any roads or other infrastructure. However, a fully functional and accurate delivery model must be deployed in order to accurately deliver goods because the current state of the system is not applicable in such scenarios.

However, drone flights in Lithuania are currently strict and are monitored by EASA representatives in Lithuania, TKA (Transport Competence Agency). Apart from the possible high impact on last-mile delivery times and costs, safety is the number one priority, and such delivery flights, which would happen in beyond visual line of sight scenarios, are very complex and hardly legally achievable in cities as there are many constraints in order to keep people on the ground safe.

4.4. Chapter Summary

The cost of projects reached 358 Eu, which is significantly lower than existing solutions in the market. One UAV delivery operation CO_2 emission if batteries are charged from the Lithuanian electric circuit is 0,0037 kg, which is 308 times lower when compared to the diesel-powered delivery. Obviously UAV can not deliver as much mass in comparison to the diesel-powered vehicle, but even with as many flights as would be needed, UAV delivery is much more environmentally friendly. The project's system how proof of concept, confirms the drone's capability of delivery, but substantial improvements must be made to make it comercial last mile delivery vehicle, which would deliver goods accurately and safely.

Conclusions

1. For the cargo compartment creation, the Multiplex EasyStar UAV digital twin was created using a HandySCAN 700 3S scanner and two compartments in the CAD software were modelled. CFD analysis was conducted in ANSYS software, k-ω SST turbulent model at three different speeds. Analysis identified that payload model version 1 increased drag force by 46% ant optimized second version by only 13%, and that is why the design was used in further project tasks.
2. For autonomous payload delivery operation, the UAV components responsible for flying were picked: Multiplex EasyStar 2, ROXXY BL 2834/08 (1120 KV, 310 W), ROXXY BL-Control 720 S-BEC, ROXXY EVO LiPo 3S 2200 mAh (24,4 Wh) and SPEKTRUM AR410. Theoretical flight range and flight time calculations in cruising speed (8 m/s) showed that the UAV flies for 20 min and 9,6 km. With a payload system, the UAV can fly for 14.6 min and 7 km and fully loaded with the compartment and cargo inside the drone can fly for 13 min and 6.2 km.
3. For the autonomous payload delivery operations Raspberry Pi Zero 2W computer, Sony IMX219 8 MP camera ir OpenCV ArUco QR code detection algorithm. Experiments identified that the system processes only 2-3 frames per second because of that QR code detection during flight is not reliable, and during real-life testing, only in four out of ten flights QR code was detected (40% success rate). With a used 35.5 cm ArUco code measured detection range reached 3 m.
4. Autonomous delivery accuracy was evaluated during real-life testing. Out of ten flights, four of them identified the target and initiated the payload dropping sequence. With a used 35.5 cm ArUco code on the ground and 2-3 m flight height, when the code was detected, delivery accuracy varied from 4.13 m to 5.64 m when measured from the centre of the QR code and exceeded the project requirement of 5 m. The system shows proof of concept identifications but lacks precision and processing speed. The main problem - Raspberry Pi Zero 2W computing power, which for future development of this system, must be improved.

List of References

1. CAMPION, M., RANGANATHAN, P. and FARUQUE, S. (2019). UAV swarm communication and control architectures: a review. Journal of Unmanned Vehicle Systems, 7(2), p. 93–106. https://doi.org/10.1139/juvs-2018-0009
2. KARTAL, M. A. and FEYZIOĞLU, A. (2025). Aerodynamic performance and energy modeling of a quadcopter drone at different RPM: an experimental and CFD investigation of future design UAVs. International Journal of Low-Carbon Technologies, 20, p. 2026–2039. https://doi.org/10.1093/ijlct/ctaf132
3. ZHANG, Y., ZHAO, Q., MAO, P., BAI, Q., LI, F. and PAVLOVA, S. (2024). Design and Control of an Ultra-Low-Cost Logistic Delivery Fixed-Wing UAV. Applied Sciences, 14(11), p. 4358. https://doi.org/10.3390/app14114358
4. OKULSKI, M. and ŁAWRYŃCZUK, M. (2022). A Small UAV Optimized for Efficient Long-Range and VTOL Missions: An Experimental Tandem-Wing Quadplane Drone. Applied Sciences, 12(14), p. 7059. https://doi.org/10.3390/app12147059
5. HOCHSTENBACH, M., NOTTEBOOM, C., THEYS, B. and DE SCHUTTER, J. (2015). Design and Control of an Unmanned Aerial Vehicle for Autonomous Parcel Delivery with Transition from Vertical Take-off to Forward Flight – VertiKUL, a Quadcopter Tailsitter. International Journal of Micro Air Vehicles, 7(4), p. 395–405. https://doi.org/10.1260/1756-8293.7.4.395
6. OKULSKI, M. and ŁAWRYŃCZUK, M. (2022). A Small UAV Optimized for Efficient Long-Range and VTOL Missions: An Experimental Tandem-Wing Quadplane Drone. Applied Sciences, 12(14), p. 7059. https://doi.org/10.3390/app12147059
7. UNIVERSITI TUN HUSSEIN ONN MALAYSIA (UTHM) et al. (2022). The Structural Design and Aerodynamics Analysis for a Hybrid VTOL Fixed-Wing Drone for Parcel Delivery Applications. PAAT, 2(1). https://doi.org/10.30880/paat.2022.02.01.006
8. JOSHI, D., DEB, D. and MUYEEN, S. M. (2022). Comprehensive Review on Electric Propulsion System of Unmanned Aerial Vehicles. Frontiers in Energy Research, 10, p. 752012. https://doi.org/10.3389/fenrg.2022.752012
9. PATRIK, A. et al. (2019). GNSS-based navigation systems of autonomous drone for delivering items. Journal of Big Data, 6(1), p. 53. https://doi.org/10.1186/s40537-019-0214-3
10. NGUYEN, P. H., KIM, K. W., LEE, Y. W. and PARK, K. R. (2017). Remote Marker-Based Tracking for UAV Landing Using Visible-Light Camera Sensor. Sensors, 17(9), p. 1987. https://doi.org/10.3390/s17091987
11. SVEINBJÖRNSSON, H. Ö. QR Code Based Navigation.
12. BHIMASENA RESEARCH, TECHNOLOGY, AND DEVELOPMENT, INDONESIA et al. (2015). Autonomous UAV System Development for Payload Dropping Mission. JIAS, 1(2), p. 72–77. https://doi.org/10.21535/jias.v1i2.158
13. MOHAMED, A. and MOHAMED, M. (2025). Unmanned Aerial Vehicles in Last-Mile Parcel Delivery: A State-of-the-Art Review. Drones, 9(6), p. 413. https://doi.org/10.3390/drones9060413
14. SCHAUMANN, S. K. et al. (2024). The flying sidekick traveling salesman problem with multiple drops: A simple and effective heuristic approach. arXiv. https://doi.org/10.48550/arXiv.2403.18091
15. SAUNDERS, J., SAEEDI, S. and LI, W. (2024). Autonomous aerial robotics for package delivery: A technical review. Journal of Field Robotics, 41(1), p. 3–49. https://doi.org/10.1002/rob.22231

16. EU, K. Q. and PHANG, S. K. (2023). Automated Parcel Loading-Unloading Mechanism Design for Delivery UAV. Journal of Physics: Conference Series, 2523(1), p. 012016. https://doi.org/10.1088/1742-6596/2523/1/012016
17. ZHANG, K. et al. (2019). Bioinspired design of a landing system with soft shock absorbers for autonomous aerial robots. Journal of Field Robotics, 36(1), p. 230–251. https://doi.org/10.1002/rob.21840
18. ISLAS-NARVAEZ, E. A., ITUNA-YUDONAGO, J. F., RAMOS-VELASCO, L. E., VEGA-NAVARRETE, M. A. and GARCIA-SALAZAR, O. (2022). Design and Determination of Aerodynamic Coefficients of a Tail-Sitter Aircraft by Means of CFD Numerical Simulation. Machines, 11(1), p. 17. https://doi.org/10.3390/machines11010017
19. SOLIMAN, A. M. S., CAGAN, S. C. and BULDUM, B. B. (2019). The design of a rotary-wing unmanned aerial vehicles–payload drop mechanism for fire-fighting services using fire-extinguishing balls. SN Applied Sciences, 1(10), p. 1259. https://doi.org/10.1007/s42452-019-1322-6
20. NIKOLAEV, S. et al. (2018). Implementation of “Digital Twin” Concept for Modern Project-Based Engineering Education. Product Lifecycle Management to Support Industry 4.0, p. 193–203. https://doi.org/10.1007/978-3-030-01614-2_18
21. ALÁEZ, D. et al. (2023). VTOL UAV digital twin for take-off, hovering and landing in different wind conditions. Simulation Modelling Practice and Theory, 123, p. 102703. https://doi.org/10.1016/j.simpat.2022.102703
22. MACDONALD, L. and BENTKOWSKA-KAFEL, A. (2017). Digital techniques for documenting and preserving cultural heritage. Leeds: ARC Humanities Press.
23. SHAMATA, A. and THOMPSON, T. (2018). Using structured light three-dimensional surface scanning on living individuals: Key considerations and best practice for forensic medicine. Journal of Forensic and Legal Medicine, 55, p. 58–64. https://doi.org/10.1016/j.jflm.2018.02.017
24. CAO, R. et al. (2022). Accuracy of three-dimensional optical devices for facial soft-tissue measurement in clinical practice of stomatology: A PRISMA systematic review. Medicine, 101(47), p. e31922. https://doi.org/10.1097/MD.0000000000031922
25. SU, X.-L. et al. (2025). Research on Intelligent Teaching of Engineering Equipment Based on CATIA 3D Modeling and Virtual Simulation Technology. Proceedings of the 2025 9th International Conference on Education and Multimedia Technology, p. 360–363. https://doi.org/10.1145/3761843.3761870
26. MUHAMMAD NABIL FARHAN KAMAL et al. (2021). A Review of Aerodynamics Influence on Various Car Model Geometry through CFD Techniques. ARFMTS, 88(1), p. 109–125. https://doi.org/10.37934/arfmts.88.1.109125
27. XIAO, T. et al. (2016). Numerical study on the flow characteristics of micro air vehicle wings at low Reynolds numbers. International Journal of Micro Air Vehicles, 8(1), p. 29–40. https://doi.org/10.1177/1756829316638204
28. GEMBA, K. SHAPE EFFECTS ON DRAG.
29. WONG, K. V. and HERNANDEZ, A. (2012). A Review of Additive Manufacturing. ISRN Mechanical Engineering, 2012, p. 1–10. https://doi.org/10.5402/2012/208760
30. DHITAL, D. and ZIEGLER, Y. (2015). ADDITIVE MANUFACTURING - APPLICATION OPPORTUNITIES FOR THE AVIATION INDUSTRY. JATS, 6(2), p. 63–86. https://doi.org/10.38008/jats.v6i2.59

31. TUNÇEL, O. and KAHYA, Ç. (2025). Performance Enhancement of Lightweight PLA Parts Printed by FFF Using Taguchi–GRA Method. Polymers, 17(17), p. 2413. https://doi.org/10.3390/polym17172413
32. ŠOSTAKAITĖ, L. et al. (2024). Investigating Additive Manufacturing Possibilities for an Unmanned Aerial Vehicle with Polymeric Materials. Polymers, 16(18), p. 2600. https://doi.org/10.3390/polym16182600
33. NGUYEN, P. H. et al. (2017). Remote Marker-Based Tracking for UAV Landing Using Visible-Light Camera Sensor. Sensors, 17(9), p. 1987. https://doi.org/10.3390/s17091987
34. SEMERIKOV, S. O. et al. (2025). Vision-Based Autonomous UAV Landing: A Comprehensive Review of Technologies, Techniques, and Applications. Journal of Intelligent & Robotic Systems, 111(4), p. 115. https://doi.org/10.1007/s10846-025-02314-4
35. YANG, S.-Y. et al. (2023). CNN-Based QR Code Reading of Package for Unmanned Aerial Vehicle. Sensors, 23(10), p. 4707. https://doi.org/10.3390/s23104707
36. RIZVI, H. H. et al. (2022). Medical Product Transportation UAV Drone. JAET, 6(2), p. 75–90. https://doi.org/10.55447/jaet.06.02.72
37. UAV Structure and Aerodynamic Character Research on two different Airfoils. (2021). Webology. https://doi.org/10.29121/WEB/V18I3/122
38. UDAPUDI, P. et al. (2023). Object identification and surveillance based on deep learning algorithms for quadcopters. ITM Web Conference, 57, p. 02008. https://doi.org/10.1051/itmconf/20235702008
39. MATHISEN, S. G. et al. (2020). Autonomous ballistic airdrop of objects from a small fixed-wing unmanned aerial vehicle. Autonomous Robots, 44(5), p. 859–875. https://doi.org/10.1007/s10514-020-09902-3
40. KANTAROS, A. et al. (2025). Composite Filament Materials for 3D-Printed Drone Parts: Advancements in Mechanical Strength, Weight Optimization and Embedded Electronics. Materials, 18(11), p. 2465. https://doi.org/10.3390/ma18112465
41. VUJICA HERZOG, N. et al. (2022). Comparison between Lux Meter Apps and Illumination Measuring Devices. DAAAM International Scientific Book, 21, p. 031–046. https://doi.org/10.2507/daaam.scibook.2022.03
42. ACKERMAN, E. and KOZIOL, M. (2019). The blood is here: Zipline's medical delivery drones are changing the game in Rwanda. IEEE Spectrum, 56(5), p. 24–31. https://doi.org/10.1109/MSPEC.2019.8701196

Appendices

Appendix 1. Autonomous payload delivery script

```
import cv2
import cv2.aruco as aruco
import pigpio
import time
import logging
from datetime import datetime
from picamera2 import Picamera2
import os

SERVO_PIN       = 18
SERVO_CLOSED    = 1800
SERVO_OPEN      = 2300
SERVO_HOLD_SEC  = 3.0

ARUCO_DICT      = aruco.DICT_4X4_50
TARGET_ID       = 17

CAMERA_WIDTH    = 1024
CAMERA_HEIGHT   = 768
CAMERA_FPS      = 30

MARKER_SIZE_CM  = 18.5

CONFIRM_FRAMES  = 1

log_filename = f"/home/admin/logs/flight_{datetime.now().strftime('%Y-%m-%d_%H-%M-
%S')}.txt"
os.makedirs("/home/admin/logs", exist_ok=True)
logging.basicConfig(
    level=logging.INFO,
    format="%(asctime)s [%(levelname)s] %(message)s",
    datefmt="%H:%M:%S",
    handlers=[
        logging.FileHandler(log_filename),
        logging.StreamHandler()
    ]
)
log = logging.getLogger("aruco-payload")

class PayloadBay:
    def __init__(self, pin, closed_pw, open_pw):
        self.pin        = pin
```

```
        self.closed_pw = closed_pw
        self.open_pw   = open_pw
        self.is_open   = False
        self.pi = pigpio.pi()
        if not self.pi.connected:
            raise RuntimeError("pigpio daemon not running! Run: sudo pigpiod")
        self.pi.set_servo_pulsewidth(pin, closed_pw)
        time.sleep(0.5)
        log.info(f"Servo init on GPIO {pin} CLOSED ({closed_pw}us)")

    def open(self):
        if not self.is_open:
            log.info("Opening payload bay")
            self.pi.set_servo_pulsewidth(self.pin, self.open_pw)
            self.is_open = True
            time.sleep(0.3)

    def close(self):
        if self.is_open:
            log.info("Closing payload bay")
            self.pi.set_servo_pulsewidth(self.pin, self.closed_pw)
            self.is_open = False
            time.sleep(0.3)

    def cleanup(self):
        self.close()
        time.sleep(0.3)
        self.pi.set_servo_pulsewidth(self.pin, 0)
        self.pi.stop()
        log.info("pigpio cleaned up")

def init_camera():
    cam = Picamera2()
    config = cam.create_preview_configuration(
        main={"size": (CAMERA_WIDTH, CAMERA_HEIGHT), "format": "RGB888"},
        controls={
            "FrameRate": CAMERA_FPS,
            "ExposureTime": 5000,
            "AnalogueGain": 1.0,
            "AeEnable": True,
            "AwbEnable": True
        }
    )
    cam.configure(config)
    cam.start()
    time.sleep(1.0)
```

```
    log.info(f"Camera started: {CAMERA_WIDTH}x{CAMERA_HEIGHT} @
{CAMERA_FPS}fps")
    return cam

def build_detector():
    dictionary = aruco.getPredefinedDictionary(ARUCO_DICT)
    params = aruco.DetectorParameters()
    params.adaptiveThreshWinSizeMin      = 3
    params.adaptiveThreshWinSizeMax      = 103
    params.adaptiveThreshWinSizeStep     = 4
    params.adaptiveThreshConstant        = 7
    params.minMarkerPerimeterRate        = 0.01
    params.maxMarkerPerimeterRate        = 4.0
    params.polygonalApproxAccuracyRate   = 0.08
    params.minCornerDistanceRate         = 0.01
    params.minDistanceToBorder           = 1
    params.errorCorrectionRate           = 0.85
    params.cornerRefinementMethod        = aruco.CORNER_REFINE_SUBPIX
    detector = aruco.ArucoDetector(dictionary, params)
    log.info(f"ArUco detector ready, target_id={TARGET_ID}")
    return detector

def detect_target(frame_rgb, detector):
    gray = cv2.cvtColor(frame_rgb, cv2.COLOR_RGB2GRAY)
    corners, ids, _ = detector.detectMarkers(gray)
    if ids is None:
        return False, None
    flat = ids.flatten().tolist()
    if TARGET_ID in flat:
        idx = flat.index(TARGET_ID)
        return True, corners[idx]
    return False, None

def main():
    log.info(f"Starting... marker size: {MARKER_SIZE_CM}cm")
    bay      = PayloadBay(SERVO_PIN, SERVO_CLOSED, SERVO_OPEN)
    cam      = init_camera()
    detector = build_detector()
    confirm_count = 0
    last_trigger  = 0
    log.info(f"Scanning for marker ID {TARGET_ID}... Ctrl+C to stop")
    try:
        while True:
            t1 = time.time()
            frame = cam.capture_array()
            found, corners = detect_target(frame, detector)
```

```
            t2 = time.time()
            if found:
                confirm_count += 1
                ts = datetime.now().strftime("%Y-%m-%d %H:%M:%S.%f")[:-3]
                log.info(f"[{ts}] Marker {TARGET_ID} detected! [{confirm_count}/{CONFIRM_FRAMES}]")
            else:
                confirm_count = 0
            if confirm_count >= CONFIRM_FRAMES and not bay.is_open:
                now = time.time()
                if now - last_trigger > SERVO_HOLD_SEC + 1.0:
                    ts = datetime.now().strftime("%Y-%m-%d %H:%M:%S.%f")[:-3]
                    log.info(f"[{ts}] DEPLOYING PAYLOAD!")
                    bay.open()
                    time.sleep(SERVO_HOLD_SEC)
                    bay.close()
                    last_trigger  = time.time()
                    confirm_count = 0
            elapsed = t2 - t1
            time.sleep(max(0.05 - elapsed, 0))
    except KeyboardInterrupt:
        log.info("Stopped by user")
    finally:
        cam.stop()
        bay.cleanup()

if __name__ == "__main__":
    main()
```