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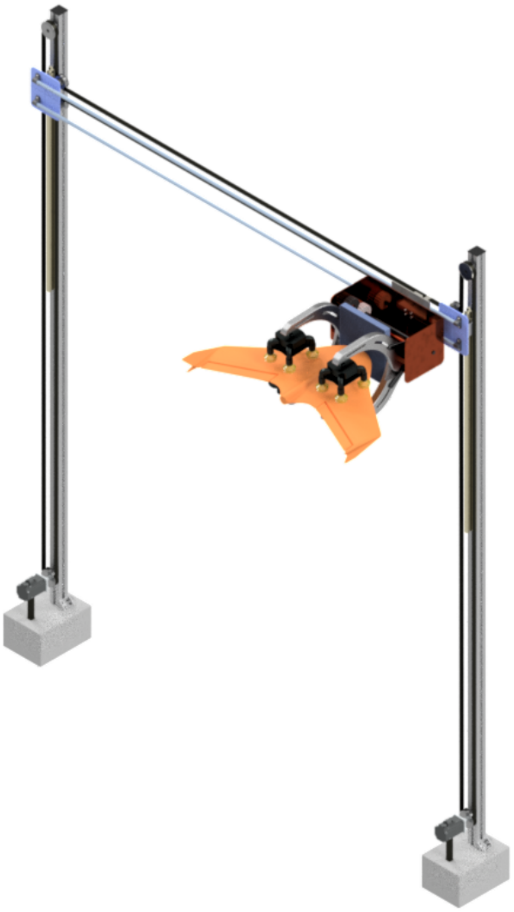

Conceptual Design of a NEW Recovery System for Small Fixed-Wing UAVs

Master's thesis in Master Programme Product Development

ABDULSAMED AHMED MOHAMED

DEPARTMENT INDUSTRIAL AND MATERIAL SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2025

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Enhancing UAV Recovery for Maritime Rescue Operations

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Abstract

Unmanned Aerial Vehicles (UAVs) are becoming an important part of modern rescue operations where quick access to information can save lives. Small fixed-wing UAVs help the Swedish Sea Rescue Society (SSRS) gain situational awareness, but recovering these UAVs after a mission comes with challenges. Today, they land on water, which works though it slows down urgent missions. Retrieval can also be difficult in bad weather, and occasionally the UAVs are lost or damaged. The goal of this thesis is to develop a new land-based recovery system to safely catch SSRS's small fixed-wing UAVs without adding extra components to the fixed-wing UAV.
To achieve this, the thesis begins by introducing the problem and reviewing existing recovery methods (from hooks and nets to more advanced control-based approaches) before detailing how concepts were generated, compared, and refined through a structured design process. The final concept combines a precise XY alignment subsystem, inspired by the motion control in 3D printers, with a mechanical capture subsystem that captures the UAV without damaging it. Based on kinematic simulation and subsystem-level evaluations, the recovery system is capable of working in practice and offers a clear path towards physical prototyping. The thesis ends by outlining the next steps needed to bring this recovery system closer to real-world testing and future use in SSRS rescue missions.

Keywords: Recovery System, Maritime Rescue, Fixed-wing UAV, Conceptual Design, Alignment subsystem, capture subsystems.

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Abdulsamed Ahmed Mohamed, Gothenburg, November 2025

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CAD	Computer-Aided Design
DARPA	Defense Advanced Research Projects Agency
DFMEA	Design Failure Mode and Effects Analysis
DOF	Degrees of Freedom
FEA	Finite Element Analysis
FMEA	Failure Mode and Effects Analysis
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IR	Infrared
LiDAR	Light Detection and Ranging
PEST	Political, Economic, Social, and Technological
PLS	Parachute Launching System
RTK	Real-Time Kinematic
SIA	Shenyang Institute of Automation+
SSRS	Swedish Sea Rescue Society
SWOT	Strengths, Weaknesses, Opportunities, and Threats
UAV	Unmanned Aerial Vehicle
WIPO	World Intellectual Property Organization

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1

Introduction

This chapter provides an overview of the thesis project, including the background of the problem and the organizations involved. The aim and research questions are also presented and explained to provide an understanding of the problem and purpose of the thesis, which focuses on developing a fixed-wing UAV recovery system for maritime reconnaissance UAVs.

1.1 Background

Unmanned Aerial Vehicles (UAVs) are being used more rapidly since they can handle tasks that would otherwise be risky or difficult for people. For instance, Unmanned Aerial Vehicles (UAVs) are increasingly being used in disaster response to provide real-time information about the environment and ongoing conditions [1]. Compared to rotary-wing UAVs, fixed-wing UAVs are widely valued for their long-range capability and energy efficiency [2].

One organization in Sweden that utilizes these UAVs is the Swedish Sea Rescue Society (SSRS), which uses them to improve its response time and gain a better overview during rescue missions. (SSRS) is a non-profit organization dedicated to saving lives at sea all around Sweden's coasts and inland waters [3]. They also have more than 70 rescue stations and rely on volunteers who respond to over a thousand emergencies every year.

1.2 Current fixed-wing UAV

Today, SSRS uses custom-built launch pads for the takeoff of its small fixed-wing drones stationed along its coastal stations [3] as shown in figure 1.1. The current fixed-wing UAV used by SSRS is lightweight, with a wingspan of 0.9 m and a total weight of approximately 1 kg, which makes it suitable for quick deployment in rescue operations. It has a flight endurance of up to 120 minutes when fully charged and is launched using a custom-built launch pad.

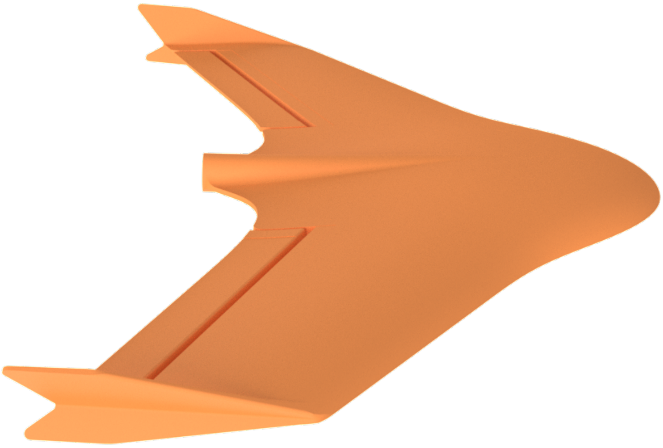


Figure 1.1: SSRS small fixed-wing UAV

The current UAV in focus has the following specifications, as shown in the table 1.1:

Table 1.1: SSRS's small fixed-wing UAV specs

Specification	**Value**
Wingspan	0.9 m
Weight	1 kg
Maximum flight time	approx. 120 min
Cruising speed	approx. 25 km/h
Launch method	custom launchpad
Landing method	Water landing

1.3 Problem description

As for the landing, their small fixed-wing drones currently belly land on coastal waters, then they are manually picked up by a person on a boat. Figure 1.2 shows a drone that has belly landed on water. Though the water landing works, it can cause delays during urgent missions where every second matters. At the same time, locating and retrieving the UAV on open water can be difficult and time-consuming, especially in rough sea conditions or low visibility. There is also a risk of the UAV drifting away and sustaining damage from waves. For these reasons, there is a need for a safer and faster land-based recovery solution that allows SSRS to retrieve the UAV quickly and that can be used at coastal rescue stations where space is limited and traditional landing methods are impractical.

Figure 1.2: Belly landing in water similar to the SSRS method [4]

1.4 Aim

This thesis aims to develop and design a UAV recovery system capable of safely catching small fixed-wing UAVs without damaging them. The system is intended to preserve the structural integrity of the drones while eliminating the need for traditional runways or controlled crash landings.

1.5 Research questions

To fulfill the aim of this thesis, the following research questions will be explored and answered:

- **What are the existing methods for UAV recovery, and what are their limitations?**

- **What mechanical principles and systems can be applied to safely catch and retrieve fixed-wing drones without causing damage?**

- **How can the system be designed to allow easy and efficient removal of the UAV after capture, with minimal manual handling?**
- **How can the capture system be tailored to suit the size and structural characteristics of small fixed-wing drones?**

1.6 Objectives

To answer the research questions, several specific objectives were defined. These include defining the functional, structural, and operational requirements for a recovery system capable of safely capturing small fixed-wing UAVs, along with determining the mechanical principles and design criteria needed to ensure non-destructive capture under typical flight and environmental conditions.

The work also involves developing a conceptual design tailored to the structural and aerodynamic characteristics of small fixed-wing drones, and finally formulating recommendations for future development, including potential implementation and experimental validation.

1.7 Purpose

The purpose of this thesis is to help SSRS improve how they can recover their fixed-wing UAV after a mission. Developing a concept for a land-based recovery system will enable the UAV to return quickly, be ready for the next task sooner, and reduce the chances of damage or loss. In addition, developing this UAV recovery system will minimize UAV maintenance, since the drone won't require water landings. In this way, the thesis aims to contribute to making UAVs more reliable and efficient for SSRS.

1.8 Scope and Delimitations

The focus of this thesis will be the mechanical design of the drone-recovery system, with signal control and other non-mechanical aspects to follow after its completion. This drone-recovery system will be designed for small fixed-wing UAVs weighing approximately 1 kg and with a wingspan of 1 to 1.5 meters. The system will not be designed to catch multi-rotor drones. The system is also not intended for anti-drone use, such as capturing unauthorized drones in flight. This is because the UAV needs to guide itself towards the catcher either by being manually controlled or flying on autopilot.

Another limitation of the project is the constrained time frame. As the thesis is expected to be completed within 20 weeks, this restricts the extent and depth of design exploration that can be undertaken. Moreover, the thesis is also constrained by budget limitations, since SSRS is a member-supported organization that values cost-effective and practical solutions. Therefore, the design is expected to remain simple and cost-effective, using components that are easy to source, assemble, and maintain.

1.9 Report overview

This thesis report describes the work carried out to design a fixed-wing UAV recovery system for maritime reconnaissance UAVs. It begins by briefly discussing why this type of recovery solution is needed and the challenges of the current solution. The theoretical background is then presented to support the engineering decisions made later on. Following this, the methodology describes how the design process was done and how different design ideas were generated, compared, and narrowed down during the concept development process.

The results chapter of the report presents the final concept and how it was verified. This includes the FMEA analysis, kinematic simulations, and structural analysis to evaluate the performance and safety of the recovery system. Finally, the thesis ends with a discussion of the key outcomes and suggestions for future improvements to further develop the fixed-wing UAV recovery system beyond this thesis project.

2

Theory

This chapter outlines the theoretical foundations for a fixed-wing UAV recovery system. It covers the flight dynamics that influence recovery, the mechanical principles for safe capture, and the positioning required for accurate alignment. Finally, it presents the critical onboard sensors that support autonomous guidance in the recovery phase.

2.1 Fixed-wing UAV flight dynamics

A fixed-wing UAV follows six-degree-of-freedom (6-DOF) flight dynamics, with three translational motions (forward, sideways, vertical) and three rotational motions (roll, pitch, yaw) [5]. This means that the flight path of a fixed-wing UAV is controlled by aerodynamic forces(lift and drag), gravity, and pilot control inputs. Mathematically, this can be described using Newton's laws, where forces such as lift, drag, thrust, and gravity determine its linear motion.

$$m\frac{d\mathbf{V}}{dt} = \mathbf{F}_{aero} + \mathbf{F}_{thrust} + \mathbf{F}_{gravity} \tag{2.1}$$

The rotational motion around the three axes is controlled by aerodynamic and control moments acting on the UAV.

$$\mathbf{I}\frac{d\boldsymbol{\omega}}{dt} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) = \mathbf{M}_{aero} + \mathbf{M}_{control}. \tag{2.2}$$

When a UAV is flying normally, the wings generate lift (L) to counteract its weight (W), while the propeller provides thrust (T) to overcome drag (D). Lift and drag are affected by the speed at which the UAV is flying, the air density, and the wing size of the UAV, as shown in the figure 2.1. Thus, lift and drag can be described in terms of the lift coefficient and drag coefficient, which are defined as follows.

$$C_D = \frac{2F_D}{\rho V^2 A} \tag{2.3}$$

$$C_L = \frac{2F_L}{\rho V^2 A} \tag{2.4}$$

For the landing approach, fixed-wing UAVs either reduce power or fly with the engine off. This allows them to glide naturally. When gliding, the lift of the wings holds the weight of the UAV, while the drag resists its forward motion. Therefore, the UAV

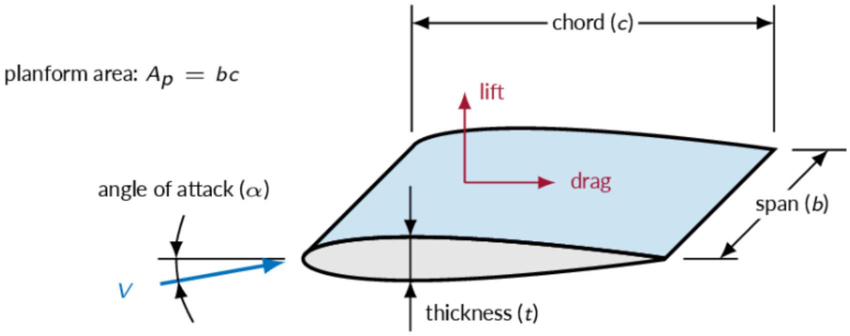


Figure 2.1: Wing geometry showing lift and drag

flies forward and down simultaneously, following a glide slope [6]. The steepness of this slope, called the glide angle γ, depends on the ratio of lift to drag.

$$\tan\gamma = \frac{D}{L} \tag{2.5}$$

Furthermore, another aspect of flight dynamics worth mentioning is the cruising speed of small fixed-wing UAVs weighing around 1 kg, which is 12–20 m/s, with about $15 m/s$ being a common nominal value [7]. However, this speed can vary depending on the structural design, the materials used for the body frame, and even the onboard avionics. For SSRS's 1 Kg fixed-wing UAV, the cruising speed is 25 m/s. The stall speed of small 1 kg fixed-wing UAVs is typically between 8 and 12 m/s, which can be affected by the airfoil and wing area of the UAV according to [8]. While SSRS's small fixed-wing UAV, which is the main focus of this thesis, has a recorded stall speed of 8 m/s.

2.1.1 Aerodynamic recovery principles

To capture a UAV safely in flight, it is important to understand its aerodynamic forces, i.e., lift and drag, described above. During recovery, the UAV slows down, and the lift force drops quickly, which makes its flight control surfaces less effective and harder to maneuver [9]. Hence, a controllable flight requires a minimum speed (V_{stall}), which can be derived from the lift equation when the wing reaches its maximum lift coefficient ($C_{L,\max}$) as shown below.

$$V_{\text{stall}} = \sqrt{\frac{2F_L}{\rho A C_{L,\max}}} \tag{2.6}$$

Therefore, it is paramount to avoid the stall speed during recovery and maintain a safety margin of 1.1–1.3 V_{stall} during recovery just like a conventional aircraft[10].

2.1.2 Effect of Wind on Recovery

UAVs are affected by wind in the same way as conventional planes are every day. During landing approaches, headwinds and tailwinds are the two types of wind that have the most effect on fixed-wing UAVs. For instance, a headwind reduces ground speed for a given airspeed, allowing a slower approach over ground [11]. This can aid UAV capture, while a tailwind does the opposite, increasing ground speed and required capture distance.

Moreover, crosswinds can cause lateral drift, and the UAV must crab during recovery (yaw into the wind) to remain on course and avoid both sideslip angle and lateral aerodynamic forces.[12].

2.2 Mechanical principles for safe UAV capture

To safely catch a fixed-wing UAV in flight, the momentum and kinetic energy of the UAV must be absorbed or transferred by the mechanical recovery system to prevent structural damage to the UAV. This can be done in the following ways;

2.2.1 Kinetic Energy Absorption

In an aircraft landing system, the landing gear is designed to absorb horizontal and vertical loads during touchdown to prevent structural damage [13]. The same principle of kinetic energy dissipation applies when a fixed-wing UAV is caught by a recovery system; otherwise, energy is released suddenly on impact, generating large forces on the airframe, which can cause damage to the components and the frame.

To dissipate kinetic energy away from the UAV, the current recovery systems described in chapter 3 use the following approaches,

- In net-based recovery systems, nets are designed to flex and absorb energy rather than just halting the UAV abruptly [14]. This prevents the UAV from slamming to an immediate halt, and the kinetic energy is converted into the motion of the net movement and then dissipated. The result is a gentle capture, after which the UAV can be unharmed in the net.
- Hook-based recovery systems dissipate kinetic energy by converting it into rotational energy. This is done after the fixed-wing UAV's weighted hook latches onto the suspended cable, causing the UAV to swing downward around the cable like a pendulum [15].

2.2.2 Momentum and Impulse in UAV Recovery

In physics, impulse is defined as the change in momentum of an object, and it equals the force applied multiplied by the duration of its application. Stopping a UAV requires an impulse equal in magnitude to the UAV's momentum at the moment it is captured.

$$\text{Momentum } (p) = m \cdot v \quad \text{(mass times velocity)} \tag{2.7}$$

$$\text{Impulse } (J) = F \cdot \Delta t \quad \text{(average force times time interval)} \tag{2.8}$$

$$\text{Impulse-Momentum Theorem} \quad J = \Delta p \quad \Rightarrow \quad F \cdot \Delta t = m \cdot \Delta v \tag{2.9}$$

Therefore, if a recovery system brings down a fixed-wing UAV in a very short time, then Δt will be small while F becomes extremely large as shown in the equation, and vice versa.

$$F = \frac{m \cdot \Delta v}{\Delta t} \tag{2.10}$$

One recovery method where impulse is distributed over time to reduce force is the use of parachutes for fixed-wing UAVs **<empty citation>** In this UAV recovery method, the UAV descends gradually instead of coming to a sudden stop. By the time the UAV reaches the ground, its velocity is nearly zero. Whereas, in the net recovery method, the net does more than just catch the UAV, but it also absorbs and redistributes the impulse [14].

2.3 UAV Positioning for capture

To successfully capture a fixed-wing UAV in flight, accurate sensing is needed for the UAV's coordination with the catching system. Currently, the SSRS uses barometric altimeters on board its $1kg$ fixed-wing UAV, which the recovery system will use to get reliable altitude data, such as distance to the ground of the UAV. They also rely on the Global Navigation Satellite System (GNSS), standard GPS, for positional information and navigation during rescue missions. In addition, the UAV's onboard camera provides situational awareness during rescue operations, serving as an eye in the sky which can be upgraded to detect the recovery system.

However, a standard GPS provides only a meter-level accuracy, and in good weather conditions this may be 2–3 m [16]. When there is interference or a poor signal, errors can increase up to 10 m, which is insufficient for UAV capture as the exact position of the drone will be off. To overcome this problem, real-time kinematic (RTK) GPS augmentation is suggested to provide centimeter-level accuracy [16], [15]. For a UAV recovery system to succeed, integrating such a high-precision GPS is essential to ensure reliable guidance during the capture of the UAV.

2.4 Critical Sensors for Successful UAV Recovery

2.4.1 Tracking Vision camera

Integrating an onboard camera that can track visual markers on the UAV recovery system can enable the fixed-wing UAV to detect and align with the system. This has already been done using vision-based net detection, and it has been shown to help fixed-wing UAVs guide themselves in for an autonomous recovery [17]. A vision camera can also be mounted on the recovery system to estimate the position of the incoming UAV. For instance, outdoor video data analysis has been shown to reliably estimate the UAV's attitude and altitude with mean errors below 1° and 1 meter [18].

2.4.2 Infrared (IR) beacons

In low visibility conditions, especially in coastal areas where the recovery system will be stationed, it is crucial that the UAV can still be recovered, regardless of the weather conditions. Thus, infrared tracking systems, which have been shown to guide fixed-wing UAVs accurately during landing, even when GPS signals can be integrated into the UAV and the recovery system [19].

2.4.3 LiDAR

Scanning LiDAR can directly measure the range and bearing of the UAV [20]. By integrating this LiDAR into the recovery system, the UAV's distance and closing speed can be monitored more accurately, helping the recovery process stay smooth and controlled.

3

Methodology

This chapter outlines the overall approach used in the development of the UAV recovery system. The methodology follows a structured engineering design process, supported by research, stakeholder input, simulation, and iterative evaluation.

3.1 Literature Search

A literature search was carried out to build a solid foundation for understanding existing recovery methods for fixed-wing UAVs and to identify areas where improvements are needed, especially in maritime environments. This involved examining academic journals, articles, and industry publications related to recovery methods for fixed-wing UAVs. The search was conducted through Google Scholar, using phrases such as “fixed-wing UAV recovery systems,” “drone catching mechanisms,” “autonomous UAV landing,” “marine UAV operations,” and “UAV retrieval design.” These keywords were selected to capture a broad range of existing solutions and technological developments.
This helped reveal the main challenges of recovering UAVs in marine environments, which guided the design focus and later stages of concept development in this thesis. Some of the recovery methods that were explored included hook-based, net-based, bio-inspired, and control-based systems.

3.2 Market Analysis

The market analysis was conducted to understand how the UAV recovery system would operate and to ensure that the design aligns with real user needs and practical conditions. Following Ulrich and Eppinger’s framework, this phase helped connect technical development with user and market understanding.

The analysis focused on the Swedish Sea Rescue Society (SSRS) as the main user and included both internal and external perspectives through SWOT and PEST analyses. The SWOT analysis highlighted SSRS’s strengths while identifying weaknesses like limited budgets and the absence of integrated UAV recovery systems. The PEST analysis provided insight into external factors, including strong national support for maritime safety, regulatory challenges for UAV use, and growing access to compact sensors and autonomous control systems.

In addition, the market for UAV recovery systems was explored across three main segments: maritime search and rescue, defense, and remote surveying. However, this thesis focuses only on maritime operations using small fixed-wing UAVs of around 1 kg, where reliable and quick recovery can make a direct impact on mission efficiency and safety. Together, these insights established the practical foundation and design direction for the system developed in this thesis.

3.2.1 Benchmarking

Benchmarking was then done to compare existing UAV recovery systems and learn from their designs. This task was carried out by searching online through Google Scholar, industry reports, and product websites to find examples of recovery systems already in use, such as net-based, hook-based, and automated landing mechanisms. These systems were compared in terms of reliability, ease of use, cost, and suitability for small fixed-wing drones. This comparison made it easier to identify what works well and where improvements are needed.

3.2.2 Patent search

A patent search was carried out to avoid infringing on existing designs and to learn from them, and understand which concepts are already protected by patents. This was done using online databases like Google Patents, Espacenet, and the WIPO (World Intellectual Property Organization) database. Search phrases such as “UAV recovery system,” “drone catching mechanism,” “autonomous UAV retrieval,” and “fixed-wing UAV recovery” were used. The results showed that most existing patents focus on larger drones or land-based recovery methods, with very few addressing small fixed-wing UAVs used in rescue operations.

3.3 Concept Development

The concept development phase followed the structured product development process described by Ulrich and Eppinger [21], where ideas are generated, analyzed, and refined into a feasible design concept.

Requirement specification began by identifying user needs and translating them into functional requirements that could guide the design and evaluation process throughout the thesis project. It was also a way to define what the UAV recovery system should achieve and to make sure the design meets the user’s needs. This was followed by brainstorming ideas on how each requirement could be solved, which were then later combined. This was later followed by combining them into different solutions through a structured concept generation method like the morphological matrix, with the help of Morpheus software, which generates a combination of different concepts.

In addition, an elimination matrix was created where the unfeasible concepts are eliminated. The remaining concepts are then compared among themselves in Pugh matrices with a set of criteria and later 3D-printed. Each concept was then evaluated in the Kesselring matrix based on performance, feasibility, simplicity, and compatibility with SSRS's operational needs. The evaluation process involved rating the concepts on a quantitative scale from 1 to 5, where higher values indicate better performance relative to the criterion, and the concept with the highest rank was identified to be the most promising.

3.4 Downstream Processes

After the concept development, the work continued with more detailed design activities. The selected recovery concept was modeled in CAD using Autodesk Inventor software, and several verification processes were carried out. For instance;

- FMEA was performed to identify and reduce potential failure modes early in the design.
- Material selection was done to ensure that the structure remained lightweight and cost-effective for SSRS operations.
- structural and kinematic dynamic simulations were conducted to verify that the system could withstand operational loads and function smoothly during the recovery process.

4

Review on existing recovery methods

This chapter presents the literature review of existing recovery methods for fixed-wing UAVs.

4.1 Fixed-Wing UAV Recovery Methods

The main recovery methods found in the literature search are summarized in this section.

4.1.1 Hook-Based Recovery Mechanisms

In a hook-based recovery mechanism, the fixed-wing drone is guided to catch a suspended cable using a weighted hook line, which rapidly decelerates and stalls the UAV in mid-air, after which the drone is retrieved [15]. This recovery method can be done in two ways. For instance, the suspended cable can be made to be horizontal with respect to the ground. [15] demonstrated this by suspending the cable in the air with two autonomous multirotor drones, each of which adjusted its position according to the drone's path. Their results showed that a fixed-wing UAV could be recovered using this method with a miss margin of 1-2.1 m, since the incoming UAV's position was not 100% accurate.

Moreover, a recovery system developed by Zipline International Inc. [23] uses the same principle as a horizontally suspended cable described above to recover its drones in Rwanda after making deliveries. It is supported by two flexible rods that extend the length of the cable, which are mounted on two stationary poles. In both methods, the hook suspension is based on pendulum mechanics, as the swinging motion of the hook allows it to be caught by the suspended cable. Meanwhile, spring-dampers attached to the suspended cable facilitate energy absorption. The figures 4.1 below illustrate the working principle of these two methods.

The suspended line can also be set vertically while supported at both ends. In this way, the same principle described above applies, with the difference that the weighted hook is mounted at the tip of one of the wings of the fixed-wing drone. An example of this method, shown in figure 4.2, is developed by Insitu, which is a subsidiary of Boeing, to recover small fixed-wing UAVs in midair [24]. It is used

Figure 4.1: Zipline's hook-based recovery method [22]

mainly in maritime operations, especially on ship decks for military operations.

Figure 4.2: Insitu's hook-based recovery method [24]

Although the hook-based recovery mechanisms described above are efficient and accurate in fixed-wing UAV recoveries, they come with some drawbacks that open the door to improvements. For example, the weighted hook adds extra weight to the fixed-wing UAV, which in turn affects its performance and efficiency. The frame of the drone must also withstand the sudden jerk when the cable is caught, meaning that the hook must have a reinforced attachment point. These extra weight structures can reduce the drone's flight endurance. [15] found that the hook-based mechanism relies on precise timing and GPS-based navigation, and in maritime operations, these can be affected by signal loss and wind disturbance, which can limit the recovery success.

4.1.2 Net-Based Recovery Systems

In a net-based recovery system, it means that a fixed-wing UAV is guided to fly into a tensioned net that absorbs its kinetic energy upon impact [14]. The net can be mounted either on a moving vehicle or suspended between two poles or two multi-rotor drones. For example, [25] developed an autonomous recovery method of suspending a net under two multirotor UAVs that were able to intercept an incoming fixed-wing UAV flying on a preset path. The fixed-wing UAV body was equipped with small hooks that get attached to the net on impact. This method was carried out at sea, and the UAV was transported to the ship afterward. However, the net-based recovery system has some drawbacks that open room for future improvements, such as if the hooks on the fixed drone loosen, it could fall into the sea and get lost or be destroyed. Also, the method requires Real-time kinematic GPS for precise navigation solutions, and in case of signal loss at sea, the UAV could never be recovered.

Figure 4.3: Net-based recovery method using two multirotor UAVs [25]

On the other hand, [26], which specializes in UAV recovery nets, has developed a ground-based net that is held on both ends. The net folds at an angle after the UAV impact to prevent it from falling to the ground. It's a simple method that only requires the drone to be guided onto the net's position, and the UAV is recovered easily as shown in the figure4.4 However, retrieving the UAV from the net can be a demanding process since the UAV propeller gets entangled in the net, hence requiring careful removal, both to protect the UAV and the net at the same time.

Figure 4.4: Embention ground net-based recovery method [26]

4.1.3 Bio-Inspired Landing Mechanisms

To overcome the need for a landing infrastructure for fixed-wing UAVs, [27] took inspiration from the way birds perch and grasp objects when landing to develop a landing gear similar to a bird's legs. The figure 4.5 shows the bio-inspired landing

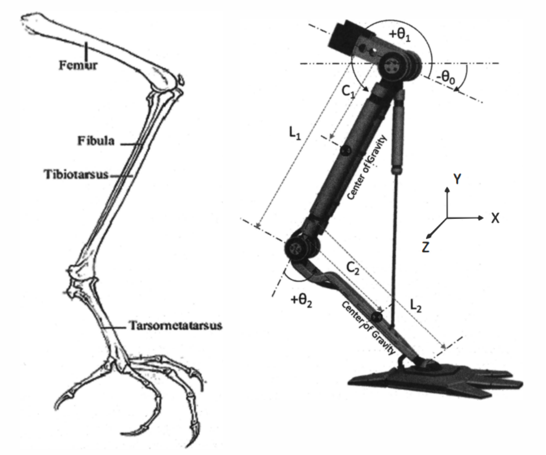


Figure 4.5: Bio-inspired landing gear [27]

gear. These landing gears allow the fixed-wing UAV to land without a runway on uneven surfaces and unfamiliar areas. Despite this novel innovation, the bio-inspired landing mechanism or gear is very complex in terms of its control system, which means that they are still far from a common deployment. The extra legs also add extra weight to the UAV and interfere with the aerodynamics of the UAV during flight.

4.1.4 Control-based Recovery Approaches

In a control-based recovery approach, the UAV's flight control is reconfigured to enable it to perform complex maneuvers and land safely either on land or via aerial docking [28]. This is done with the help of advanced guidance such as infrared cameras, control algorithms, and navigation systems. The aerial docking system shown in Figure 4.6 was developed by DARPA and Aurora Life Sciences in the USA [29]. It is a sidearm and consists of a hook on top of a fixed-wing UAV, which is captured midair by a retractable rail-mounted capture system, which gradually decelerates along the rail until it comes to a stop.

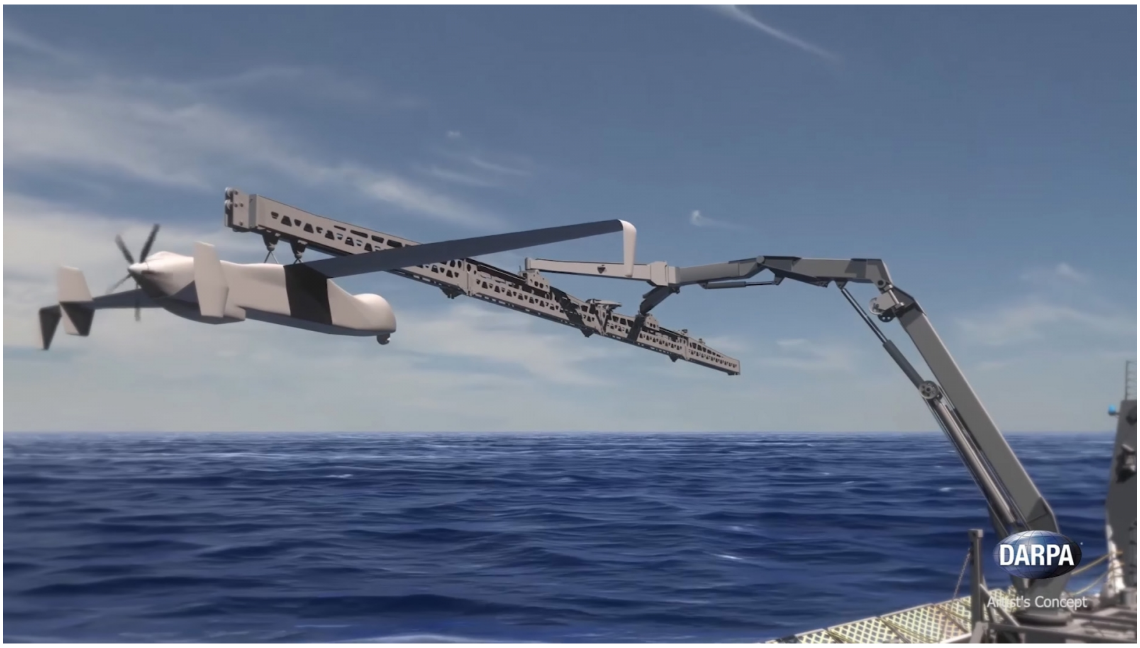


Figure 4.6: DARPA aerial docking UAV recovery system [29]

Furthermore, deep stall landing is also a control-based recovery method where the UAV enters a sustained stall to counteract gravity and drops almost vertically at low speed [30]. In some landing stalls, morphing wings are used to provide extra control to manage the speed, sink rate, and attitude under different conditions [31]. This allows the UAV to land accurately even in small or challenging areas.

5

Market Analysis

This chapter outlines how the Swedish Sea Rescue Society (SSRS) positions itself within the market for UAV recovery systems. The analysis is based on a combination of methods, including SWOT and PEST analysis, benchmarking against industry actors, and a review of relevant patents.

5.1 Swedish Sea Rescue Society (SSRS)

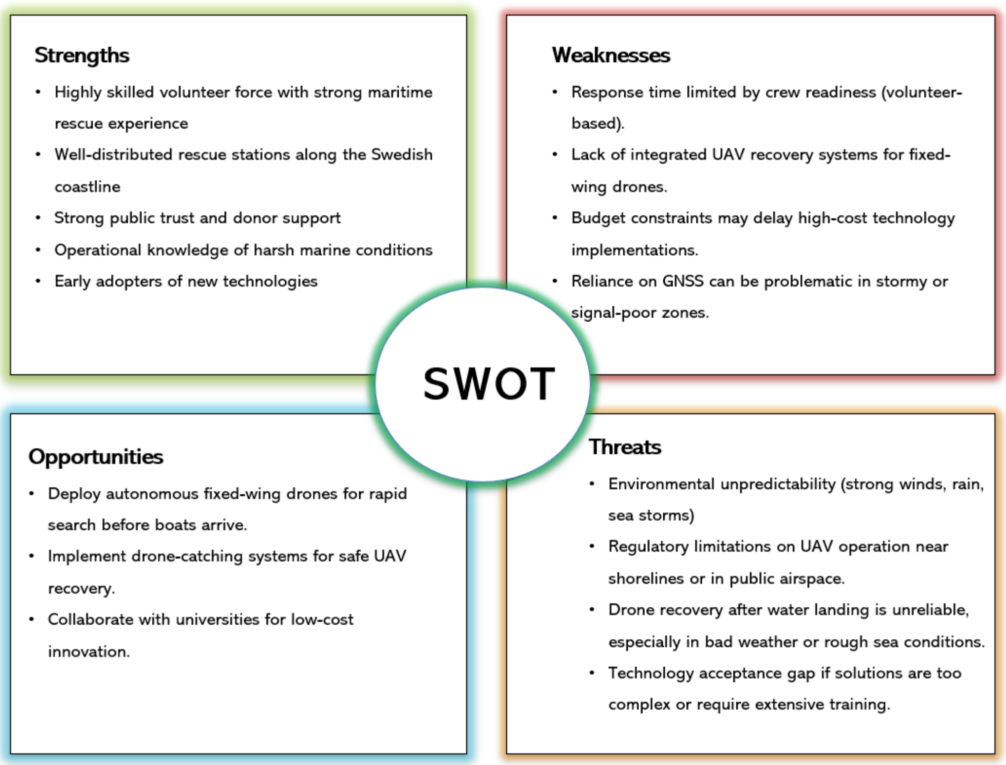
The Swedish Sea Rescue Society (SSRS) is a non-profit organization dedicated to saving lives at sea [32]. SSRS operates a wide network of rescue stations along Sweden's coast and inland waters, ensuring that help is always close when an emergency occurs. The organization combines human dedication with advanced rescue technology, continually innovating in rescue equipment. In this thesis project, SSRS is collaborating to develop a fixed-wing UAV recovery system that supports its goal of making sea rescue operations safer and more efficient.

5.1.1 SWOT analysis of SSRS

A SWOT analysis was carried out to understand SSRS's strengths, challenges, and overall operating environment as shown in figure 5.1. The analysis shows that SSRS benefits from experienced volunteers and a strong rescue network but faces some limitations in technology and resources. It also points to clear opportunities for using UAVs to make rescue missions faster and safer, while highlighting the challenges faced, like tough weather conditions and UAV flight regulations. Overall, the SWOT analysis reveals that there is a need for a simple and reliable UAV recovery system to help SSRS carry out its rescue missions more efficiently.

5.1.2 PEST analysis of SSRS

To understand the external factors that could affect the use of UAV recovery systems within SSRS operations, a PEST analysis was carried out as illustrated in Figure 5.2. From a political perspective, there is strong national support for maritime safety, but on the other hand, UAV regulations in Sweden and in the EU limit flight zones and autonomous drone use at sea, which affect the development of the UAV recovery system. At the same time, collaboration with other Baltic Sea rescue organizations could open opportunities for shared UAV recovery systems.



Strengths

- Highly skilled volunteer force with strong maritime rescue experience
- Well-distributed rescue stations along the Swedish coastline
- Strong public trust and donor support
- Operational knowledge of harsh marine conditions
- Early adopters of new technologies

Weaknesses

- Response time limited by crew readiness (volunteer-based).
- Lack of integrated UAV recovery systems for fixed-wing drones.
- Budget constraints may delay high-cost technology implementations.
- Reliance on GNSS can be problematic in stormy or signal-poor zones.

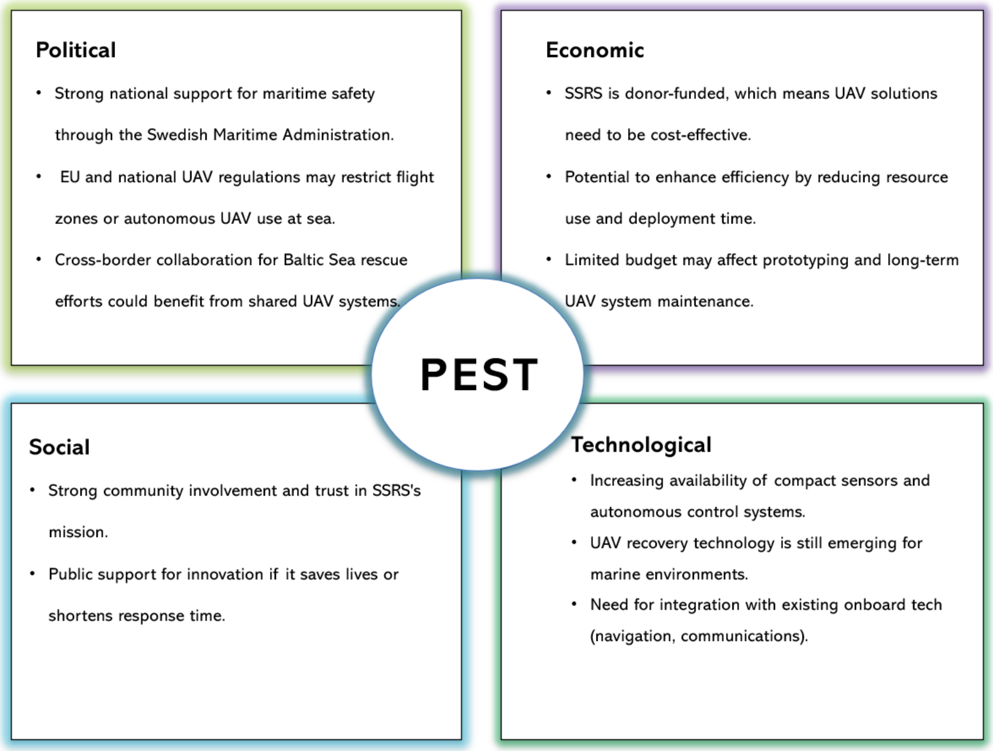
Opportunities

- Deploy autonomous fixed-wing drones for rapid search before boats arrive.
- Implement drone-catching systems for safe UAV recovery.
- Collaborate with universities for low-cost innovation.

Threats

- Environmental unpredictability (strong winds, rain, sea storms)
- Regulatory limitations on UAV operation near shorelines or in public airspace.
- Drone recovery after water landing is unreliable, especially in bad weather or rough sea conditions.
- Technology acceptance gap if solutions are too complex or require extensive training.

Figure 5.1: SWOT analysis of the Swedish Sea Rescue Society (SSRS).



Political

- Strong national support for maritime safety through the Swedish Maritime Administration.
- EU and national UAV regulations may restrict flight zones or autonomous UAV use at sea.
- Cross-border collaboration for Baltic Sea rescue efforts could benefit from shared UAV systems.

Economic

- SSRS is donor-funded, which means UAV solutions need to be cost-effective.
- Potential to enhance efficiency by reducing resource use and deployment time.
- Limited budget may affect prototyping and long-term UAV system maintenance.

Social

- Strong community involvement and trust in SSRS's mission.
- Public support for innovation if it saves lives or shortens response time.

Technological

- Increasing availability of compact sensors and autonomous control systems.
- UAV recovery technology is still emerging for marine environments.
- Need for integration with existing onboard tech (navigation, communications).

Figure 5.2: PEST analysis of the Swedish Sea Rescue Society (SSRS).

Economically, SSRS relies on donations, which means that any fixed-wing UAV recovery system needs to be affordable and easy to maintain.

On a social level, SSRS enjoys strong public trust and community involvement, and people are generally supportive of new technologies that can save lives or improve rescue times. While from a technological perspective, compact sensors and autonomous systems are becoming more accessible, making UAV use more feasible. However, recovery technology for marine environments is still developing and must be well integrated with existing navigation and communication systems.

5.2 Market segments

The market for fixed-wing UAV recovery systems is mainly divided into three areas where safe and efficient recovery is especially important: maritime search and rescue, defense, and remote surveying. However, the system developed in this thesis is specifically tailored for maritime operations and small fixed-wing UAVs, and therefore does not target defense applications.

5.2.1 Maritime Search & Rescue

In maritime operations, UAVs are increasingly used to support search and rescue missions by providing situational awareness by identifying distressed vessels to assess the situation before the rescue arrives, and also determining their exact position. The Swedish Sea Rescue Society (SSRS), for example, relies on reliable UAV deployment to improve response time and safety during rescue missions [32]. At the moment, UAVs used by SSRS usually land on water, which can take valuable time during critical, life-or-death situations. With the proposed recovery system, the UAV will be able to return directly to the base and be recovered safely with minimal human involvement, making the whole rescue process faster and more efficient.

5.2.2 Defense

In defense applications, UAVs are used for reconnaissance, surveillance, and tactical support. The ability to safely retrieve UAVs without the need for runways or large landing zones provides a significant operational advantage, particularly in confined or mobile environments such as naval vessels. However, there are already some effective UAV recovery methods used in defense operations, such as [29]. But the system developed in this thesis is not intended for that purpose since it is specifically designed for small fixed-wing UAVs weighing around 1 kg.

5.2.3 Remote Surveying

In remote surveying operations, such as coastal monitoring, infrastructure inspection, mining, and environmental data collection, they often take place in difficult-to-access or hazardous areas and require fixed-wing UAVs [33],[34]. This market segment would benefit from a fixed-wing UAV recovery system that offers a practical solution for ensuring UAV retrieval in these environments. This not only reduces operational risks but also supports continuous data collection and improved system reliability across various industries. On the other hand, this may be affected by the size of the UAV used and what kind of regulations exist in these areas.

5.3 Benchmarking

The market landscape for fixed-wing UAV recovery systems reflects a diversity of approaches tailored to different operational needs as described above. But for this thesis, the main focus is on how the civilian sectors have driven the development of recovery methods. Thus, these recovery methods are assessed based on their degree of autonomy, infrastructure requirements, landing precision, and cost-effectiveness. For instance;

Embention, a Spanish company that specializes in UAV systems, has developed a net recovery system called RN86 for fixed-wing UAV recovery [26]. The RN86 is a frame-mounted net, and the UAVs are guided to it for interception during landing. This net recovery system(RN86) can handle drones weighing up to 40 kg with stall speeds of around 25 m/s. The RN86 is mobile and designed for deployment in remote or maritime environments where traditional landing infrastructure is unavailable. Its success rate depends on precise UAV alignment, and it favors fixed-wing UAVs with rear-mounted propellers to avoid damage upon capture.

Manta Air in Israel is a company that develops autonomous recovery systems for UAVs, such as a Parachute Launching System (PLS) that uses a mechanical spring mechanism to deploy the parachute canopy [35]. The PLS can be triggered at low altitudes and is designed for rapid emergency deployment and for normal landings. The system first deploys the parachute, followed by the inflation of an airbag beneath the fuselage before impact. As a result, there will be a reduced risk of damage to the drone. However, the effectiveness of this system depends on having enough altitude for both the parachute and the airbag to function. Overall, Manta Air's solution offers a fully autonomous recovery method and provides layered protection to the UAV during landings and emergencies.

In addition, Target Arm in the U.S. offers a recovery solution for fixed-wing UAVs that features bars that extend from above and below inside an enclosure to gently but securely catch the UAV [36]. It's designed to work both on stationary platforms and on moving trucks or boats, giving deployment flexibility. Nevertheless, its success rate depends on proper alignment to ensure a clean capture.

Similarly, the Shenyang Institute of Automation (SIA), under the Chinese Academy of Sciences, has developed an automated recovery system for small and medium fixed-wing UAVs [37]. The system integrates real-time guidance with a flexible arresting mechanism, allowing precise runway-free landings in constrained environments such as ship decks.

Overall, the benchmarking shows that existing civilian fixed-wing UAV recovery systems offer a range of solutions. For instance, the systems provide autonomy and eliminate the need for runways. They often rely on precise alignment, sufficient altitude, or controlled environments to operate effectively. These limitations indicate a gap for recovery methods that are simpler, more reliable, and better suited to small fixed-wing UAVs operating in constrained or unpredictable conditions.

5.4 Patent search

To explore potential solutions and avoid infringement on existing technologies for UAV recovery systems, an extensive patent search was conducted using Google Patents and Espacenet databases. The goal was to identify innovative design mechanisms for the safe, automated recovery of fixed-wing UAVs and to draw inspiration from these patents. This resulted in patents described below, which were found to be most inspiring and relevant. For instance;

A kind of fixed-wing unmanned plane safe recovery device
This recovery system uses an inflatable airbag runway with both energy-absorbing and sloped sections [38]. The system also has an adjustable bracket to control the landing angle, as shown in Figure 5.3.

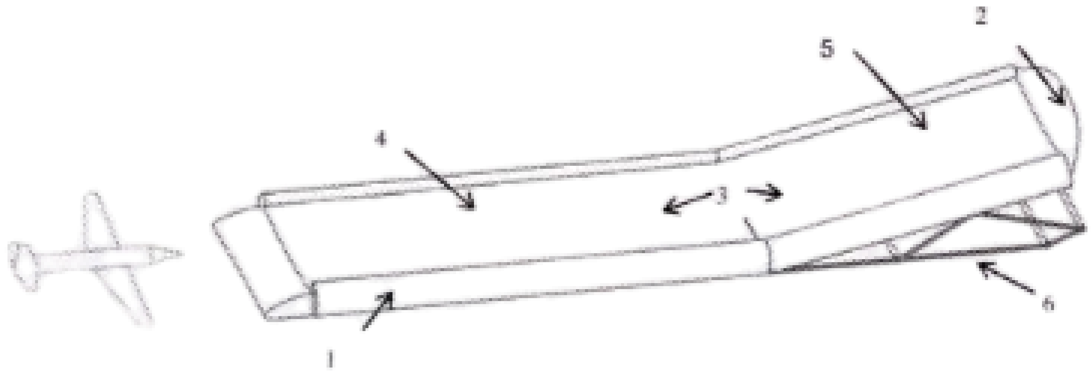


Figure 5.3: A kind of fixed-wing unmanned plane safe recovery device[38]

Strength: The inflatable runway cushions the landing.
Weakness: It takes time and space to set up.

Automatic recovery and transfer system for fixed-wing UAV
Another patented fixed-wing UAV recovery system, shown in Figure 5.4, consists of the following components: an arresting unit, vertical rails for adjusting position, and transfer and conveying systems that work together to capture, move, and store the UAV. The alignment rail, in concept 698, was inspired by this patent, allowing it to align the catching system with the UAV's trajectory.

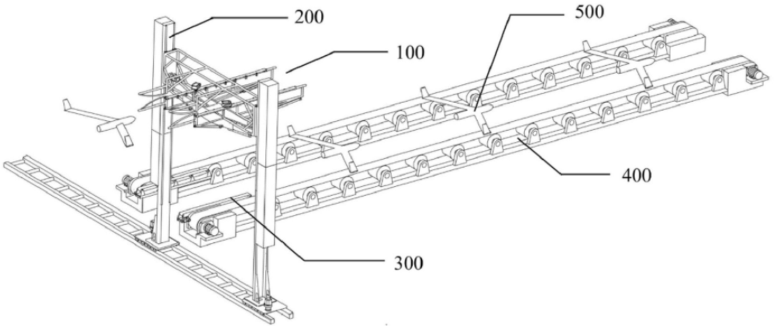


Figure 5.4: Automatic recovery and transfer system for fixed-wing UAV [39]

Strength: By automatically capturing and storing UAVs, it minimizes manual intervention.
Weakness: The system is quite complex, which can make it more expensive and harder to maintain.

Fixed-wing UAV interception and recovery system
This system consists of a base that supports a central rod. Three rods extend from the upper and lower ends of the rod. And between these rods, there is a tensioned rope positioned to catch incoming fixed-wing drones, as shown in figure 5.5. The applicant of the patent claims it is movable and modular, allowing for flexible arrangement and easy deployment in different locations [40].

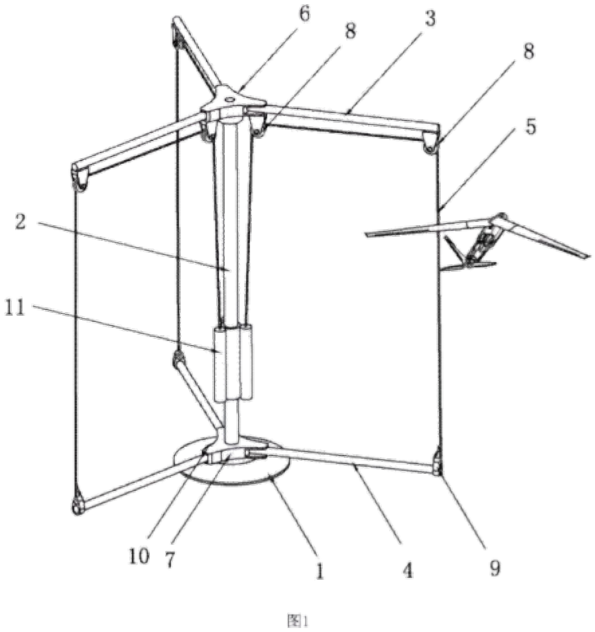


Figure 5.5: Fixed-wing UAV interception and recovery system [40]

Strength: It is easy to set up, so it can be moved and deployed anywhere.

Weakness: Requires precise alignment to capture the UAV accurately.

Magnetic recovery systems and magnetic docking mechanisms for fixed-wing unmanned aerial vehicles

This recovery system in figure 5.6 uses magnetic steel plates attached to the UAV, and a corresponding magnet is mounted on a moving vehicle [41]. During recovery, the magnetic attraction helps align and lock the UAV into position on the docking frame.

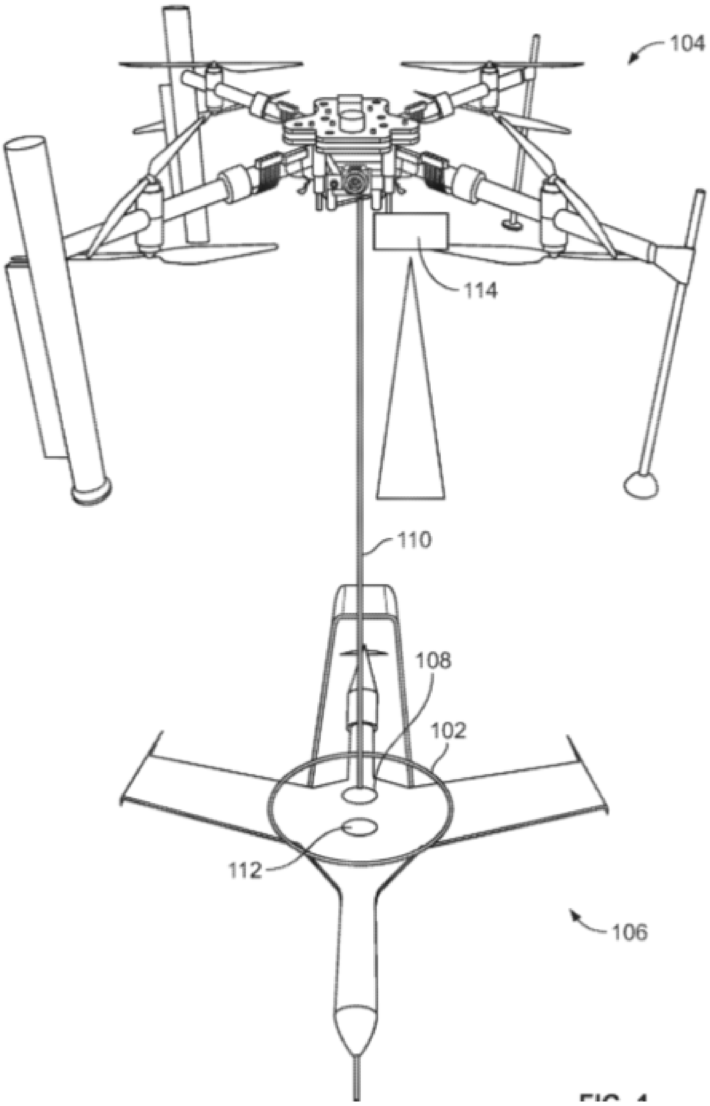


Figure 5.6: Magnetic recovery systems and magnetic docking mechanisms [41]

Strength: There is no physical stress on the UAV, since it is a contact-free docking.
Weakness: Since the magnets can be affected by distance and vibration, both magnets need to have equal strength.

Unmanned Aerial Vehicle Launching and Recovery Device
The system in figure 5.7 is designed to launch and recover small fixed-wing UAVs and consists of a rotating arm, a supporting frame, and a recovery station [42]. It also has a pair of upper and lower jaws that open and close to hold the UAV after capture. To absorb impact shocks and protect the drone, the system has a flexible strip in between the jaws. Furthermore, the system features an attitude adjustment mechanism on the lower jaw that aligns with the UAV before recovery.

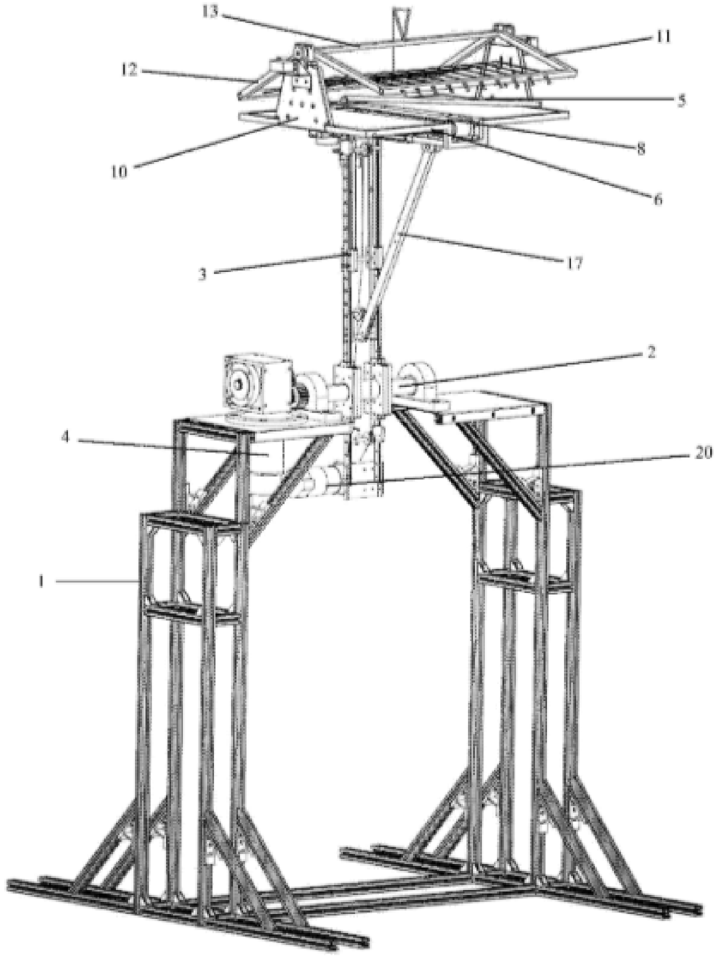


Figure 5.7: Unmanned aerial vehicle launching and recovery device [42]

> **Strength:** The jaws provide a secure grip and reduce the risk of damage with the help of the flexible strip.
> **Weakness:** The adjustment mechanism only adjusts height but not lateral position, so if the UAV's approach trajectory is slightly off, the UAV capture may not be reliable.

6

Concept Development

This chapter describes the process of developing and evaluating different fixed-wing UAV recovery system concepts, from understanding stakeholder needs to selecting the final concept design.

6.1 Stakeholders

The stakeholders involved in the development of the fixed-wing UAV recovery system were divided into different categories based on their level of interaction with the UAV recovery system as shown in table 6.7. The primary users are the UAV operators who handle the drone during rescue operations. The secondary users are the crew members responsible for setting up, resetting, and maintaining the system. While, the tertiary users, including the rescue crew and nearby individuals, are indirectly affected by the safety and effectiveness of the system.
Additionally, external stakeholders, including maritime authorities and donor members, influence the use of such a system through regulations. Finally, the customers are represented by the SSRS management, who oversee the system's development, implementation and long-term use. By identifying all these stakeholders in this way, it was meant to help the design process consider all relevant perspectives of those who use, maintain, or are affected by the system, hence a more reliable and user-centered solution.

Table 6.1: Stakeholders

Category	**Stakeholders**
Primary users	UAV operators
Secondary users	Crew responsible for setting up, resetting, and maintaining the system
Tertiary users	Rescue crew and neighbors
External stakeholders	• Maritime authorities (e.g., Transportstyrelsen, the coast guard) • Donor members
Customers	SSRS management

6.2 Customer needs analysis

After analyzing the needs of the stakeholders, a customer needs list was put together, which contains what the customers need and desire in an organized and prioritized layout as shown in table 6.2. Some of the main needs of SSRS/customer include:
For SSRS, reliability and precision are paramount. They seek UAV recovery systems that consistently perform with accuracy, ensuring confidence during drone retrieval. To minimize costs, simplicity in setup and minimal maintenance are essential to them. Safety is another fundamental need since SSRS operates within populated areas, so the recovery system must be able to recover drones without compromising the well-being of nearby individuals, and at the same time it should be lightweight

In addition, SSRS requires minimal manual intervention, though it is not a necessity for the organisation, as it reduces operational costs. Furthermore, minimizing modifications to the UAV frame is desirable, but SSRS prefers a solution that can integrate seamlessly with its existing $1Kg$ fixed-wing UAV without adding extra weight to it.

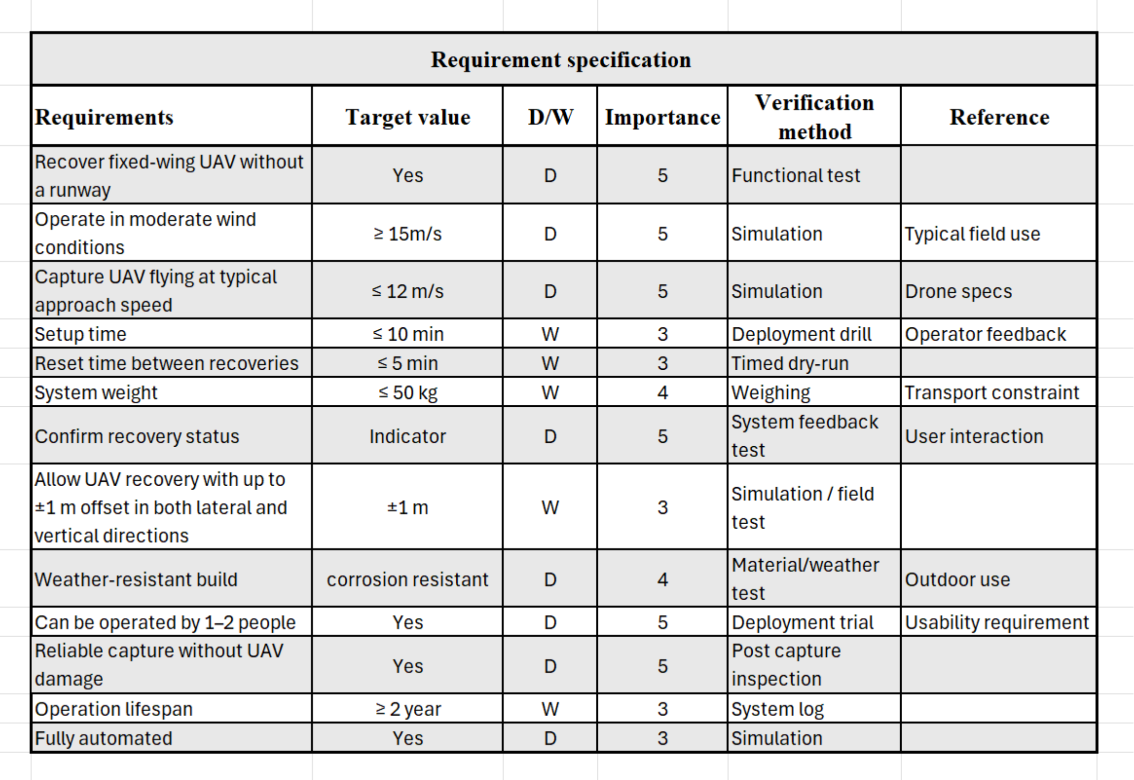
These needs provide a clear understanding of customer expectations and will guide the development of requirements in the subsequent design phase of the thesis.

Table 6.2: Customer Needs List

No.	**Need**	**Necessity/Desirable**
1	Reliable and precise	Necessity
2	Minimal manual intervention	Desirable
3	Simple to set up, reset, and minimal maintenance	Necessity
4	Safe drone recovery without compromising the safety of nearby individuals	Necessity
5	Complies with maritime UAV regulations and safety standards	Necessity
6	Modern and innovative	Desirable
7	Lightweight and affordable	Necessity
8	Improves UAV mission's outcomes	Necessity
9	Minimal modifications to UAV frame	Desirable

6.3 Requirement specification

The requirement specification in Figure 6.1 was developed after evaluating the needs of SSRS. The requirements are divided into demands, denoted as “D,” or wishes, denoted as “W”. To assess the level of importance of each requirement, a quantitative scale was used with "5" representing the highest level of importance and "1" representing the lowest. The requirements of the fixed-wing UAV recovery system have been updated throughout the thesis project since the target values were changed as more knowledge was gained. Thus, a verification method was added for each requirement using its corresponding verification method, and the result is to be compared with a reference value or method.



Requirement specification

Requirements	Target value	D/W	Importance	Verification method	Reference
Recover fixed-wing UAV without a runway	Yes	D	5	Functional test	
Operate in moderate wind conditions	≥ 15m/s	D	5	Simulation	Typical field use
Capture UAV flying at typical approach speed	≤ 12 m/s	D	5	Simulation	Drone specs
Setup time	≤ 10 min	W	3	Deployment drill	Operator feedback
Reset time between recoveries	≤ 5 min	W	3	Timed dry-run	
System weight	≤ 50 kg	W	4	Weighing	Transport constraint
Confirm recovery status	Indicator	D	5	System feedback test	User interaction
Allow UAV recovery with up to ±1 m offset in both lateral and vertical directions	±1 m	W	3	Simulation / field test	
Weather-resistant build	corrosion resistant	D	4	Material/weather test	Outdoor use
Can be operated by 1–2 people	Yes	D	5	Deployment trial	Usability requirement
Reliable capture without UAV damage	Yes	D	5	Post capture inspection	
Operation lifespan	≥ 2 year	W	3	System log	
Fully automated	Yes	D	3	Simulation	

Figure 6.1: Requirement specification

6.4 Functional Analysis

The functional analysis was carried out to understand how the fixed-wing UAV recovery system works and how its main functions connect to each other. This step helps identify what goes into the system and what comes out, as well as how energy, motion, and control signals move through the different parts of the system. By mapping this out early, it becomes easier to design and organize the subsystems later in the process and to make sure everything works together.

6.4.1 Black Box

A black box model was created to give a simple overview of the UAV recovery system without going into its internal details. The main purpose of this is to show how the system interacts with its surroundings and to define the limits of what is included in the design. The inputs and outputs make it easy to visualize how the system as a whole operates, as shown in the table 6.2. The main inputs are the in-flight fixed-wing UAV and the energy required to power the recovery mechanism. While, the outputs include a captured UAV and flight data that can be used to analyze and improve system performance.

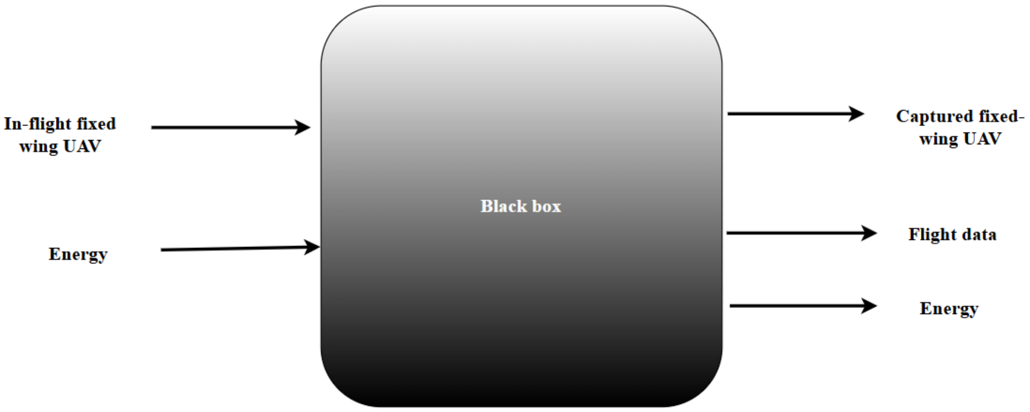


Figure 6.2: Blackbox

In addition, the black box also provides a clear picture of the system's overall function before diving into the internal details. Therefore, the black box serves as a foundation for the next step, the functional flow model, which explains how the internal functions work together to achieve a smooth and reliable UAV recovery.

6.4.2 Functional flow model

To understand how the fixed-wing UAV recovery system works, a functional flow model was created to explain step by step how the different parts of the system interact to detect, align with, and capture a UAV in flight, as illustrated in figure 6.3. The UAV recovery process starts when the system detects an incoming fixed-wing UAV that is on autopilot within 50-100 *meters* range using sensors and onboard communication. Once the UAV is detected, its flight path is tracked and analyzed so that the system can predict its movement by taking into account the wind speed, the speed of the fixed wing UAV and altitude.

The next step is to validate the UAV's trajectory to make sure the flight path is suitable for capture. During this stage, the recovery system activates the alignment subsystems and adjusts the position of the catching subsystem for capture. This is done continuously as the UAV approaches which helps the system stay synchronized with the UAV's motion and reduce the chances of a failed attempt.

On the other hand, if the capture is about to fail, the recovery system communicates with on onboard communication of the UAV to abort its trajectory, and the autopilot does another trial, and the system automatically rechecks the trajectory and attempts another recovery. After a successful capture, the UAV is safely transferred for inspection or storage so it can be reused.

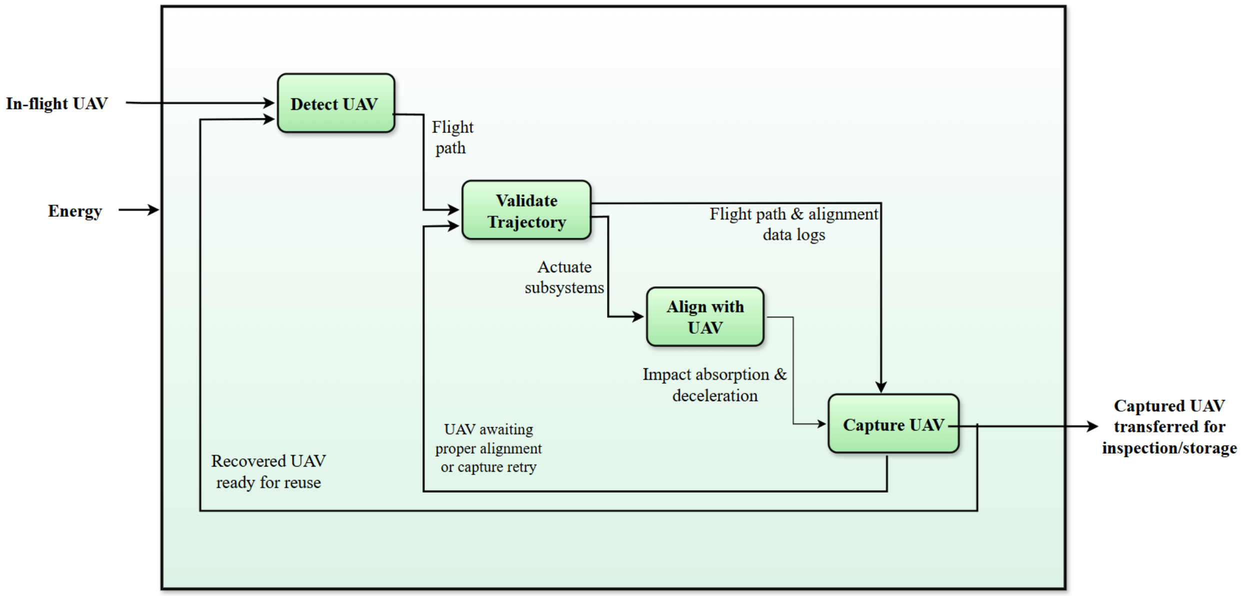


Figure 6.3: Functional Flow Model

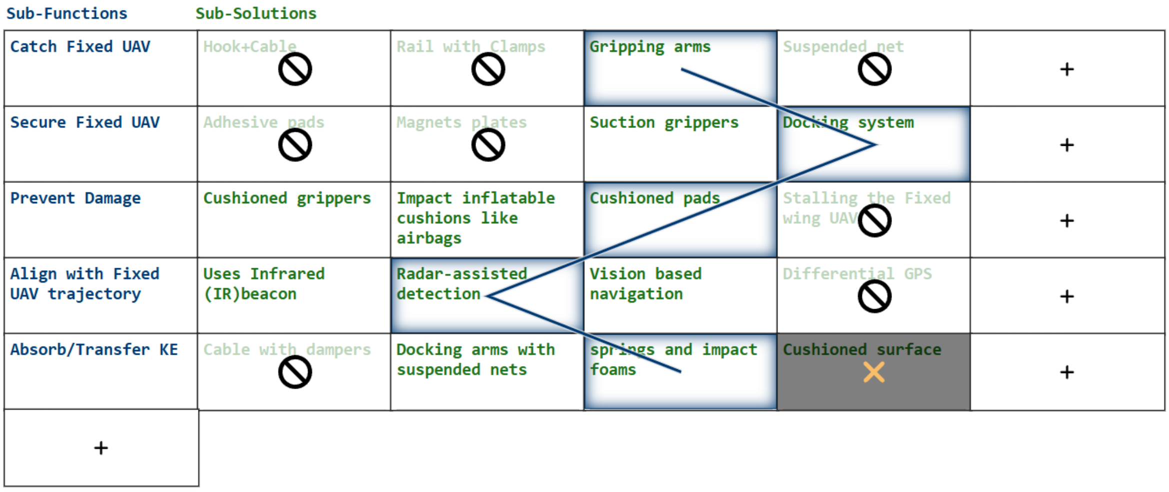
6.5 Concept Generation

6.5.1 Free idea generation

During the initial idea generation, a brainstorming session was conducted for every function of the UAV recovery system. For example, how the system should detect the fixed UAV in flight, how the system can align with the incoming fixed-wing UAV, how to capture it, and how to avoid damaging it. The brainstorming also included what happens to the UAV after capture and how it is retrieved from the system later, either for storage or to be put back in operation. The sub-solutions developed during this brainstorming process are presented in Appendix A.1.

6.5.2 Morphological matrix

The ideas obtained from the patent search, together with the identified sub-solutions from the free idea generation, were combined using a software tool called Morpheus, which generates possible combinations of the sub-solutions for all ideas. Initially, the software produced 1,064 possible concepts for the UAV recovery systems. However, a limitation was discovered because the software did not account for incompatibilities, nor did it filter out solutions that were either too costly or unfeasible. But these solutions were filtered out using built-in features like thematic strategy and pragmatic strategy, as shown in Figure 6.4, which reduced the number of concepts to 48 and later reduced to 28 feasible concepts. These concepts were later compiled into a concept catalog, which is presented in Appendix B.1.



Sub-Functions	Sub-Solutions				
Catch Fixed UAV	Hook+Cable 🚫	Rail with Clamps 🚫	Gripping arms	Suspended net 🚫	+
Secure Fixed UAV	Adhesive pads 🚫	Magnets plates 🚫	Suction grippers	Docking system	+
Prevent Damage	Cushioned grippers	Impact inflatable cushions like airbags	Cushioned pads	Stalling the Fixed wing UAV 🚫	+
Align with Fixed UAV trajectory	Uses Infrared (IR)beacon	Radar-assisted detection	Vision based navigation	Differential GPS 🚫	+
Absorb/Transfer KE	Cable with dampers 🚫	Docking arms with suspended nets	springs and impact foams	Cushioned surface ✕	+
+					

Figure 6.4: Morphological matrix

6.6 Concept Evaluation

6.6.1 Elimination matrix

In concept selection, an elimination matrix facilitates a structured approach by methodically eliminating solutions that cannot meet the requirements ref [43]. Based on the requirement specification, elimination criteria were developed for the elimination matrix in Appendix C.1. These criteria include the following.

- The system can reliably capture a fixed-wing UAV in flight.
- It can hold the UAV in place after capture.
- Protect the fixed-wing UAV from impact.
- Allows for precise positioning/alignment with the incoming fixed-wing UAV.
- Meets the weight requirement of less than 50 kg.
- The system fulfills the company's requirements on post-capture.
- Allows for positional offset capture of ± 1 meter.
- Feasible to design, build, and test using available resources

These criteria were applied across all the concepts to ensure a transparent and objective process of narrowing down the concepts from 28 to 6. Moreover, concepts 689 and 689 were similar and incorporated into concept 685. The other concepts that didn't meet the set criteria were deemed unsuitable and eliminated.

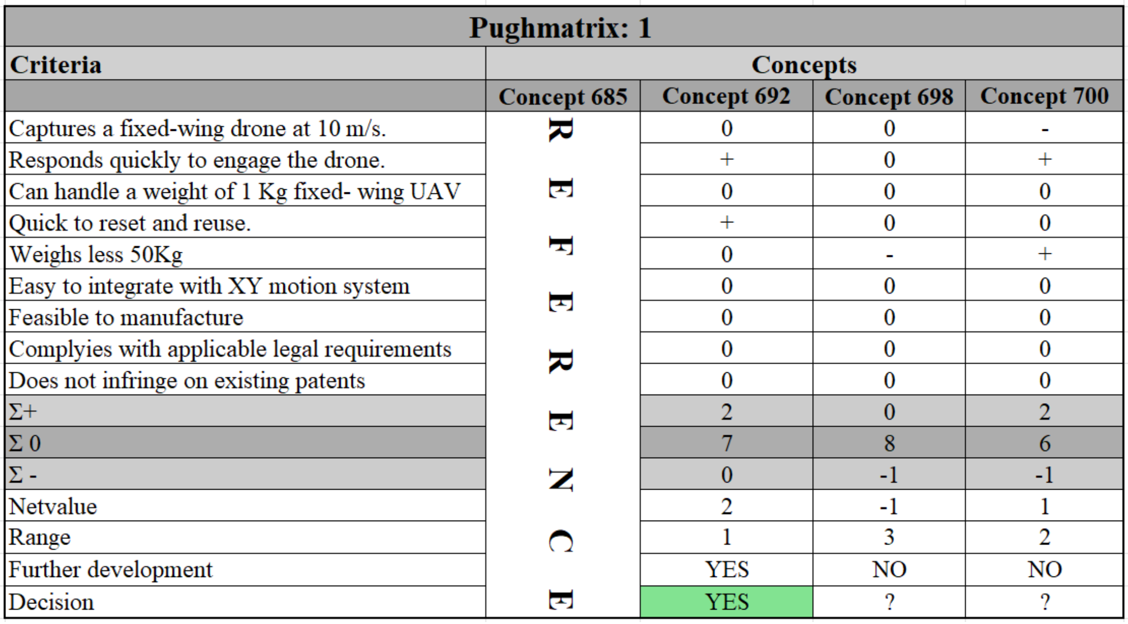
6.6.2 Concept Screening

To compare the remaining four concepts, ensure fair comparisons, and minimize bias, quick prototyping was carried out in which each concept was sketched, 3D-modelled, and 3D-printed, as shown in the Appendix D.1.
Afterwards, three Pugh matrices were created. In each Pugh matrix, relative scores of "better than"(+), "same as"(0), or "worse than"(-) are used for comparing each criterion of every concept against a chosen reference concept. Once all the concepts were rated, the sum for each concept was entered in the matrix's lower rows based on "better than," "same as," and "worse than" the reference concept.

6.6.2.1 Pugh Matrix 1

For the first Pugh matrix in table 6.3, the reference concept was Concept 685. This concept could capture a fixed-wing drone moving at 10 m/s, respond quickly, and be reset for reuse. After comparing this concept with the others, all the alternatives showed positive net values. This meant that the reference concept's performance was not favorable compared to the rest. The main reason for this was the way it handled impacts and how well it integrated with the motion system.

Table 6.3: Pugh matrix 1

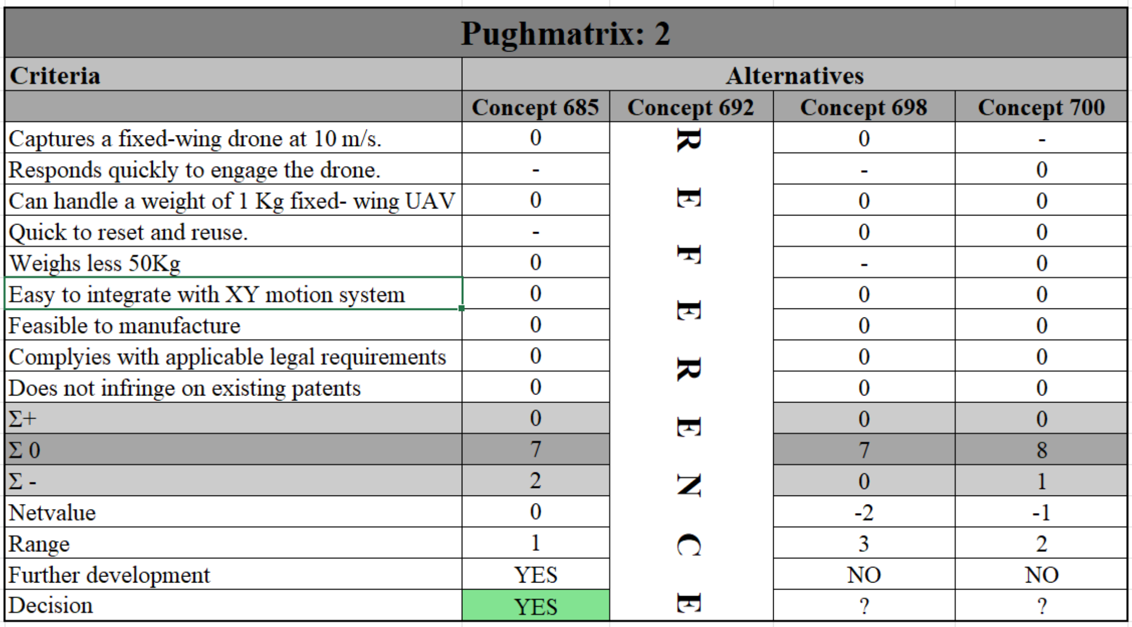


Pughmatrix: 1				
Criteria	Concepts			
	Concept 685	Concept 692	Concept 698	Concept 700
Captures a fixed-wing drone at 10 m/s.	REFERENCE	0	0	-
Responds quickly to engage the drone.		+	0	+
Can handle a weight of 1 Kg fixed- wing UAV		0	0	0
Quick to reset and reuse.		+	0	0
Weighs less 50Kg		0	-	+
Easy to integrate with XY motion system		0	0	0
Feasible to manufacture		0	0	0
Complyies with applicable legal requirements		0	0	0
Does not infringe on existing patents		0	0	0
Σ+		2	0	2
Σ 0		7	8	6
Σ -		0	-1	-1
Netvalue		2	-1	1
Range		1	3	2
Further development		YES	NO	NO
Decision		YES	?	?

6.6.2.2 Pugh Matrix 2

In the second Pugh matrix, the best-performing concept from the previous round, Concept 685, was again set as the reference, as shown in table 6.4. The same evaluation criteria were used to compare it with the other concepts. The results showed that Concept 685 continued to perform well, while Concept 698 and Concept 700 had lower net values. This meant that Concept 685 was still the most suitable option and should be taken forward for further development.

Table 6.4: Pugh matrix 2

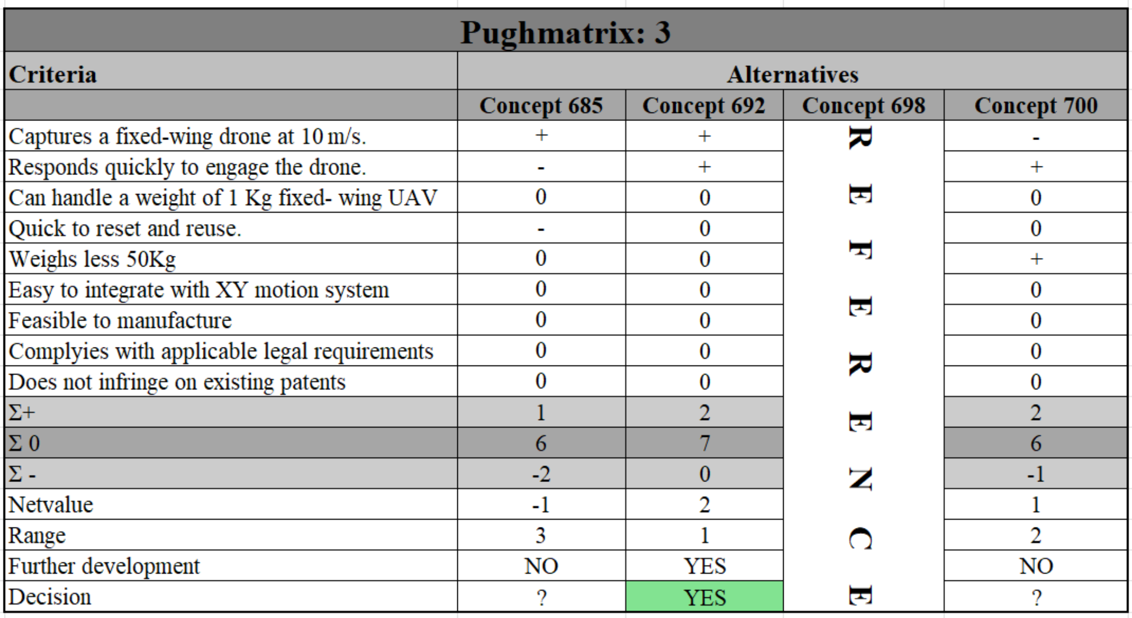


Pughmatrix: 2				
Criteria	**Alternatives**			
	Concept 685	**Concept 692**	**Concept 698**	**Concept 700**
Captures a fixed-wing drone at 10 m/s.	0	REFERENCE	0	-
Responds quickly to engage the drone.	-		-	0
Can handle a weight of 1 Kg fixed- wing UAV	0		0	0
Quick to reset and reuse.	-		0	0
Weighs less 50Kg	0		-	0
Easy to integrate with XY motion system	0		0	0
Feasible to manufacture	0		0	0
Complyies with applicable legal requirements	0		0	0
Does not infringe on existing patents	0		0	0
Σ+	0		0	0
Σ 0	7		7	8
Σ -	2		0	1
Netvalue	0		-2	-1
Range	1		3	2
Further development	YES		NO	NO
Decision	YES		?	?

6.6.2.3 Pugh Matrix 3

To refine the screening further, a third Pugh matrix was made with Concept 698 as the reference concept, as shown in Table 6.5. This concept was chosen because it performed similarly to the previous reference concept. After comparing the alternatives, Concept 692 had the highest net value, while Concept 685 and Concept 700 performed slightly worse. This showed that Concept 692 was the most promising option after all three screening rounds.

Table 6.5: Pugh matrix 3



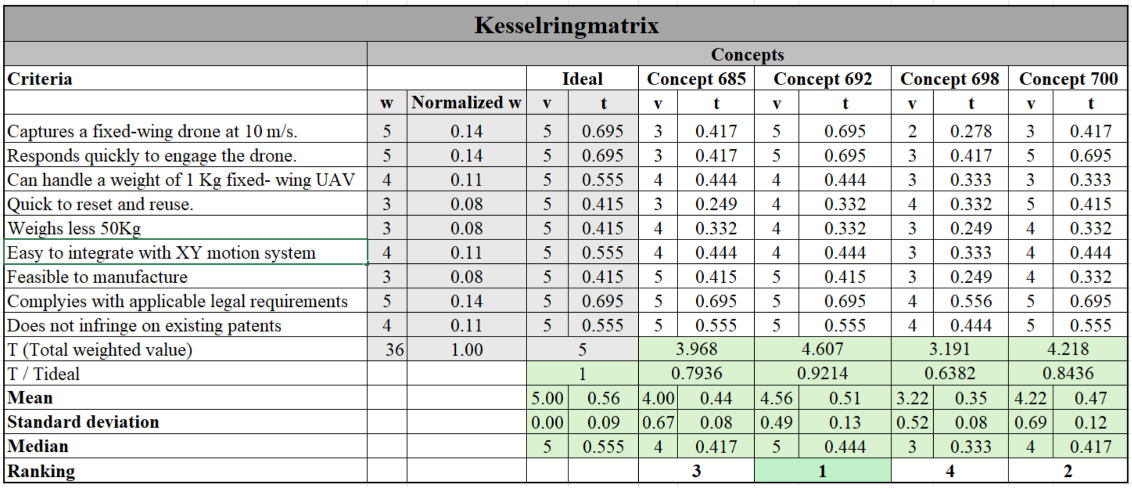
Pughmatrix: 3				
Criteria	**Alternatives**			
	Concept 685	**Concept 692**	**Concept 698**	**Concept 700**
Captures a fixed-wing drone at 10 m/s.	+	+	REFERENCE	-
Responds quickly to engage the drone.	-	+		+
Can handle a weight of 1 Kg fixed- wing UAV	0	0		0
Quick to reset and reuse.	-	0		0
Weighs less 50Kg	0	0		+
Easy to integrate with XY motion system	0	0		0
Feasible to manufacture	0	0		0
Complyies with applicable legal requirements	0	0		0
Does not infringe on existing patents	0	0		0
Σ+	1	2		2
Σ 0	6	7		6
Σ -	-2	0		-1
Netvalue	-1	2		1
Range	3	1		2
Further development	NO	YES		NO
Decision	?	YES		?

6.6.3 Concept selection

To further develop the concepts and do a more detailed comparison was considered time-consuming at this stage of the thesis project. Therefore, the Kesselring Matrix shown in table 6.6 was used to select the best-performing concept from the remaining four concepts by weighing the criteria. The Kesselring matrix compares each concept against an ideal concept rather than using an existing concept as a reference, like in the Pugh matrix.

Moreover, each criterion was first assigned a weight according to its relative importance, and the weights were then normalized so their sum equals one, ensuring a fair comparison. The concepts were then rated on a quantitative scale from 1 to 5, where higher values indicate better performance relative to the criterion. These scores were multiplied by the corresponding normalized weights. The weighted scores were then summed to give a total value for each concept, which was further normalized against the ideal. Based on this evaluation, Concept 692 ranked highest, followed by Concept 700, Concept 685, and Concept 698. Therefore, concept 692 was selected as the best choice and developed further, as described in the following section.

Table 6.6: Kesselring Matrix



Kesselringmatrix												
	Concepts											
Criteria			**Ideal**		**Concept 685**		**Concept 692**		**Concept 698**		**Concept 700**	
	w	**Normalized w**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**
Captures a fixed-wing drone at 10 m/s.	5	0.14	5	0.695	3	0.417	5	0.695	2	0.278	3	0.417
Responds quickly to engage the drone.	5	0.14	5	0.695	3	0.417	5	0.695	3	0.417	5	0.695
Can handle a weight of 1 Kg fixed- wing UAV	4	0.11	5	0.555	4	0.444	4	0.444	3	0.333	3	0.333
Quick to reset and reuse.	3	0.08	5	0.415	3	0.249	4	0.332	4	0.332	5	0.415
Weighs less 50Kg	3	0.08	5	0.415	4	0.332	4	0.332	3	0.249	4	0.332
Easy to integrate with XY motion system	4	0.11	5	0.555	4	0.444	4	0.444	3	0.333	4	0.444
Feasible to manufacture	3	0.08	5	0.415	5	0.415	5	0.415	3	0.249	4	0.332
Complyies with applicable legal requirements	5	0.14	5	0.695	5	0.695	5	0.695	4	0.556	5	0.695
Does not infringe on existing patents	4	0.11	5	0.555	5	0.555	5	0.555	4	0.444	5	0.555
T (Total weighted value)	36	1.00	5		3.968		4.607		3.191		4.218	
T / Tideal			1		0.7936		0.9214		0.6382		0.8436	
Mean			5.00	0.56	4.00	0.44	4.56	0.51	3.22	0.35	4.22	0.47
Standard deviation			0.00	0.09	0.67	0.08	0.49	0.13	0.52	0.08	0.69	0.12
Median			5	0.555	4	0.417	5	0.444	3	0.333	4	0.417
Ranking					**3**		**1**		**4**		**2**	

6.7 Further development of the selected concept

While working on Concept 692, one challenge that came up was how to align the concept accurately with the UAV's trajectory. The concept itself worked well in principle, but the struggle was how to position the concept precisely before the drone arrived to overcome the positional offset of the UAV caused by the GPS. During the quick prototyping sessions, it was observed that a 3D printer achieves high precision through coordinated motion along two axes. This observation inspired the development of an XY motion system.

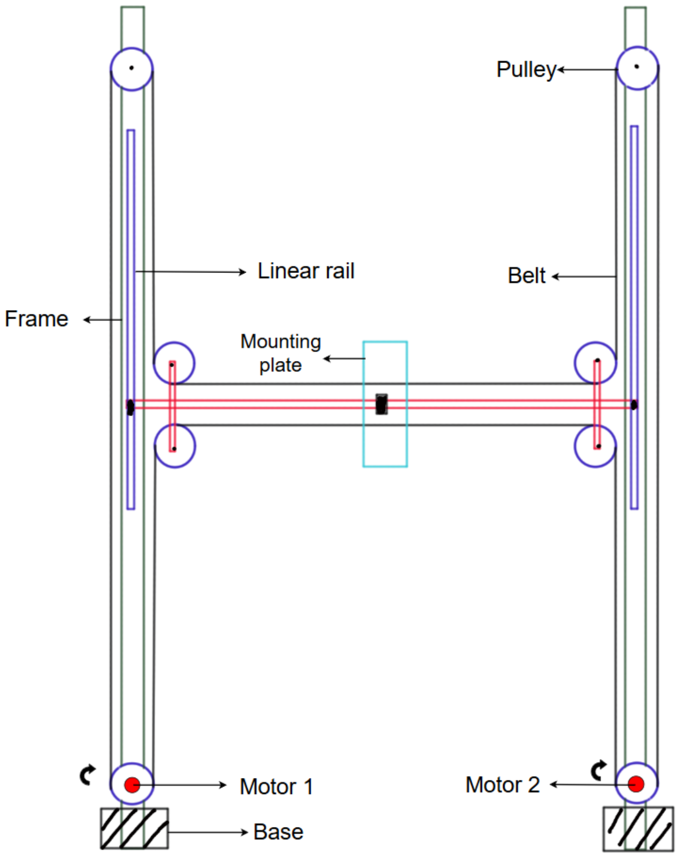


Figure 6.5: XY motion alignment subsystem

This XY motion system allows the catching subsystem (concept 692) to move in both horizontal and vertical directions. In this way, the catching subsystem could be adjusted in real-time to align more accurately with the UAV flight path. With this improvement, the recovery system can handle positional errors.

The XY motion (alignment subsystem) is operated by two motors that drive two motor pulleys and 6 idle pulleys that guide the motion belt [44]. The motion depends on how the motors rotate together. As shown in figure 6.5, when both motors rotate clockwise, the catching subsystem moves right, and when they rotate counterclockwise, it moves left. If they rotate in opposite directions, the system moves up or down depending on the combination.

Table 6.7: Direction of motion based on motor rotation.

Motor 1	**Motor 2**	**Result**
Clockwise	Clockwise	Right
Counterclockwise	Counterclockwise	Left
Clockwise	Counterclockwise	Up
Counterclockwise	Clockwise	Down

7

Results

7.1 System design

After further developing concept 692 of the UAV recovery system, the architecture of each subsystem was developed. Each subsystem in this concept can stand alone and can be designed and tested separately. As described before, the detection subsystem will not be designed in this thesis project, but will take into account how it affects the alignment and capture subsystems. Figure 7.1 shows how these subsystems and their components interact within the overall system.

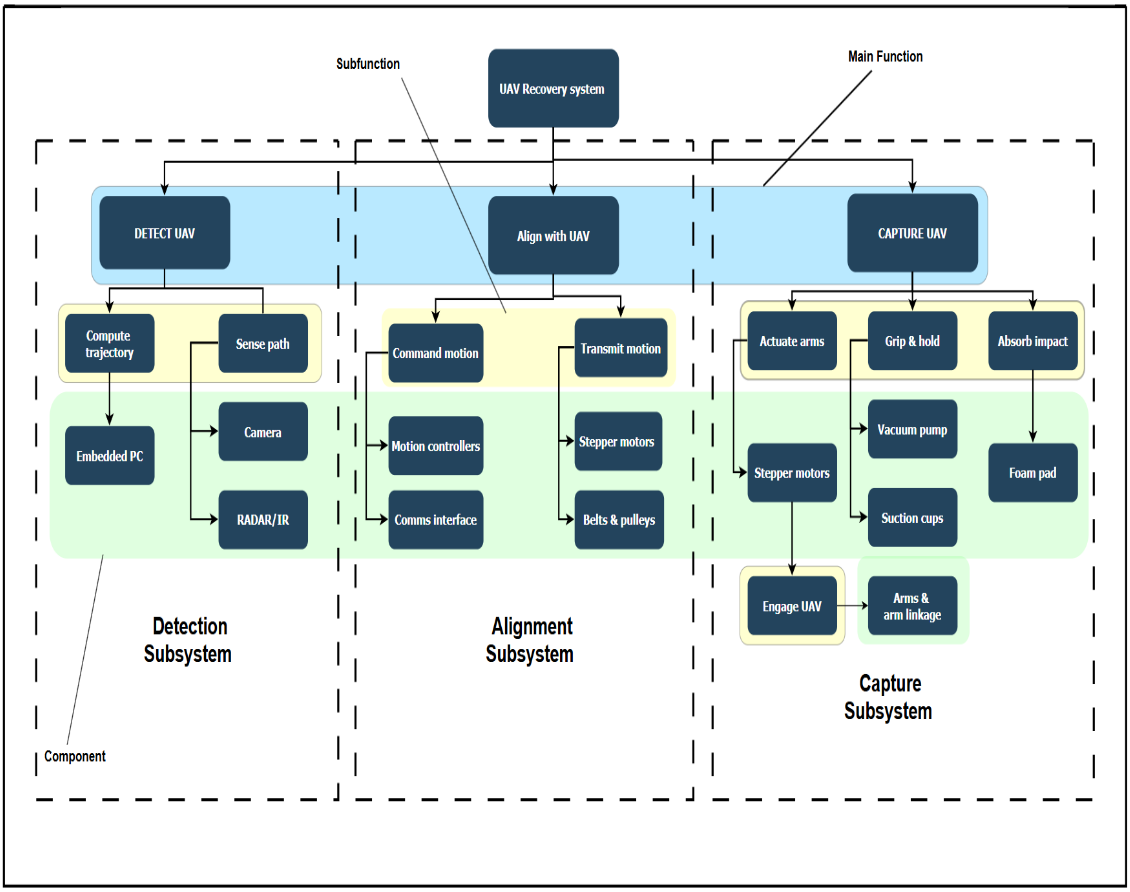


Figure 7.1: Detailed Concept Flow Diagram

7.1.1 Detection Subsystem

The detection subsystem detects and calculates the trajectory of incoming fixed-wing UAVs in real time, and it then provides the trajectory data, such as velocity and position provides it to the alignment subsystem. To carry out these functions, the logical functions of a detecting subsystem after a quick research are an embedded PC that processes the flight path data together. The embedded PC relies on inputs from a combination of a camera and radar/infrared sensors that detect and track the drone's position as described in 2.4.

7.1.2 Alignment Subsystem

The alignment subsystem ensures that the capture subsystem is in the correct position to catch the fixed-wing UAV. This subsystem relies on the trajectory data from the detection subsystem, which is translated into alignment motion. This motion is generated by a motion controller, which initiates command signals and transmits them via a communication interface in the detection subsystem. These signals drive two stepper motors, which provide precise and controllable movement to the belt driving the capture subsystem horizontally (X) and vertically (Y). In addition, the direction of movement depends on how the two motors rotate, as shown in Figure 6.5.

7.1.3 Capture Subsystem

The capture subsystem is responsible for physically engaging with the UAV. Its operation involves three coordinated functions: actuation, gripping, and impact absorption. A Stepper motor drives the four arms, which open and close in response to the entry of the fixed-wing UAV. Once contact is made, suction cups powered by a vacuum pump hold the UAV securely in place. To reduce the risk of structural damage during capture, a foam pad is integrated to absorb the impact and decelerate the UAV.

Furthermore, the modular nature of the design allows each subsystem to be developed and tested independently before integration. This approach not only enhances robustness but also facilitates future adaptation of the system to different UAV sizes or mission requirements.

7.2 System cad models

This section presents the detailed CAD models developed for the system. The models were created in Autodesk Inventor to visualize the recovery system's architecture and verify that the geometry and functionality align with the selected concept.

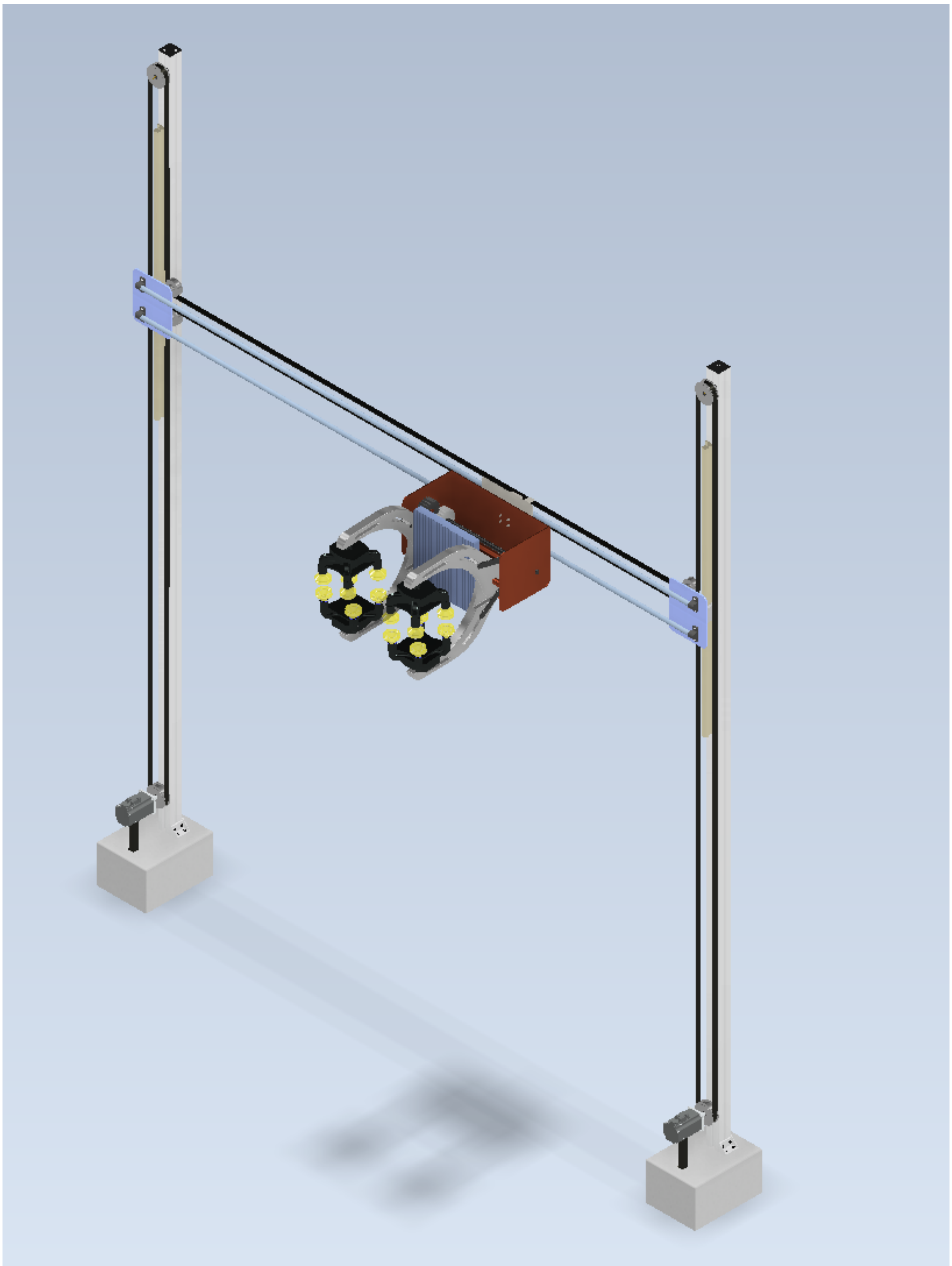


Figure 7.2: Assembly of the recovery system and the capture subsystem in its default position

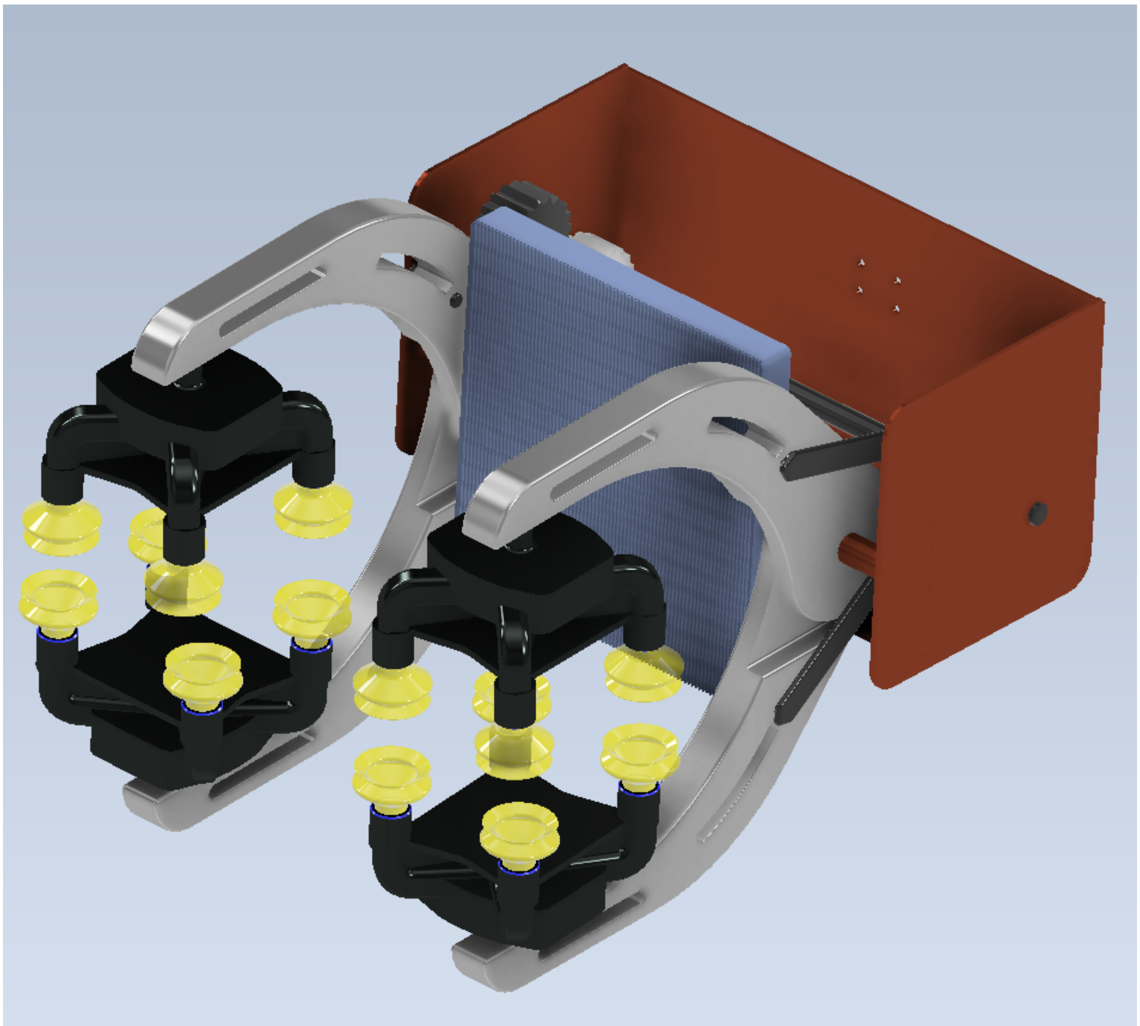


Figure 7.3: Assembly of the catching subsystem

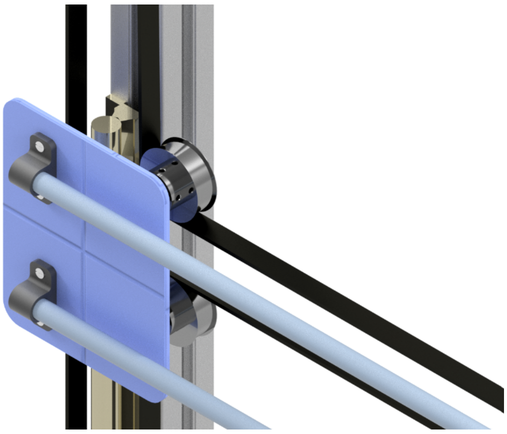


Figure 7.4: subassembly of the linear rail and idle pulley holder

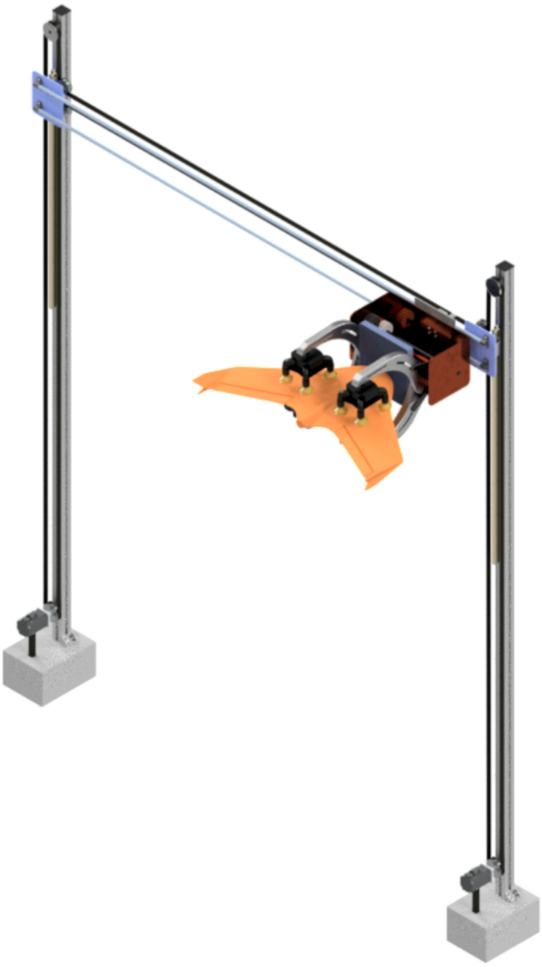


Figure 7.5: Assembly of the recovery system with a captured fixed-wing UAV

Figure 7.6: A closeup of one of the pulleys and the belt

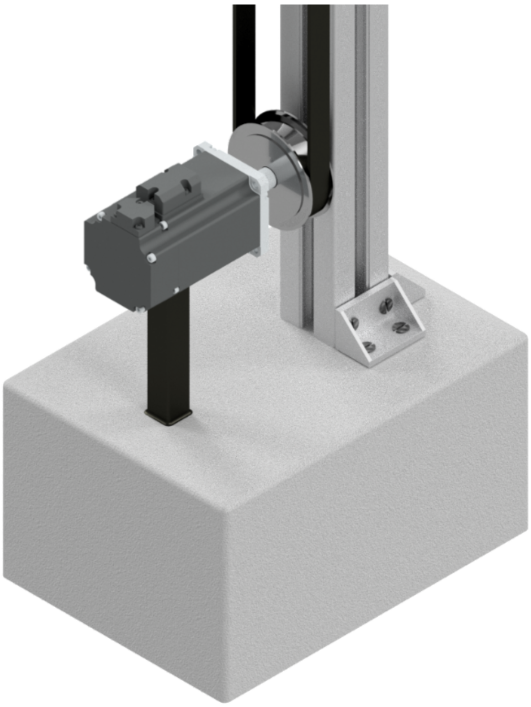


Figure 7.7: subassembly of the base and one of the motors

7.3 Verification

7.3.1 FMEA

The Design Failure Mode and Effects Analysis (DFMEA) shown in Appendix E.1 was conducted to address potential risks in the UAV catching system that could occur during operation. The analysis was performed after the design phase, once all major components had been modeled in CAD.

This DFMEA highlights:
- the failure modes of each component of the alignment and the catching subsystems,
- their possible causes and effects on system performance,
- the likelihood and severity of each failure,
- and the corresponding Risk Priority Number (RPN) used to prioritize corrective actions.

The RPN is calculated by multiplying the severity (S), occurrence (O), and detection (D) ratings, which helped identify where improvements were most needed in the design.

For example, the motors had the highest RPN of 108 due to inconsistent tuning that could lead to position errors during acceleration. Therefore, component testing during assembly was recommended. The motor pulleys also had a high RPN of 90 due to belt edge wear, which could result in instant position loss. This will be managed through regular maintenance. The belt had an RPN of 80 due to low

tension or high acceleration that could cause incorrect positioning of the catching subsystem. To overcome this problem, regular maintenance was recommended to ensure stable belt behavior.
Other components showed moderate risk levels. The linear rail had an RPN of 48, which will be reduced by component testing during assembly. Similarly, the sliding blocks also had an RPN of 48, and adding dust seals will help prevent stick–slip issues from debris. The mounting plate and catching arms had RPN values of 40, addressed through regular maintenance and redesign of thin sections, respectively, to prevent deformation or misalignment. The frame had a lower RPN value of 24, which can be reduced further by strengthening through bracing.

7.3.2 Materials selection

The material selection for the UAV recovery system is shown in the BOM Appendix F.1 after the components have been identified and 3D modeled during the design phase. Every component had to meet the requirements, such as being lightweight and manufacturable.
The selection process focused on materials that offered the best balance between strength, weight, and manufacturability. The frame is made from Aluminum 6061-T6 T-slot profiles due to their high stiffness-to-weight ratio and corrosion resistance, making them ideal for structural support. The mounting plate is also made from Aluminum 7075-T6, which provides higher strength and impact resistance since it holds the catching subsystem.

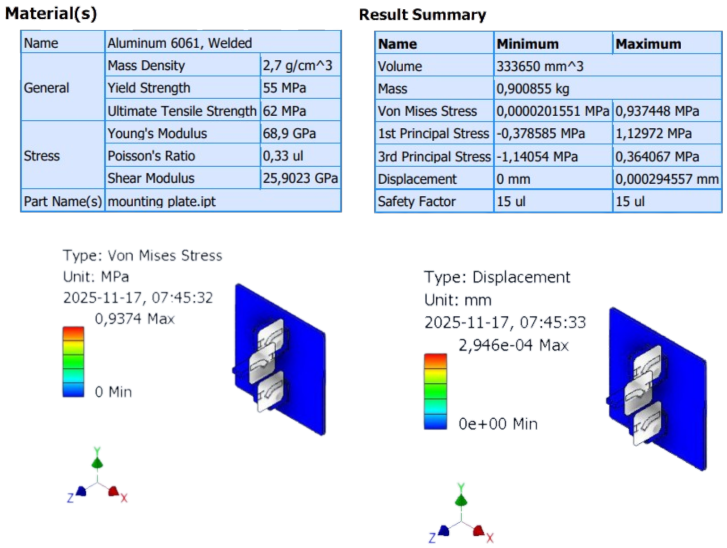
The linear rails and sliding blocks are aftermarket components made from hardened bearing steel, ensuring low friction and high precision for smooth motion. The motor and idler pulleys, along with the pulley holders, are also machined from 6061-T6 aluminum. Meanwhile, the belt is made from polyurethane, known for its flexibility, low wear rate, and excellent resistance to tension loss. The arms and the linkarms are also made from 7075-T6 aluminum. The suction cup vacuum uses a silicone cup and an ABS plastic housing.

Through this careful material selection, the total system weight requirement was successfully fulfilled, resulting in an approximate overall weight of 36.5 kg.

7.3.3 Structural Analysis

7.3.3.1 Structural Analysis of the mounting plate

In the UAV recovery system, the belt carries most of the load and drives the overall motion of the system. The mounting plate that holds the catching subsystem experiences the highest stress when moving in the XY direction since it is attached to the belt. To study its performance, a quick structural analysis was performed on this component, as shown in the figure 7.8. Based on the results of the FEA analysis, the mounting plate can support the weight of the catching subsystem.



Material(s)

Name	Aluminum 6061, Welded	
General	Mass Density	2,7 g/cm^3
	Yield Strength	55 MPa
	Ultimate Tensile Strength	62 MPa
Stress	Young's Modulus	68,9 GPa
	Poisson's Ratio	0,33 ul
	Shear Modulus	25,9023 GPa
Part Name(s)	mounting plate.ipt	

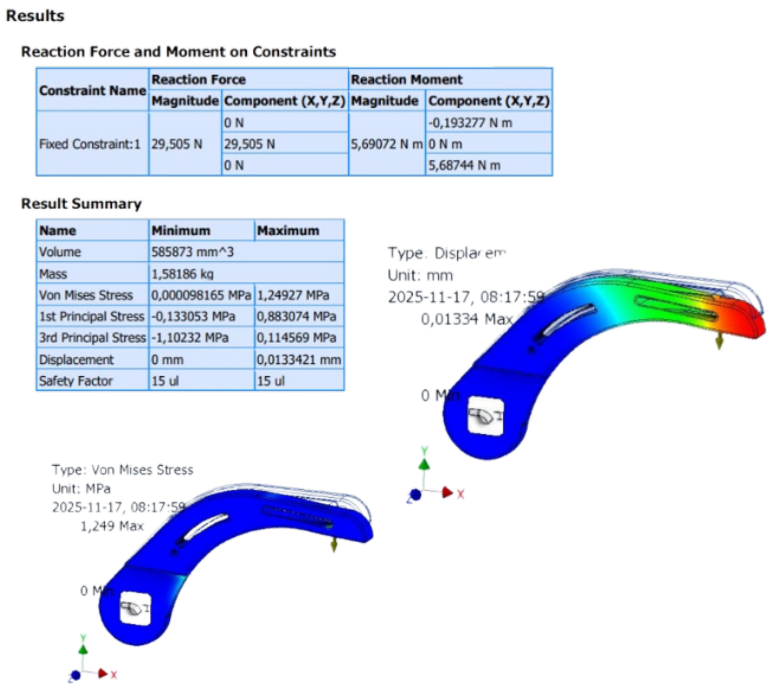
Result Summary

Name	Minimum	Maximum
Volume	333650 mm^3	
Mass	0,900855 kg	
Von Mises Stress	0,0000201551 MPa	0,937448 MPa
1st Principal Stress	-0,378585 MPa	1,12972 MPa
3rd Principal Stress	-1,14054 MPa	0,364067 MPa
Displacement	0 mm	0,000294557 mm
Safety Factor	15 ul	15 ul

Figure 7.8: FEA analysis of the mounting plate

7.3.3.2 Structural Analysis of the Catching Arm

The suction cups and suction base with a small suction pump are mounted onto the catching arm of the catching subsystem. Therefore, it needs to be strong enough to support the drone's weight during capture and the suction components while staying stable and precise. To verify if the arm can handle these forces safely, a quick structural analysis of one arm was performed, and the results obtained are shown in Figure 7.9. The maximum stresses were well below the material limit of Aluminium by a factor of 15, and displacement stayed extremely small. So structurally, the catching arm is safe, even during higher speed captures.



Results

Reaction Force and Moment on Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed Constraint:1	29,505 N	0 N	5,69072 N m	-0,193277 N m
		29,505 N		0 N m
		0 N		5,68744 N m

Result Summary

Name	Minimum	Maximum
Volume	585873 mm^3	
Mass	1,58186 kg	
Von Mises Stress	0,000098165 MPa	1,24927 MPa
1st Principal Stress	-0,133053 MPa	0,883074 MPa
3rd Principal Stress	-1,10232 MPa	0,114569 MPa
Displacement	0 mm	0,0133421 mm
Safety Factor	15 ul	15 ul

Figure 7.9: FEA analysis of the catching arm

7.4 Dynamic Modeling Theory for UAV Recovery

The dynamic model presented in this section describes how the alignment subsystem generates motion, how the catching subsystem responds, and how the entire system accelerates to align and catch an incoming fixed-wing UAV flying at up to 15 m/s.

7.4.1 Kinematic Modeling

The alignment subsystem converts motor rotation into movement of the catching subsystem. The subsystem uses eight pulleys, but only the two motor pulleys actually change the belt length. The rest are just idlers that guide the belt around the frame. This means the catching subsystem motion is determined entirely by how much belt the motors pull in or let out.

By rotating both motors at the bottom synchronously, motion along x is produced, and motion along y is produced by rotating them counterclockwise. For instance;

- Let the position of the catching subsystem be defined by its Cartesian coordinates (x, y).
- Let the two motors that drive the alignment subsystem, and their shaft angles are denoted by ϕ_1 and ϕ_2.
- Let the radius of the motor pulley be denoted by r.

. Hence, the geometric relationship between motor rotation and catching subsystem position is:

$$x = \frac{r}{2}(\phi_1 + \phi_2), \tag{7.1}$$

$$y = \frac{r}{2}(\phi_1 - \phi_2). \tag{7.2}$$

By differentiating the above expressions, the catching subsystem velocity is given as:

$$\dot{x} = \frac{r}{2}(\omega_1 + \omega_2) \tag{7.3}$$

$$\dot{y} = \frac{r}{2}(\omega_1 - \omega_2) \tag{7.4}$$

The angular velocity can be calculated from the speed n rpm of the motors.

$$\omega = \frac{2\pi n}{60} \tag{7.5}$$

Since the catching subsystem is driven by the tension in the belt, created by the motor torques, and its own weight, which is also subjected to gravity.

$$F_x = \frac{\tau_1 + \tau_2}{r}, \tag{7.6}$$

$$F_y = \frac{\tau_1 - \tau_2}{r} - Mg, \tag{7.7}$$

$$where \tag{7.8}$$

$$\tau = \frac{P}{\omega}. \tag{7.9}$$

7.4.2 Catching Subsystem Dynamics

Assuming the subsystem as a rigid body and neglecting rotor inertia for simplification, and by applying Newton's second law, the dynamics of the catching subsystem is as follows;

$$M\ddot{x} = \frac{\tau_1 + \tau_2}{r} = F_x, \tag{7.10}$$

$$M\ddot{y} = \frac{\tau_1 - \tau_2}{r} - Mg = F_y. \tag{7.11}$$

In instances when both mothers are either rotating clockwise or anticlockwise together, they produce the same torque, which simplifies the equations to;

$$a_x = \frac{2\tau}{rM}. \tag{7.12}$$

$$a_y = -g \tag{7.13}$$

<

8

Discussion

This chapter discusses the performance of the fixed-wing UAV recovery system concept by reflecting on the design process, highlighting the implications of the concept and future research.

8.1 Evaluation Against Research Questions

8.1.1 Research question 1

The first research question concerns how small fixed-wing UAVs are currently recovered and their limitations. From the literature review, it is clear that the current methods used today all come with trade-offs that limit their practicality. For example, the hook and cable-based recovery methods require extra components on the fixed-wing UAV, which adds weight and drag. Nets are simple, but they often damage propellers, which makes them not the best option. Bio-inspired mechanisms are too complex for small, lightweight fixed-wing UAVs. Control-based recovery mechanisms require high-end sensors and algorithms that are expensive and not always reliable in wind or poor visibility.

These findings showed that current recovery methods do not fully meet the needs of small fixed-wing UAVs without adding weight, complexity, or risk of damage. Hence, this gap motivated the development of the concept in this thesis, which offers a lightweight, low-cost, and mechanically simple recovery method that can safely capture a UAV without damaging or requiring any modifications.

8.1.2 Research question 2

The second research question examined mechanical principles and systems applied to catch and retrieve fixed-wing UAVs safely. This question was answered by developing a concept based on mechanical principles like momentum conservation, impulse control, and energy dissipation. The suction cup grippers in the catching subsystem and the foam cushion pad increase the duration of deceleration by deforming slightly when the UAV makes contact, which reduces the peak impact force acting on the UAV. The X-Y motion mechanism also ensures that the catching subsystem is aligned with the fixed-wing UAV's trajectory, hence minimizing the relative velocity at the moment of contact.

However, the performance of these mechanical principles in the design has not been verified in a full dynamic simulation. This was because the dynamic simulation environment in Autodesk Inventor could not support the level of contact modelling in the designed concept. While the kinematic simulation successfully verified that the X–Y motion mechanism can align the catching subsystem with the UAV's trajectory, confirming that the recovery system can minimize the relative velocity at the moment of contact.

8.1.3 Research question 3

The third research question focused on how the system could be designed to allow easy and efficient removal of the UAV after capture. This requirement was essential for SSRS, and it has been fulfilled in the developed concept with the suction ripper of the catching subsystem. Suction grippers automatically release the fixed-wing UAV once pressure equalizes, providing a quick, safe removal. In addition, the open frame structure of the catching subsystem offers clear operator access, unlike net-based systems, which require manual untangling and handling. Therefore, the developed concept significantly reduces turnaround time and risk of accidental damage.

8.1.4 Research question 4

The fourth research question also examines how the recovery system can be tailored to the size and structural characteristics of small fixed-wing UAVs. The catching subsystem in the designed recovery system concept can be used for UAVs with a wingspan between 0.8 and 1.5 m. It is optimized to hold the UAV once caught using the geometry of the arms and the spacing of the suction cup grippers.

Thus, all four research questions were addressed throughout the thesis through systematic design, mechanical reasoning, and performance evaluation.

8.2 Limitations of the designed concept

The designed recovery system presents several limitations that highlight areas where the design has not yet been fully validated. For example: The recovery system concept relies on the X–Y motion mechanism to position the catching subsystem accurately. The kinematic simulations revealed that the mechanism can align with the UAV, although real-world effects like belt stretch, wind, and friction were not included. These factors could influence positioning accuracy, thereby affecting the reliability of the system.

The choice of lightweight materials in the concept design is debatable, since no prototype was built to validate these material selections due to time constraints. As a result, the maximum UAV size or speed the system can safely handle is unclear. The concept design may perform well for the targeted 1 kg fixed-wing UAV, but it might be more sensitive to variations than expected.

The alignment and capture subsystems were designed in a simplified manner to keep the design easy to manufacture and cost-effective. Since dynamic stress analysis was not performed, it is difficult to determine where the stress points will be during the dynamic capture event. As a result, it becomes uncertain how these parts will behave during UAV capture or at high-speed UAV approaches.

The coastal environment is subject to wild winds, so how headwinds affect ground speed was not simulated, which affects the reliability of the recovery system. It is also possible for a Fixed-wing UAV to drift due to crosswinds, which requires the alignment system to make constant adjustments, increasing the wear on the subsystem.

8.3 Reflection on the Design process

The design process in the thesis influenced the final concept in several ways. For example, the requirements specifications developed from the customer needs were largely based on input from SSRS, which meant the needs were not compared against other companies, organizations, and UAV recovery standards. A broader investigation could have strengthened the foundation of the requirement specification.

During the concept selection phase, after the elimination matrix, similar concepts were merged into one, resulting in four concepts that were carried forward to the Pugh matrices. This led to more manageable concept screening, which also meant certain features of those concepts were lost.

The recovery system verification process mainly focused on evaluating the complete system rather than assessing the performance of each component. This could have provided clearer insights and reduced uncertainty in the later stages of the design process, which occurred during the dynamic simulation analysis. This was due to the Autodesk Inventor dynamic simulation environment not being able to support it. Another software called MSC Adams also supports this type of dynamic simulation. However, the assembly became distorted once imported into the software due to the number of interconnected parts, thereby making the dynamic simulation verification unsuccessful.

8.4 Future development recommendation

The concept UAV recovery system developed in this thesis is in its initial conceptual phase. It assumes precise and continuous tracking of the UAV since the detection subsystem wasn't part of this thesis. Therefore, exploring suitable sensor technologies and real-time UAV trajectory estimation methods would support bringing the concept closer to an operational solution.

Further development of the fixed-wing UAV recovery concept should also focus on validating the dynamic behaviour of the alignment subsystem. This should be carried out by using more advanced multi-body simulation environments that are capable of handling detailed contact interactions.

Moreover, future work should include building a full prototype of the fixed-wing UAV recovery and conducting experimental trials to evaluate its reliability and verify the assumed motion of the alignment subsystem.

Furthermore, future work should include a detailed cost analysis to assess each proposed material and manufacturing process in relation to SSRS's budget constraints. In addition, more FEA analysis on fatigue, durability, and alternative materials would help define the operational limits of the recovery system as well as increase its longevity.

Lastly, exploring the modularity of this UAV recovery concept could broaden its applicability to different UAV sizes. The recovery system could be further developed by exploring add-ons such as an integrated charging interface that recharges the UAV after its capture, thereby increasing its operational value.

9

Conclusion

This thesis set out to design a mechanical system capable of safely recovering small fixed-wing UAVs for SSRS. By following a systematic design process, a conceptual fixed UAV recovery system was developed. The system consists of an X-Y alignment subsystem and a catching subsystem.

As discussed in the previous chapter, the kinematic simulations confirmed that the alignment subsystem can position the catching subsystem quickly and accurately. This demonstrates the feasibility of the overall motion of the system, with the two motor rotations reliably producing the required X–Y translation. However, this remains conceptual and will need more detailed dynamic simulation analysis in future work.

Overall, this thesis provides a solid foundation for a new approach to how fixed-wing UAVs could be recovered. To move this concept closer to real-life application, future development should include building prototypes and integrating sensors. To conclude, this concept has the potential to become a practical and reliable method for recovering fixed-wing UAVs from maritime environments.

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A

Idea generation

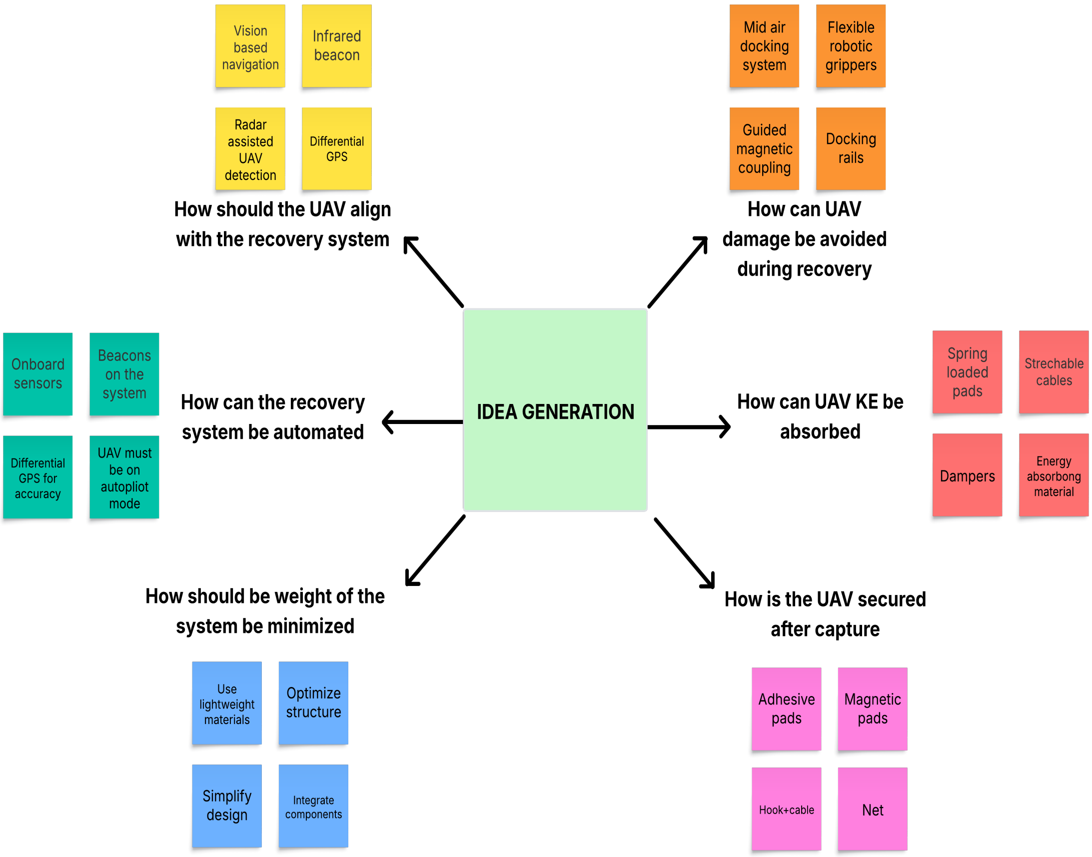


Figure A.1: Free idea generation

B

Concept Catalog

Table B.1: Concept Catalog

Solution Number	**Combination**
685	Robotic grippers , Docking system , Inflatable air cushions like Airbacks upon impact , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
686	Robotic grippers , Docking system , Caushioned grippers , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
687	Robotic grippers , UAV Falls on to a Net , Inflatable air cushions like Airbacks upon impact , Integrate Visionbased navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
688	Robotic grippers , UAV Falls on to a Net , Caushioned grippers , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
689	Robotic grippers , Magnetic pads , Inflatable air cushions like Airbacks upon impact , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact

Continued on next page

Table B.1 – continued from previous page

Solution Number	Combination
690	Robotic grippers , Magnetic pads , Caushioned grippers , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
691	Robotic grippers , Adhesive pads , Inflatable air cushions like Airbacks upon impact , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
692	Robotic grippers , Adhesive pads , Caushioned grippers , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
693	Rail with arms , Docking system , Inflatable air cushions like Airbacks upon impact , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
694	Rail with arms , Docking system , Caushioned grippers , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact
695	Rail with arms , UAV Falls on to a Net , Inflatable air cushions like Airbacks upon impact , Integrate Vision-based navigation system on to the UAV to detect the system , Docking pads or capture nets that move backward upon impact

C

Elimation Matrix

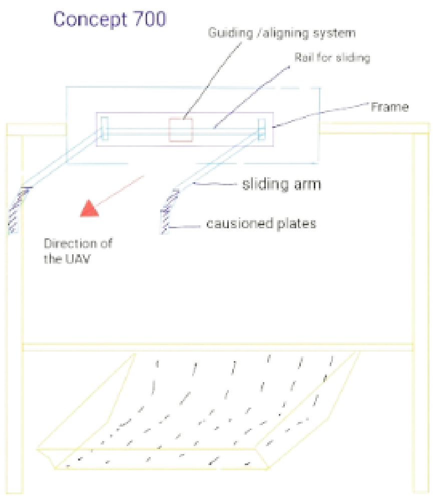
Table C.1: Elimation Matrix

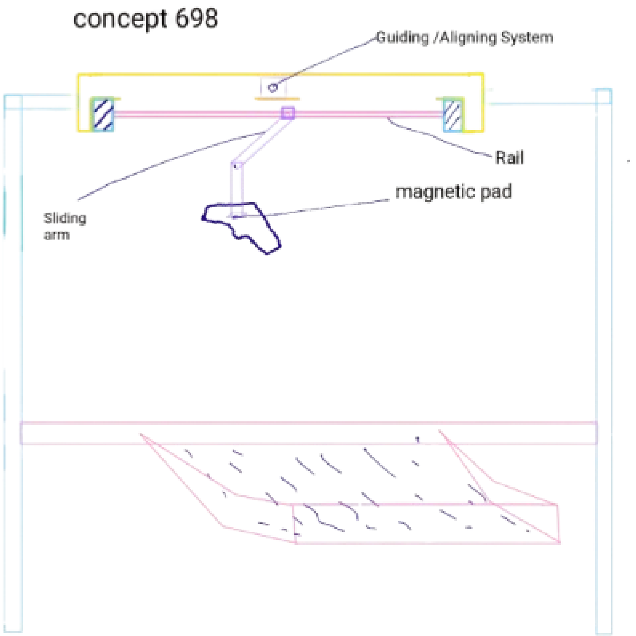
Chalmers	**Elimination Matrix**									
UAV Recovery system	Created: 15/06/2025 Modified: 26/05/2025									
Author: Abdulsamed	(+)Yes (-) No									(+) Keep solution (-) Eliminate solution
Solution number	**Elimination Criteria**								**Comments**	**DECISION**
	Can reliably capture the UAV in motion	Can hold the UAV after capture	Protects the UAV from impact	Allows precise positioning	Fulfils weight requirement	Suits company (post-capture)	Allows positional offset capture	Feasible to design/build/test		
685	+	+	+	+	+	+	+	+		(+)
686	+	+	+	+	+	+	+	+		(+)
687	+	-	+	+	+	+	+	+		(-)
688	+	-	+	+	+	+	+	+		(-)
689	+	+	+	+	+	+	+	+		(+)
690	+	+	-	+	+	+	+	+		(-)
691	+	+	-	+	+	+	+	+		(-)
692	+	+	+	+	+	+	+	+		(+)
693	+	-	+	+	+	+	+	+		(-)

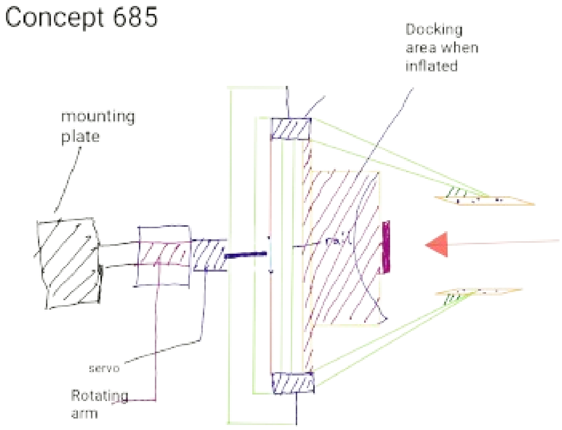
694	+	-	+	+	+	+	+	+		(-)
695	+	-	+	+	+	+	+	+		(-)
696	+	-	+	+	+	+	+	+		(-)
697	+	+	-	+	+	+	+	+		(-)
698	+	+	+	+	+	+	+	+		(+)
699	+	+	-	+	+	+	+	+		(-)
700	+	+	+	+	+	+	+	+		(+)
701	+	-	+	+	+	-	+	+		(-)
702	+	-	+	+	+	-	+	+		(-)
703	+	+	+	+	+	-	+	+		(-)
704	+	+	+	+	+	-	+	+		(-)
705	+	-	-	+	+	-	+	+		(-)
706	+	+	+	+	+	-	+	+		(-)

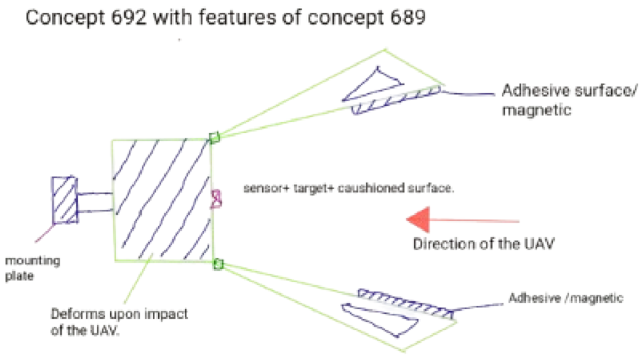
D

Concept sketches



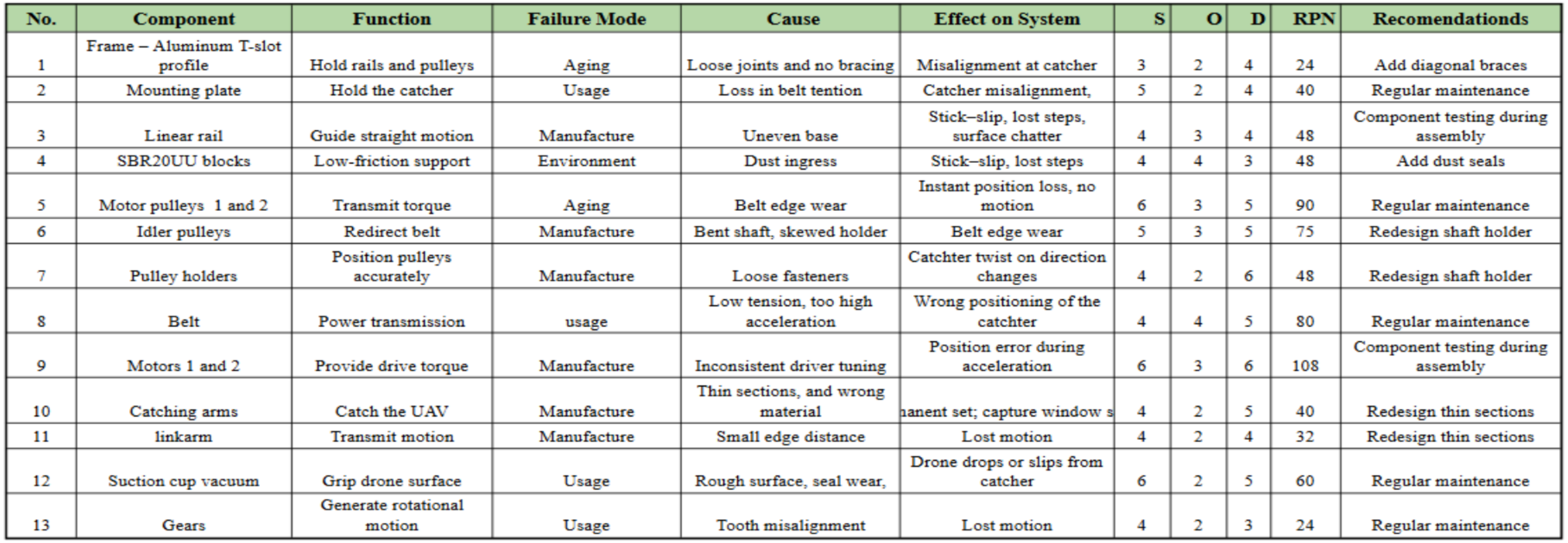






E

DFMEA

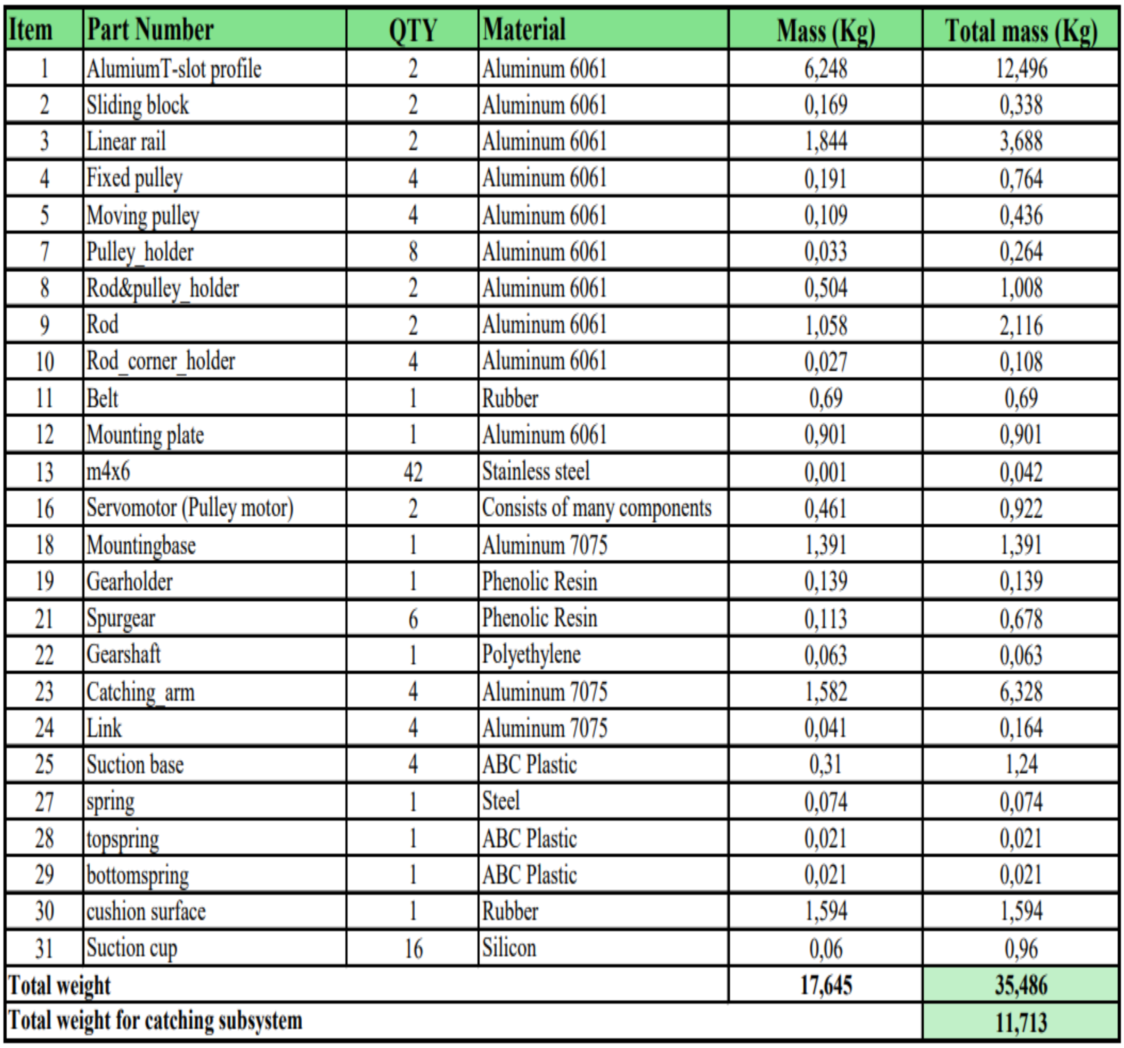


No.	Component	Function	Failure Mode	Cause	Effect on System	S	O	D	RPN	Recomendationds
1	Frame – Aluminum T-slot profile	Hold rails and pulleys	Aging	Loose joints and no bracing	Misalignment at catcher	3	2	4	24	Add diagonal braces
2	Mounting plate	Hold the catcher	Usage	Loss in belt tention	Catcher misalignment,	5	2	4	40	Regular maintenance
3	Linear rail	Guide straight motion	Manufacture	Uneven base	Stick–slip, lost steps, surface chatter	4	3	4	48	Component testing during assembly
4	SBR20UU blocks	Low-friction support	Environment	Dust ingress	Stick–slip, lost steps	4	4	3	48	Add dust seals
5	Motor pulleys 1 and 2	Transmit torque	Aging	Belt edge wear	Instant position loss, no motion	6	3	5	90	Regular maintenance
6	Idler pulleys	Redirect belt	Manufacture	Bent shaft, skewed holder	Belt edge wear	5	3	5	75	Redesign shaft holder
7	Pulley holders	Position pulleys accurately	Manufacture	Loose fasteners	Catchter twist on direction changes	4	2	6	48	Redesign shaft holder
8	Belt	Power transmission	usage	Low tension, too high acceleration	Wrong positioning of the catchter	4	4	5	80	Regular maintenance
9	Motors 1 and 2	Provide drive torque	Manufacture	Inconsistent driver tuning	Position error during acceleration	6	3	6	108	Component testing during assembly
10	Catching arms	Catch the UAV	Manufacture	Thin sections, and wrong material	anent set; capture window s	4	2	5	40	Redesign thin sections
11	linkarm	Transmit motion	Manufacture	Small edge distance	Lost motion	4	2	4	32	Redesign thin sections
12	Suction cup vacuum	Grip drone surface	Usage	Rough surface, seal wear,	Drone drops or slips from catcher	6	2	5	60	Regular maintenance
13	Gears	Generate rotational motion	Usage	Tooth misalignment	Lost motion	4	2	3	24	Regular maintenance

Figure E.1: DFMEA

F

BOM



Item	Part Number	QTY	Material	Mass (Kg)	Total mass (Kg)
1	AlumiumT-slot profile	2	Aluminum 6061	6,248	12,496
2	Sliding block	2	Aluminum 6061	0,169	0,338
3	Linear rail	2	Aluminum 6061	1,844	3,688
4	Fixed pulley	4	Aluminum 6061	0,191	0,764
5	Moving pulley	4	Aluminum 6061	0,109	0,436
7	Pulley_holder	8	Aluminum 6061	0,033	0,264
8	Rod&pulley_holder	2	Aluminum 6061	0,504	1,008
9	Rod	2	Aluminum 6061	1,058	2,116
10	Rod_corner_holder	4	Aluminum 6061	0,027	0,108
11	Belt	1	Rubber	0,69	0,69
12	Mounting plate	1	Aluminum 6061	0,901	0,901
13	m4x6	42	Stainless steel	0,001	0,042
16	Servomotor (Pulley motor)	2	Consists of many components	0,461	0,922
18	Mountingbase	1	Aluminum 7075	1,391	1,391
19	Gearholder	1	Phenolic Resin	0,139	0,139
21	Spurgear	6	Phenolic Resin	0,113	0,678
22	Gearshaft	1	Polyethylene	0,063	0,063
23	Catching_arm	4	Aluminum 7075	1,582	6,328
24	Link	4	Aluminum 7075	0,041	0,164
25	Suction base	4	ABC Plastic	0,31	1,24
27	spring	1	Steel	0,074	0,074
28	topspring	1	ABC Plastic	0,021	0,021
29	bottomspring	1	ABC Plastic	0,021	0,021
30	cushion surface	1	Rubber	1,594	1,594
31	Suction cup	16	Silicon	0,06	0,96
Total weight				**17,645**	**35,486**
Total weight for catching subsystem					**11,713**

Figure F.1: BOM

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