Design and Development of a UAV Recovery System for use on RAN Patrol Boats

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Since WW II unmanned aerial vehicles (UAV) have shown a steady increase into service and have proven their effectiveness in the battlefield, the UAV capability provides a vast number of services to a wide range of customers. The integration of a UAV into naval patrolling forces has infinite possibilities and could enhance the operational capability endlessly. A UAV will directly impact the roles and responsibilities of the patrol boat, hence enhancing the intelligence, surveillance and reconnaissance (ISR) capabilities within the Australian Defence Force (ADF). While the use of rotary wing UAV eliminates recovery problems the advantages of a fixed wing aircraft far out way the difficulties upon recovery. This thesis explores possible solutions in recovering a UAV onboard an Armidale Class Patrol Boat (ACPB). Firstly, through the use of various design processes a specific set of customer requirements were established and various benchmark systems were compared against them. Customer requirements were continually referred to during development; this ensures the final produce will fulfill their needs. After comparisons, three designs were selected for further development. Using spring modeling the designs were evaluated and the results produced demonstrated the relationship between two of the governing limitations of the recovery phase. The g limits of the UAV and the recovery distance available on the ACPB dictated if the system could provide a successful recovery. The results from the spring model determined that using the g limit specified by the designer, the UAV cannot be recovered in an appropriate distance without exceeding this structural limit. From these findings additional research was undertaken to evaluate the structural limits of the UAV and a significant assumption was made. It was assumed that due to the difference in direction of the force which dictates the g limits presented by the UAV designer and that produced during recovery, the UAV can withstand significant additional loading in the required direction. Using this assumption the development of a recovery system continued and a final design concept was selected. The recovery system developed is a horizontal arresting line system positioned at the bow of the vessel with hydraulic brakes and automatic recovery navigation system. Additional development of this thesis will result in a recovery system that can be integrated onboard the ACPB, successful enhancing its capabilities through the use of a ship based UAV system.

1 Aeronautical Engineering Thesis Project ZEIT 4500.
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I. Introduction

Unmanned aerial vehicles have proven their value in strategic reconnaissance and surveillance through many peacetime and operational roles. Whilst this has been a great advantage for the Australian Army, the Royal Australian Navy (RAN) is yet to fully employ the capability. This is due to the fact that the systems required to launch and recover a UAV on various classes of ships have yet to be developed. The development of these systems for a RAN patrol boat would greatly improve the reconnaissance and surveillance roles for the boats patrolling Australian waters that do not have direct access to conventional air assets (Cameron, 1995). For clarity throughout this report the term UAV will be defined as being a powered, aerial vehicle that does not carry human operators, while the term Unmanned Aerial System (UAS) will refer to the entire system including flight vehicle, ground control station, and launch and recovery equipment (Raymer, 2006).

A. Aim

The purpose of this thesis is to develop the requirements for a UAV recovery system for use on a RAN patrol boat. It is also a goal of this thesis to design several conceptual solutions and to evaluate these solutions against the requirements. Additionally it is a desirable objective to commence work on a preliminary design of the recovery system. The implementation of a UAS on patrol boats would enhance the RAN’s existing patrol boat capability by carrying out the same functions more efficiently and achieving additional advantages over current practices. The thesis objectives were reached by following the method of design based on Raymer’s (2006) methodology.

B. Scope

The aim of this report is to define the thesis, detail the work completed and justify the choices that have lead to the final design concept. This report will begin with a discussion on the platform which the UAV will be deployed and recovered on; the Armidale Class Patrol Boat (ACPB). Throughout this discussion the roles and responsibilities of the ACPB are explored, along with its existing capabilities. The UAV is then defined and examined based on a design proposed by a former ADFA@UNSW student. These studies demonstrate the advantages of merging these two assets. The report will also present the relevant research conducted and a set of benchmark systems were formed which were then compared against the requirements. All components of the UAS capability were investigated to determine any influential parameters that could affect the use of the capability. This includes the UAV and the launching system, both of which will be affected by the recovery system employed. From there a number of design concepts were chosen and evaluated more extensively. This report will analyze each of the chosen designs and present the calculated data on some basic aspects of the recovery phase. Taking into account a number of assumptions and data gathered a final design was constructed. The final stage of this report will present a preliminary design and recommendations for future work. The scope of this report is to present the relevant research, outline existing systems, to detail the work that has been completed, present a final design concept and recommend additional research.

C. Limitations

The restrictions that will limit the results and objectives achieved for this thesis are mostly based on time, money and resources. The time allocated for this project is ten months; this had a large influence on how much progress was made on some of the desirable objectives. The funds available for this thesis are also limited and any major expenses, such as field trips will be taken out of personal funds. Finally there are no experimental resources allocated to this thesis, which restricts the ability of testing.

D. Project Management

Before beginning this thesis the appropriate planning was completed. By outlining a plan for this thesis the objectives were detailed and methods for reviewing the progress were put in place. The project planning begins with the project specification which defines the project, details the essential and desirable objectives and outlines any funds or limitations that may restrict the thesis. An important factor in project specification is the completion date by which the thesis must be concluded. To make the project manageable it was broken down into smaller tasks which give measurable achievements along the way. These tasks are expanded into a detailed task breakdown structure which outlines what must be achieved in a certain time frame. Using this data a project schedule was formed, this helps to keep focused on the tasks at hand and gives a good indication of how much progress has been made on the project so far. While the thesis is broken into smaller jobs it was still important to make note of the significant milestones in a chart as a reminder of deadlines and future objectives. The final stage in project management was a risk analysis to determine any significant risks that may arise throughout the thesis. All the relevant data for project management can be found in Appendix A; this includes the project specification, project task outline, task breakdown structure, milestone chart, risk analysis and a Gantt chart.
E. Summary

This thesis aims to produce a conceptual design of a recovery system capable of being implemented onto the Armidale Class Patrol Boat. By developing the requirements involved in a shipboard UAV recovery it ensures that the conceptual design will fulfill the needs of each customer. Through the use of project management the thesis was completed on time, meeting all the outcomes outlined in the scope.

II. Background

A. Armidale Class Patrol Boat (ACPB)

The patrol boat plays a very important role in the protection of our shores. The Armidale class patrol boat is the most recent class of the patrol boat within the Royal Australian Navy. Replacing the Fremantle class, the Armidale patrol boat is a highly versatile vessel which is capable of conducting a wide variety of missions. The Armidale was further developed to improve performance capabilities including the ability to conduct surveillance and response boarding operations in Sea State 4 (wave heights of 2.5m) (Stevens, 2001). The ACPB also has an increased range, endurance and speed compared to the Fremantle class, allowing it to conduct 42 day missions and be capable of deployment to Christmas and Cocos Islands in Northern Australia (Welcome to the Armidale Class, 2006). In regards to equipment, the ACPB contains onboard surveillance and communications vital to its patrol and response capability. The system comprises of twin radar, a radar warning system and an electro-optical detection system for short range detection. (Welcome to the Armidale Class, 2006). There are also two Rigid Hulled Inflatable Boats (RHIB) situated at the stern of the vessel which can be deployed into the water within two minutes. These many capabilities are currently operated by the RAN via 21 crews containing 21 people each, with each crew rotating through 14 hulls (Ashworth, 2010).

During peacetime, some of the responsibilities of the ACPB include providing vital border protection against illegal fishing, people smuggling, drug and arms interdiction, along with Defence Force aid to civilian authorities and quarantine operations (Australian Navy Doctrine, 2010). All these operations occur inside the Australian maritime zones, which are represented by the shading in Fig 2. However majority of incursions into Australia's exclusive economic zone occur in the North. This is the reason there are 10 ACPB base at HMAS Coonawarra in Darwin and the remaining 4 are located at HMAS Cairns in North Queensland (Ashworth, 2001). The ACPB can also be deployed for overseas operational duties as it has the capacity to operate alongside large vessels and to provide maritime interception, intelligence and warning capabilities at a lower cost than larger vessels (Australian Navy Doctrine, 2010).

After examining the roles and responsibilities of the patrol boat it is quite easy to see the many benefits from having a UAV deployable from and recovered aboard an ACPB. Implementation of a UAS on board an ACPB will not only provide significant reach and intelligence, it will also reduce risks to boarding party personnel and decrease costs of using civilian or Royal Australian Air Force (RAAF) patrolling aircraft. The increased performance of the Armidale class patrol boat and the addition of a UAS onboard would greatly improve the roles and responsibilities of the patrol boat in the defence of our nation and its interests.

B. Unmanned Aerial Vehicle (UAV)

A UAV is an aircraft without a pilot on board. It can be remotely controlled or flown autonomously based on pre-programmed flight plans or more complex automation systems (McGonigle, 1992). The UAV is currently
deployed in a number of environments and provides many capabilities for military use. The concept of using an unmanned vehicle for tactical advantages is not a new one; it was first used in the American Civil War where the vehicle took the form of a balloon (Cameron, 1995). Over the years as technology has developed, the use of UAVs has vastly increased, as they have become more sophisticated and beneficial for surveillance and reconnaissance missions.

1. Role of the UAV
   
   As war is becoming extremely information based, the UAV is beginning to play a key role in all military operations. UAVs can provide information at or close to real-time without placing humans at risk. UAVs have been designed to cover a number of tasks including line of sight flights that last for several minutes in order to support ground troops, or flights that last for several days which require complex launch and recovery systems. Due to the vast range of missions UAVs are now constructed in various sizes and fulfill a multitude of roles depending on their configuration (Banks, 2000). Since each service requires different capabilities, UAVs can be grouped into the following categories; Micro, Tactical and Endurance (Banks, 2000). The roles of the UAV in each category also vary depending on its capabilities. This chapter outlines the various capabilities of a UAV and contributes to the justification of this thesis.

   UAVs are capable of fulfilling various missions which can be categorized as reconnaissance and surveillance missions or combat missions. Reconnaissance and surveillance missions can include reconnaissance and surveillance, target acquisition, designation and battle damage assessment (BDA), communications relay, communications and electrical intelligence and attack or chemical and biological warfare detection (Ashworth, 2001). The type of mission dictates the various supporting systems necessary to ensure its effectiveness.

   The sourcing of general information is defined as reconnaissance while surveillance is explained as the specific and systematic observation of a particular area or target. UAVs have been used for this purpose since their inception and prove to provide valuable information for both peacetime and operational situations.

   The role of target acquisition is an important tool when trying to detect, locate, track and identify targets of interest. This capability is vital for Navy patrol boats which depend on reliable intelligence to identify vessels and personnel in their maritime zones before boarding. A UAV can also be used for target designation in the situation of an air-attack to ensure a successful hit. Following this engagement the UAV can then provide necessary battle damage assessment to the mission commander (Bank, 2000).

   An important aspect of the UAV capability is the communications relay, which simply bridges the communication gap between a deployed force and the mission commander. This is especially relevant for naval forces that operate at large distances from the unit. A UAV can also be used to detect and identify an enemy’s emitter; this is a vital capability in gathering information of enemy location and activities. The UAV can also be used to jam emitters (Ashworth, 2001).

   Finally, the last non-combat role the UAV plays is chemical and biological warfare detection. This entails the UAV testing an operating environment for contaminants, which reduces the risk of any human pilot to be affected by chemical or biological warfare.

   Combat roles that the UAV plays include land strike, maritime strike and suppression of enemy air defence (SEAD). Both the land strike and maritime strike capabilities will entail the deployment of weapons from the UAV on both land and maritime enemy forces. The SEAD capability was first used by Israeli forces; it used a loitering UAV to detect emitters that then activate a homing device on the UAV forcing it to dive towards the target where a high explosive fragmentation warhead detonates. This capability is used in the vicinity of known air defence sites and eliminates manned aircrafts and drones (Ashworth, 2001).

   As explained above, the UAV is used in a variety of roles and can fulfill a number of responsibilities. These roles depend on the environment it is placed in, the service it is operated by and the size of the UAV. The RAN could easily use a UAV on a patrol boat for very specific roles which could greatly enhance the capabilities of the ACPB.

Advantages of UAVs (Cameron, 1995)

- Ability to operate in very high-risk areas with no risk to human life
- Reduced likelihood of injury or loss of life in the form of aircrew
- Relieves the demand for manned aircraft
- Can withstand long endurances without the effects of fatigued aircrew
- Withstand significantly more gravitational loading without a human pilot

Disadvantages (Banks, 2000)

- Combat survivability of the UAV remains the most significant limitation to its operational deployment.
- Financial aspect of procuring UAV
2. Design basis

One of the objectives of this thesis is to develop requirements for the recovery of a UAV onboard a RAN patrol boat. There are two components of a UAS that directly affect the limitations of the recovery phase; these components include the UAV and the launching device. A suitable UAV and launching system were selected before continuing with the development of customer requirements.

The recovery system was developed to be suitable for the SeaEagle, a UAV being developed by another UNSW@ADFA student, Lieutenant (LEUT) Rod Davis. There are a number of reasons for this decision including the advantages of fixed wing aircraft and the specific design requirements of the SeaEagle. Firstly, a fixed wing aircraft has significant advantages over rotary wing aircraft in regards to speed, endurance, efficiency and range and hence is more suitable for the patrolling of large seas (Raymer, 2006). Secondly, the development of the SeaEagle design was chosen for its related design requirements including being suitable for launch and recovery on an ACPB. The SeaEagle was designed to be operated by the RAN and specifically requires the ability to be launched and recovered onboard the ACPB. The specifications of the SeaEagle are an essential component in developing a successful recovery system. The SeaEagle design is very similar to a medium-range, long endurance Scan Eagle, designed by Boeing and the Insuit group. Figure 4 can be compared with the conceptual drawing in Figure 5 to demonstrate the similar configuration. While there are some minor variations in the configuration and performance of this design early design development of a recovery system was based off the Scan Eagle UAV while LEUT Davis was still completing his design. The Scan Eagle weighs approximately 20kg and has a wingspan of 3.04m, with a range of 100km from a ground control station (GCS). It is launched using a pneumatic wedge catapult launcher and flies a pre-programmed or operator initiated missions guided by its onboard flight-control systems (Boeing, 2010). For the later calculations the specifications of the SeaEagle were used, the specifications can be seen in table 1.

For the earlier stages of this thesis it was assumed that a catapult launching system will be used as the method of launching the UAV from the patrol boat. A launching system has also been designed alongside the development of the recovery system. Throughout the progression of this thesis constant consideration has been given to the launching designer and by monitoring the changes in the launching technique, a conflict between the two systems has been avoided. While at the beginning of this thesis a catapult launching system was assumed, a bungee cord launching device developed by Jack Francis is now considered the method of launching for the SeaEagle.
C. Summary

This chapter has outlined the purpose of this thesis by providing a background to the operational responsibilities of the Armidale Class Patrol Boat and the various functions of the UAV. Throughout this background it becomes clear why the ACPB was chosen as the vessel to integrate a recoverable UAV onto. It is also apparent now why a fixed wing aircraft is used and more specifically the Sea Scan and then the SeaEagle. A brief description was given as to how the UAV will be launched which is an important consideration to make when designing the recovery system. This chapter covers all the necessary background information needed to understand the importance of this thesis.

III. Literature Review

A. Benchmark Recovery Systems

Benchmarking is a tool used to ensure improvement on a design or concept; this is achieved through comparison with other designs or organizations that are recognized as the best within the area (Anderson, 1996). For the purpose of this thesis the benchmark systems were selected based on their performance, safety and practicality. Although it may seem that some existing systems cannot be employed on a RAN vessel, these systems have proven their success in other environments and can be considered for emergency landings or in addition to another system. The following benchmark systems have been selected as the most relevant and useful in a maritime environment and with development capable of being employed on a RAN ACPB.

1. Skyhook (Insuit, 2009)

This system is described best by Insitu’s business development director Erik Edsall when he claims, “The SkyHook in its original manifestation was a Genie Lift mechanism that you could buy from the local Home Depot” (Trimble, 2010). The simplicity of this system makes it low cost, practical, easy to maintain and even easier to modify for use on a patrol boat. The system includes a nylon rope, two Global Positioning Systems (GPS) on the boom and the UAV and a hooking device on the wing of the aircraft (Fig 6). Using the GPS algorithm the UAV would fly past and at a certain point yaw to allow the nylon rope to track down the wing and latch onto the hook.

Advantages (Insuit, 2009)
- Run-way independent captures
- Simple to use, maintain and set up
- No need for storage space
- Minimal changes to UAV, doesn’t interfere with launching
- Excess weight isn’t added to the UAV
- GPS system will increase capture rates regardless of weather

Disadvantages
- Permanent fixture to vessel
- Modifications must be made to the vessel
- Significant loads would be place on the wing structures and joints
- Permanent hook on UAV will affect the aerodynamics

Table 1. Specifications of the SeaEagle (Davis, 2010)

<table>
<thead>
<tr>
<th>Weight and Performance specifications of the SeaEagle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Weight Estimate Max Take-off</td>
</tr>
<tr>
<td>Max Velocity</td>
</tr>
<tr>
<td>Stall Velocity</td>
</tr>
<tr>
<td>Wing span</td>
</tr>
<tr>
<td>Absolute Ceiling</td>
</tr>
<tr>
<td>G loading limits</td>
</tr>
</tbody>
</table>

Figure 5. CATIA Drawing of the SeaEagle (Davis, 2010)

Figure 6. SkyHook System (Insuit, 2009)
This system has already proven its capability on a Singaporean naval vessel, by using the SkyHook system the UAV ScanEagle was recovered safely. This benchmark can be used to develop an improved recovery system, by taking the advantages and positive characteristics of this design and combining them with other designs and ideas.

2. **Arresting Line** (Watts, 2007)

This system is a similar concept to the SkyHook however instead of using a vertical nylon rope; the arresting line is a cable deployed horizontally above a beam (Fig 6). The UAV is equipped with a capture device which is positioned on the underneath of the fuselage close to the centre of gravity. This capture device is deployable from the fuselage of the UAV using a spring system which lowers the device before attempting a recovery. This reduces the aerodynamic affects of having a fixed hook. The system uses pulleys to ensure a safe recovery of the UAV when it latches into the cable. The arresting line system has been patented by a number of US engineering organisations.

**Advantages**
- Run-way independent
- Simple to use, set up and maintain
- Limited damage to the UAV
- Minimal modifications to UAV

**Disadvantages**
- Significant modifications to the vessel
- Permanent modifications to UAV
- Lacks guidance system

3. **SkyLark** (Lloyd, 2007)

SkyLark is a man-packed tactical UAS that employs inflatable pillows to reduce the impact of landing. This recovery system begins with a deep stall manoeuvre which triggers the inflation of the cushions. The UAS weighs 5.5 kg at take-off which is significantly smaller than both the Scan Eagle and the SeaEagle. The Skylark is successfully operated by the Australian Army in Iraq; however the concept could be adapted for use in the RAN.

**Advantages**
- Reduced impact
- Can be easily incorporated into another system
- Easy to store, set up and maintain

**Disadvantages**
- Increased weight on UAV
- Requires additional systems in UAV
- Uncontrollable landing, not practical for sole recovery system
- Major changes to UAV, could impact launching system

4. **Net** (Blending Wing UAV, 2007)

A NASA designed UAV uses a recovery net system for land based captures. The UAV is equipped with net hooks on the nose and the ends of the winglets that provide a three-point recovery to ensure that the vehicle doesn’t tumble out of the net upon impact. Being a pusher prop arrangement it also ensures that there is no damage to the propellers when the UAV comes into contact with the net. This UAV may look vastly different to the UAV design this thesis is based on, however they both have the same pusher prop configuration, making this system a viable method of recovery.

**Advantages**
- Simple design
- Minimal modifications to the UAV
- Large area of capture
- Increased success rate
- Less affected by movement of the vessel
Disadvantages
- Difficult to set up and pack up
- Large storage space
- Requires large deck space
- Possibility of damaging the UAV upon impact
- Difficult to retrieve UAV once captured

5. Sea Sled Landing (Labouchere, 2007)

This system involves a sled being lowered into the water and towed by the vessel awaiting the recovery of a sea plane UAV. The sea plane is flown past a link transversely until it is attached. After it has engaged with the link a winch draws the UAV inside the sled and the whole system is then recovered by the crew. Though this system usually uses a seaplane UAV the idea of a sled or additional floatation device away from the ship has possible advantages.

Advantages
- Provides additional space
- Larger target for the UAV operator

Disadvantages
- Possibility of sea water contamination
- Maintenance of UAV increase
- Cost of producing a sled/ tovable platform
- Drag on the vessel may affect performance
- If floats need to be fitted to UAV additional drag, weight, adverse effects to performance
- Storage of the float when not in use

6. Parachute and parafoil capture (Khantsis, S, 2006)

Parachute and parafoil capture techniques are quite difference however they involve the same basic principle of using a chute of some shape to decelerate the UAV before impact. The difference between the parachute and parafoil is the level of control and guidance that each offer. The drag-only parachutes, as seen in Figure 10, have a limited degree of control and are really only useful when a large landing area is available. The parafoil or gliding parachute consists of a rectangular or elliptical plan formed, two-skinned chute with an airfoil cross-section when it’s inflated with ram air (Fig 11). Control of the parafoil can be achieved by deforming the trailing edges, via pull-down brakes. The parafoil can be used in two different approaches when recovering a UAV. Firstly it can be the conventional chute attached to the UAV and deployed upon approach. The second approach is to use the parafoil to elevate a recovery system to be above the vessel when there is limited space onboard. There are disadvantages with the hassle of a chute and advantages for its simplicity, each will be assessed against the requirements.
Advantages
- No modifications to the vessel
- Simple recovery procedure
- Chutes are low cost
- Parafoil provides some control

Disadvantage
- Limited control
- Need to large landing space
- Unreliable landing position
- Impact of UAV upon landing
- Complex to pack away
- Maintenance of parachute/parafoil
- Possible damage upon impact

7. Ditch Landing
The final option is to ditch land the UAV in the water within a reasonable vicinity of the RAN vessel. This option has the advantage of being a simple solution, not requiring addition modifications to the vessel and minor modifications to the UAV. The limited training required to retrieve the UAV and water landings can be simpler for the UAV operator. However there are significant issues related to damage that the UAV may incur upon impact and long term. The impact of the water can be dangerous for the UAV especially if there is challenging weather or sea conditions. The affect of sea water to the UAV systems is also important to consider. The maintenance life of the UAV will decrease dramatically as it will require more attention to prevent corrosion and damage caused by the water. All the advantages and disadvantages have been considered and it is apparent that this system is too dangerous for the life of the UAV to be implemented as the sole recovery technique; however it is still possible to use this system as an emergency landing.

B. Summary
This chapter involves the research and gathering of all relevant benchmark systems. The concept of a benchmark system is defined and the advantages and disadvantages of each system are outlined. Although not all of these systems are specifically designed for a ship borne recovery the concepts can be used and modified to adapt to the ACPB. These benchmark systems are further evaluated in the following chapters.

IV. Conceptual Design

A. Conceptual Design Process
To achieve the objectives of this thesis a conceptual design method based on Daniel P. Raymer’s aircraft design process was used. The conceptual design phase is where the basic questions of configuration arrangement, sizing and weight, and performance are answered (Raymer, 2006). This process begins with a
specific set of requirements, which were gathered using the quality functional development technique, which is discussed in more detail below. Using these requirements a number of conceptual sketches were developed including rough sizing values and general configuration. From these concepts a preliminary design could be developed in more detail, continually referring back to customer requirements to ensure the design meets the customer’s needs. It is at this stage that the Raymer process becomes more specific for aircraft conceptual designs; however the basic principles can still be used. For example, after the development of the preliminary design all the major changes have be finalized and there are only small modifications to be made in order to optimize the design, it is important to draft a more detailed drawing of the design. Drawings detailing the basic configuration of the system were completed using Computer Aided Three-dimensional Interactive Application (CATIA) software. By following this process all the objectives of this thesis were achieved and the chance of a successful design is greatly increased.

B. Quality Functional Development (QFD)

A conceptual design begins with design requirements being established for the prospective customer or stakeholders. QFD is an excellent tool that can be used to establish and prioritize customer requirements. It provides a specific method for ensuring a design quality that is aimed at satisfying the customer needs (Vidosic, 1969). The purpose of this method is to establish necessary requirements and to translate them into technical solutions (Blanchard, 1998). By employing this method the customer requirements related to this thesis were established and analysed before the conceptual design process commenced. There are a number of stages in the QFD process to ensure that all the customers are considered and their requirements are ranked accordingly, these stages are explore in more detail below.

8. Identifying the Customers

This is the first stage of the QFD process which requires the designer to consider all stakeholders that are affected by the outcome of the final design. The customers identified as being affected by the outcome of this project are listed in Appendix C1. It is important that all the essential customer attributes be met otherwise the design will not fulfill the desired role. A description of each customer can be found in Appendix C, however for the evaluation of customer requirements all the customers are considered of equal importance.

9. Determining the Customer Requirements

A list of customer requirements was developed by conducting in depth discussion with each customer or their representative. Some of the major types of requirements to investigate are performance, appearance, time, cost, standards, safety, maintenance and repair, and impact of implementation. It is important to gain a thorough understanding of what each customer expects the design to be capable of before continuing with the process. Some of the requirements may be subjective, such as “easy to maintain”, this is why it is important to get a full understanding of what the customer wants before analyzing all the requirements. A list of customer requirements is presented in Appendix C2. As a result of steps one and two a problem understanding form can be generated. This is simply a table that contains the list of requirements against the customers identified. This form is developed throughout the process by adding information and comparing against the requirements.

10. Determining Relative Importance of the Requirements

This step involves ranking the requirements for each customer, this demonstrates which requirements are essential and those that are desirable. The essential requirements are marked with an asterisk and the desirable requirements are rank from one to ten, one being least important and ten being the most. This table only presents the different view of each customer as they have different rankings for different requirements; it does not assign a ranking to the requirements. The best way to achieve a ranking for the desirable requirements is to evaluate them in a pairwise comparison. Pairwise comparison is a method used to gain a relative ranking for a group of items, requirements in this case. Only the desirable requirements are placed in a table which can be seen in Appendix C3. They are then compared against each other and using a 1 or 0 to indicate which is the most important out of the two compared. This is repeated for the complete list of desirable requirements and then the total is calculated. The final calculated results give the relative ranking of the requirements. This can be checked by using Eq. 1 to calculate the total number of combinations and compare to the total in the table.

\[
\text{Number of Combinations} = \frac{N \times (N-1)}{2}
\]

Where N is the total of the ranking values

Using this method the most important desirable requirements were found to be ‘no significant modification to the UAV and vessel’ and ‘easily to integrate into service’. The least important desirable requirements presented from the pairwise comparison were ‘ease of storage’ and ‘the ease of set up’.

Initial Thesis Report 2010, SEIT, UNSW@ADFA
11. Competing Benchmarks

Step four involves researching the existing competing benchmark systems that are relevant to this design. When researching the benchmarks it is important to assess the strengths and weaknesses of each system and comment on what can be improved and what aspects will not be useful in this situation. I have chosen seven different benchmark designs that will be compared against the customer requirements to determine which is more suited to fulfill the customer needs. The comparison of benchmark systems and customer requirements can be seen in the problem understanding table in Appendix C4. A one to five scale was used to determine if the benchmark meets the requirement or not, one being the requirement is not met at all and five being it is fully met. This is a subjective approach and it is important to continually refer back to the customer for guidance.

When analyzing the table of data it is important to take notice of the rankings of each requirement and take special note of those benchmark systems that do not acceptably fulfill the essential or highly ranked desirable requirements. The systems that rated the highest using the problem understanding table are the SkyHook, the Arresting line and the net.

12. Generate Measurable Engineering Specifications

By using the data gathered on relevant benchmark systems and the specifications determined for the UAV design and the limitations of the ACPB, basic engineering specifications can be listed. These specifications were then added to the problem understanding table in Appendix C5. The engineering specifications range from cost of manufacture and implementation, to the number of crew required to operate the device, these targets must be measurable.

13. Relate Customer Requirements to Engineering Specifications

This step involves ranking the engineering specifications against the customer requirements using a one to five ranking system. One indicates a weak relationship where as five suggests a strong relationship. This demonstrates the requirements interaction with each specification. This data is presented in Appendix C6.

14. Identify relationship between Engineering Specifications

The relationship between each engineering specification was then examined. Using a one, three, nine or blank scale each specification was compared against the others, one representing a weak relation and nine showing a strong dependency, while the blank indicates no relationship at all. This demonstrates how each engineering specification is affected if some are cut to accommodate for others. This data is presented in Appendix C7.

15. Setting Engineering targets for the Design

The final step of the QFD process is setting realistic engineering targets for the design outcome. These values are based off the benchmark systems, while considering the customer requirements. They can be a specific value or a range of values. The development of engineering specifications began by using the specifications stated by LEUT Rod Davis in his initial thesis report for the UAV design. Several of the engineering specifications are design dependent and vary significantly with each benchmark system, hence only those that are independent of the design have been calculated so far. Firstly, by varying the time taken for the UAV to come to rest the varying deceleration speeds were calculated using Eq. 2, the recovery distances using Eq. 3, the braking forces required using Eq. 4 and the g loading experienced by the UAV using Eq. 5. The results can be seen in Appendix C8. By plotting the g-force experienced by the aircraft during deceleration against the recovery distance, the affects of the UAV g-limit of recovery distance were presented (Fig 8). This plot indicates that the g-limit of the UAV will dictate the minimum recovery distance possible. Based on engineering specifications of the SeaEagle, the positive g-loading limit occurs at 6 g. By using this value an initial minimum recovery distance was taken from the intersection if the red lines on Fig 8, resulting in a distance of approximately 6.7 m.

Additionally the impact velocity of the UAV and the takeoff weight were used to calculate the energy

![Figure 12. Graph demonstrating the g-limits of the UAV and Minimum Recovery Distance](image-url)
that must be absorbed by the recovery system (Eq. 3). By equating this to the spring equation below (Eq. 2), and using the approximate recovery distance, the systems spring constant was determine, this is presented in table 2. This value can be used in the structural design of the recovery system. All these calculations are assuming constant force and constant deceleration and the impact velocity are calculated using the stall speed of the UAV with an additional 10% safety factor.

\[ E_s = \frac{1}{2} k \times s^2 \]  
\text{Energy spring equation} \quad (2)

Where \( E_s \) is the mechanical energy absorbed by the recovery system [J], \( k \) is the stiffness of the recovery system [N/m], and \( s \) is the recovery distance [m].

\[ E_k = \frac{1}{2} m \times v_i^2 \]  
\text{Kinetic Energy} \quad (3)

Where \( E_k \) is the kinetic energy stored in the UAV [J], \( m \) is the take-off weight of the UAV [kg]; \( v_i \) is the impact velocity of the UAV [m/s].

\[ s = (v_i \times t) - \left( \frac{1}{2} \times d \times dt \right) \]  
\text{Recovery Distance} \quad (4)

Where \( s \) is the recovery distance [m], \( v_i \) is the impact velocity [m/s], \( t \) is the time taken to stop [s] and \( d \) is the deceleration \( [\text{m/s}^2] \).

\[ d = \frac{v_i - v_f}{t} \]  
\text{Deceleration} \quad (5)

Where \( d \) is the deceleration \( [\text{m/s}^2] \), \( v_i \) is the impact velocity, \( v_f \) is the final velocity \( [\text{m/s}] \) and \( t \) is the time [s].

The engineering targets presented in Table 2, are a result of consultation with customers and reviews of the benchmark systems. These targets are a basis for which all possible recovery designs will be measured against to determine their suitability. A number of targets were calculated using the process above and will be reviewed later in this document. The remaining targets are determined from limitations dictated by the UAV and the ACPB.

<table>
<thead>
<tr>
<th>Table 2. Engineering Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recover distance</td>
</tr>
<tr>
<td>Braking force required</td>
</tr>
<tr>
<td>Energy to absorb</td>
</tr>
<tr>
<td>Spring Constant</td>
</tr>
<tr>
<td>Crew required</td>
</tr>
<tr>
<td>Deceleration (min recovery distance)</td>
</tr>
<tr>
<td>Time to set up</td>
</tr>
<tr>
<td>Storage volume</td>
</tr>
<tr>
<td>Maintenance hours</td>
</tr>
<tr>
<td>UAV wing span</td>
</tr>
<tr>
<td>UAV capture speed</td>
</tr>
<tr>
<td>UAV weight</td>
</tr>
<tr>
<td>UAV g limits</td>
</tr>
<tr>
<td>Height of system</td>
</tr>
<tr>
<td>Length of system</td>
</tr>
</tbody>
</table>

Use of the QFD methodology ensures the “voice of the customer” is reflected in the ultimate design. This process provides the understanding of the customer requirements and forces them to be prioritized and compared against each other; this means each customer attribute can be satisfied with a technical solution (Blanchard, 1998).
C. Selection of Design Concepts

After researching benchmark systems they were compared against the requirements as previously stated. A scale of 1 to 5 was used to rank how much the system meets each requirement. The total ranking indicates how suitable the benchmark system is in regards to the customer requirements. The total rankings only varied slightly between the systems ranging from 44 to 49 out of 75. While this gives a good indication as to which system meets the most requirements and to what level, this comparison considers all the requirements equal. The second total in the problem understanding table in appendix C4, is a summary ranking of the essential requirements. This total demonstrates how much each system meets the essential requirements. These two totals were used to finalize three design concepts which will be further developed. Based on research of benchmark systems and evaluation against customer requirements the three systems selected for further analysis are the skyhook system, the horizontal arresting line and the net recovery. After completing the QFD phase it was decided that the best design solution would result from modifying benchmark systems to suit the customer requirements. No original designs were considered a suitable solution.

D. Summary

Using the conceptual design process outlined at the start of this chapter, the most suitable design concepts were selected for further development. The QFD process ensures that these systems can be developed into a successful recovery device that meets the customer’s needs. Throughout this process engineering specifications were developed and gathered to formulate quantitative limitations that the system must meet. These targets were developed alongside the design to ensure the specifications reflected to requirements of the customers. The three design concepts were further developed with constant consideration to the customer requirements.

V. Evaluation of Design Concepts

A. Introduction

The evaluation of design concepts is an important stage in ensuring that the final product is an effective system suited all the customers. The engineering specifications developed at the start of this thesis must be analyzed more thoroughly. Since these specifications were intended to represent all the systems they are significantly inaccurate and a number of aspects must be reanalyzed. The important factors that greatly affect the safety and practicality of the recovery system include the recovery distance and the deceleration experienced by the UAV during recovery. This section will outline the numerical data that has been calculated to ensure the systems chosen can function safely on an ACPB with minimum risk to the UAV.

B. Non-Constant Deceleration

The engineering specifications calculated previously assume constant force and hence constant deceleration. This produced inaccurate results which are only useful for the early conceptual stages. Due to the nature of the three recovery systems chosen it is clear that the force is not constant over a period of time. As the UAV makes contact with the recovery system the deceleration will vary depending on the braking system used. By removing the constant force assumption the time dependent kinematics equations used to produce the initial engineering specifications are no longer valid. Using spring models more accurate estimations were calculated.

C. Modeling Conceptual Designs

The most appropriate method of achieving accurate estimations of the forces being placed on the UAV is to produce a mathematical model. The model developed to represent the system should produce accurate results, while remaining as simple as possible. A number of different models were considered including, friction, viscous and spring. While the frictional and viscous model would most accurately represent the skyhook system and the horizontal arresting line, the complex calculations were not justified for the approximations that are required for the conceptual design stages. A spring model was decided to be the most appropriate solution to achieve the estimations that were required. First a basic spring model was developed which can be seen in Figure 13. This was used as a validation technique to compare against the second model and ensure the results were acceptable. The second model best represents both the arresting line systems (Fig 14). The net recovery system could be represented by a three dimensional version of model 2, which could be simulated in various computer software such as MatLab and Ansys. After consulting numerous academic staff it was apparent that a simulation of the net recovery system would be extremely complex and time consuming. Therefore due to the time limitations of this thesis and the nature of conceptual designs it is assumed that the spring net recovery system can be represented accurately enough by model 2.
16. Single Spring Model

Model one uses the spring force equation seen in Eq. (7), along with Newton’s second law of motion seen in Eq. (8), to calculate the distance it would take for the object to come to rest (recovery distance). As demonstrated in Fig 13, the force produced by the UAV causes the spring to compresses and the equal and opposite force is calculated using the spring force equation. Using a time step of 0.5 milliseconds the spring force, deceleration, velocity and recovery distance were calculated once each during recovery. The use of a small time step increases the accuracy of the calculated data. The numerical calculations can be seen in appendix D1, and plots of this data can be seen in the results chapter below. The objective of these calculations was to observe the deceleration that the UAV would experience and the corresponding recovery distance. The deceleration was measured in gravitational loading in order to directly compare against the UAV g limits. Both the g limits of the UAV and recovery distance are two limitations that cannot be changed and must be met for a successful recovery. The UAV g limit is set by the designer and has adverse structural implications if it is exceeded. Additionally the recovery distance of the system is set by the space available on the ACPB, if this is exceeded the recovery may not be successful. In order to produce a comprehensive graph of recovery distance compared to deceleration the spring constant \( k \) was varied. By varying the spring constant the deceleration and recovery distance is directly affected. Since the force of the UAV and the corresponding spring force remains constant by increasing the spring constant the recovery distance must decrease. However as the spring constant increases the deceleration increases and so does the g loading experienced by the UAV. The results from using a simple spring model highlight the relationship between recovery distance, deceleration and the spring constant. These relationships can be expected when using a double spring model and the results of model one can be used to validate the trends seen in model 2.

\[
F = k \times x \quad \text{Spring Force} \tag{7}
\]

Where \( F \) is the spring force produced by the spring [N], \( k \) is the spring constant [N/m] and \( x \) is the displacement due to the compression of the spring [m].

\[
F = m \times a \quad \text{Newton’s Second Law of Motion} \tag{8}
\]

Where \( F \) is the force produced by the UAV, \( m \) is the mass of the UAV [kg] and \( a \) is the acceleration of the UAV.

17. Double Spring and Wire Model

Model 2 consists of two springs attached to a wire. It is assumed for the purpose of this model that the UAV will hook onto the centre of the wire, this is obviously a simplification of the true system, however it is a valid assumption for the results needed. As the UAV is hooked onto the wire there is a reaction force produced by the system onto the UAV which contributes to the deceleration, this is represented by the arrow in Fig 14. By using trigonometry and the spring force equation derivations were created to calculate the extension of the springs from their initial horizontal condition, a trigonometric diagram can be seen in Fig 15. The spring force for each spring was then calculated and resolved into the total force \( F_T \) which is represented by the arrow in Fig 14. A time step of 0.01 was used to gain an accurate representation of how the system would react to the capture of the UAV. The length of the wire between the two springs is 3 meters, this ensures that the wing span of the UAV will comfortably fit within the supporting structure. In order to produce a appropriate graph that clearly demonstrates the relationship between the deceleration and recovery distance the spring constant was varied. By increasing the spring constant the recovery distance necessary to bring the UAV to a stop is reduced, however the force required to stop it is increased, hence the g loading on the UAV is also increased. The spring constant was varied between 50 N/m to 200 N/m. Based on arresting lines used to stop carrier jets the expected spring
constant for a UAV recovery system would be within this range (Ahn, 2005). Reflecting back to the engineering
targets calculated earlier suggests that a spring constant of over 350 N/m is required to decelerate the UAV.
However, due to the constant decleration assumption used these calculations are inaccurate and further research
was conducted. The spring constant used when arresting a carrier jet was scaled down to accomodate the
significant reduction in weight and velocity of a UAV. Using an excel spreadsheet which can be seen in
appendix D3, the spring constant was easily varied. After the spring constant was set the maximum
displacement was selected which corresponds to the minimum recovery distance required to safely recover the
UAV onboard the ACPB. Since a spring model was used it is expected that the results would show a spring
back and additional oscillations due to the nature of a spring. This is demonstrated by the curve in Fig 16. After
the spring reaches maximum extension it is pulled back and begins to oscillate. Due to the lack of a damping
system the oscillations will continue indefinitely, the true recovery system will have a braking system that will
dampen the oscillations and the UAV will come to a stop. Hence it was important to identify the initial stopping
point of the UAV, which occurs at the first maximum displacement. When the spring constant is varied so does
the recovery distances. The corresponding recovery distances and g loading were identified for each spring
constant and used to produce a comprehensive graph.

![Figure 14. Representation of Model 2](image1)

![Figure 15. Trigonometric diagram for model 2](image2)

![Figure 16. Graph demonstrating the movement of the spring model with time.](image3)
D. Results

Using the spring model there were a number of graphs produced, each graph giving a different perspective about how the UAV and recovery system will interact. The most important plot produced is one that demonstrates the relationship between deceleration and recovery distance. The two limitations that dictate the recovery distance and the deceleration force are the space available on board an ACPB and the g loading limits of the UAV respectively. While all three of the recovery systems can be placed over the side of the vessel the length and height of the ACPB limit the recovery distance. The second limitation is the g limits on the structure of the UAV. As stated in the initial calculations the g limits of the SeaEagle are +6 to -3g. These g limits are used to restrict the gravitational force experienced during maneuvers and the vertical movement of the wings, however these limits are being used for the purpose of these calculations and considerations will be discussed later in this chapter.

18. Results for Single Spring Model

The first graph presents the results calculate for the single spring; this can be seen in Fig 17. The graph shows how the recovery distance increases as the g loading decreases. This result was expected after using the spring force equation, which dictates that should spring constant k increase, displacement x must decrease to achieve the same force. There are two data labels on the graph that help identify important minimums. The first data point is the minimum deceleration that the UAV will experience in the spring constant range that was applied. This is a minimum g loading of -3.72 g, which corresponds with a recovery distance of approximately 22 meters. The second data point indicates the minimum recovery distance that is possible with in the spring constant range. The minimum recovery distance is 10.95 meters and corresponds with a g loading of approximately -7.4 g. The results of this model indicate that the minimum recovery distance possible in this range of spring constants is 11 meters, however to avoid exceeding the g limit the recovery distance must be greater than 22 meters. This is clearly an unacceptable distance when considering the dimensions of the ACPB and the structural limits of the SeaEagle. However this model was only produced to ensure the results of model two can be validated.

19. Results for the Double Spring and Wire Model

The results of this model will be used to determine if the conceptual designs chosen are acceptable to be implemented onto an ACPB and can successfully recovery the SeaEagle UAV. The results for model 2 were compared to model 1 to ensure the model and calculations are accurate. The same limitations are placed on model 2 including the g loadings from the UAV and the space available on the ACPB. The results of this model are particularly important as they represent the three recovery systems chosen. The results were plotted in a graph using the same method as model one with a larger range of spring constants; this can be seen in Fig 18. The spring constant for model 2 was ranged from 10N/m to 100N/m; this provides a graph that can be directly compared against the plots for model 1. The graph presenting the model 2 results includes data points, a trend line and a red g limit line that indicated the -3 g limit of the SeaEagle. Firstly the data points indicate the minimum g loading and recovery distance achievable for the spring constant range used. The g loading at a recovery distance of 22 meters is approximately -2 g, this is a significant decrease compared to the -3.7 in model one. This reduction was expected due to the configuration of two springs in relation to the UAV, when the total force is resolved it becomes less than the spring force for model 1. The minimum distance calculated in the range of spring constants is approximately 6 meters, though this is much smaller than model 1 it is still too large for this system to be implemented onboard a ACPB. A 6th order polynomial was used as a trend line in order to simulate the results from larger spring constants. This indicates that a g loading of at least -14 g is required to achieve a recovery distance below 5 meters. These results indicate that it is not possible to recovery the UAV in a reasonable distance without exceeding its’ g limits. Based on these results alone the recovery system cannot be any of the three concepts chosen, or any other concepts that involves deceleration beyond the limits of the UAV. Due to the space limitations of the ACPB and the requirements of the customers none of the benchmark systems were considered suitable for a recovery system. The only solution to this problem would be to develop a stronger and lighter UAV that can withstand the additional loadings or implement this system onboard a different vessel. Since neither of these solutions is viable further research was conducted into the g limits place on the UAV, this research is presented below.
Figure 17. Graph demonstrating the relationship between g loading and recovery distance for model 1

Deceleration vs Recovery Distance, varying spring constant. (Model 1)

Deceleration vs Recovery Distance varying spring constant. (Model 2)

Figure 18. Graph demonstrating the relationship between the g loading and recovery distance for model 2
20. Short Transverse Stresses on a Wing

From the results above it has been concluded that for the systems to be feasible one of the limiting factors must be changed. Since the physical dimensions of the ACPB cannot be changed, the g limits on the UAV were investigated. These limits were dictated by the designer to prevent structural failure or fatigue of the UAV, while still enabling it to perform to the customers’ requirements. The design loads for various structural components are usually determined through complex analysis of three different categories; airloads, ground loads and miscellaneous (Niu, 1999). While each of these categories contribute to the external loads experienced by the aircraft the airloads due to high-g maneuvering are most relevant to this thesis. As you can see in Fig 19 a wing is made up of spars and springers running spanwise and ribs and formers running chordwise. The spars are the principle structural member of the internal structure of a wing, they support all distributed loads as well as concentrated weights (Raymer, 2006). During flight loads are first imposed on the skin which transfers the load to the ribs and then the spars (Megson, 2007). The loading during the recovery phase will be centralized at the attachment on the hooking device; however the rapid deceleration will result in additional loads throughout the entire airframe.

The SeaEagle has g limits set to ensure a certain turn performance. This means the g loading set by the UAV designer is a limit in the vertical direction to ensure the wing can withstand the generation of lift during high g maneuvers (Raymer, 2006). When a wing experiences a gust or conducts a maneuvered a moment is created where the wing is connected to the fuselage. This moment is a result of the upwards force created by the additional lift. This moment can be calculated using the distance to the centroid of the spar (c), its second
moment of inertia \((I)\) and the yield stress of the material which the spar is made from \((\sigma_y)\) (Eq. 9). Using the yield stress of the material ensures that the bending won’t cause permanent deformation of the spar (Riley, 2002). The second moment of inertia for a rectangle is expressed first in the \(x\) direction (Eq. 10) and then in the \(y\) direction in (Eq. 11). Using the convention indicated in Fig 21 it can be seen that the \(x\) direction and \(y\) direction correlates to the lateral axis and longitudinal direction respectively.

\[
M = \frac{I}{c} \sigma_y \quad (9)
\]

Where \(M\) is the moment [N/m], \(c\) is the distance to the centroid [m], \(I\) is the second moment of inertia \([m^4]\) and \(\sigma_y\) is the maximum absolute value of stress [MPa].

\[
I_x = \frac{bh^3}{3} \quad (10)
\]

\[
I_y = \frac{b^3h}{3} \quad (11)
\]

Where \(I_x\) and \(I_y\) are the second moment of inertia in the \(x\) direction and \(y\) direction respectively \([m^4]\), \(b\) is the distance of the spar from root to tip [m] and \(h\) is the length of the chord of the airfoil [m].

Throughout the recovery phase the entire wing will be experiencing a \(g\) force in the longitudinal direction. Figure 21 demonstrates the axis system of a conventional aircraft. A load in the longitudinal direction will create a short transverse load on the spars in the wing structure of the UAV (Niu, 1999). The rapid deceleration will try to pull the wing back in the longitudinal direction towards the tail, creating another moment about the connection at the fuselage. This moment can be calculated using the same principles as the moment created by transverse loads. Since the load is now in the longitudinal direction the second moment of inertia is larger than in the axial direction. As a result the moment at the fuselage connection is less for a short transverse load than an axial transverse load. Due to the differences in directional loading upon the wing it is assumed that the \(g\) limits in the vertical direction should be significantly greater than the \(g\) limits in the longitudinal direction. In conclusion, it is assumed that the UAV can withstand greater \(g\) forces during the recovery phase compared to \(g\) high maneuvering which the initial limits are based off. This assumption can be further proven through experimental tests.

21. Scaling Factor

When a design is based off a larger scale benchmark system that system can easily be scaled down to accommodate the design. Majority of the structural members can be manufactured to a smaller scale and the structural integrity of these components is simply scaled to compensate. However there are a number of components in a UAV that cannot be scaled by the same amount due to the impractically of fabricating them. These components include the thickness of the skin and the size of the fasteners. Additionally the lack of lightening holes affects the allowable load limits of the UAV.

While the length and width of components can easily be scaled, the thickness becomes more difficult. The thickness it is significantly smaller then the structural members it is placed over and as a result it becomes impractical to scale to the same extent or even at all. If the skin was to be scaled down to the same extent the manufacturing process would become extremely complex and the risk of tearing the skin would increase significantly. Since scaling the skin down would make it unworkable the thickness of the skin is commonly unchanged or scaled down less than other components of the design. If the thickness of the skin is unchanged than the cross sectional area is unchanged. Since the allowable stress and strain of the skin is directly related to the cross sectional area, it is concluded that the allowable loads that the skin can withstand are increased.

The size of a fastener is chosen based on the aviation standard for each connection. While there is a large range of fasteners used in the aviation industry there is a limited range of sizes. It is common practice when scaling a design that the fastener remains constant to make the fabrication process simpler and cheaper. Scaled fasteners are not commonly used and the manufacturing costs of producing scaled fasteners are greater than using an oversized fastener. Since fasteners are not commonly scaled down the structural limits of connections are increased hence they can withstand additional loading.

While lightening holes in piloted aircraft reduce unnecessary weight in the wing, the need for them in a UAV is less important. After a structural member has been scaled down it becomes impractical to include
lengthening holes to reduce an insignificant amount of weight. By not creating lightening holes in the wings the members are structurally stronger and able to withstand greater loads.

Although the SeaEagle has used a number of UAV benchmarks; piloted aircraft have also influenced the design. After considering the scaling factors above it has been assumed that the structural limits of the aircraft should be greater than what has been defined by the designer. Using this assumption the horizontal arresting line recovery system will provide a safe and reliable recovery for the SeaEagle. This assumption can be further proven through experimental tests of the UAV, however due to time constraints sufficient testing could not be completed.

E. Summary

The evaluation of the three recovery systems produced a variety of results and further considerations that were not taken into account at the beginning of this thesis. Firstly, by removing the assumption of constant deceleration the engineering targets required recalculating using a spring model. By selecting the double spring model it could be used for all three systems. The data presented in this chapter demonstrated the relationship between the g loading on the UAV and the recovery distance required for it to stop. These results indicated that the UAV cannot be recovered in a suitable distance without exceeding its structural g limits. Additional considerations were then presented to justify further development of this thesis. The direction of the stresses was evaluated, along with the direction of the g limit defined by the UAV designer. This evaluation highlighted the additional strength of the UAV and presents the assumption that when being recovered the SeaEagle can withstand a higher g loading. Additionally a scaling factor was discussed that also indicates that the UAV will be able to handle greater g loading. Using these results and assumptions presented in this chapter a final design concept can be selected and further developed.

VI. Design Summary

A. Design Description

The final design concept chosen involves a horizontal arresting line attached to a moveable horizontal structure. The arresting line is fixed to a hydraulic braking system that allows the arresting line to lengthen upon the capture of the UAV and gradually decelerates to a stop at an appropriate distance. This design is based off a benchmark system; however it includes a number of modifications to allow it to perform most effectively on the ACPB. Modifications include the installation of a braking system, specific sizing to accommodate the SeaEagle and the use of an automatic recovery navigational system to ensure a safe recovery. Each of these components will be discussed in more detail below. The conceptual design was also developed into the beginnings of a preliminary design by fixing the basic dimensions and configuration of the system. The preliminary design can be seen in the computer generated drawings below (Fig 26).

1. Navigation System

The SeaEagle is equipped with a Piccolo’s ground station which supplies differential GPS corrections to the avionics of the UAV providing a bridge between the UAV and the operator (Davis, 2010). As you can see in Fig. 22, this system is packed into a hard cover suitcase which can be easily integrated onto an ACPB. While the UAV has a guidance system an additional GPS system incorporated into the recovery phase to ensure a safe and reliable recovery regardless of sea states and weather conditions. A conventional GPS system uses radio signals from several satellites orbiting the Earth to calculate positioning. To achieve a higher accuracy window a differential GPS mode must be used which requires a ground-based station. Due to the patrolling nature of the ACPB a ground-station is not always available and hence the differential mode of the GPS system cannot be used. Though there are methods of compensating for the lack of this station they are to complex and costly to be considered for this thesis.

Alternatively, a UAV common automatic recovery system (UCARS) can be used instead. Sierra Nevada Corporation developed the UCARS specifically for rotary and fixed wing UAV recovery, land based and shipboard (UAV Common Automatic Recovery System, 2006). This system is very similar to the Transponder Landing System used for conventional piloted aircraft which provides glide path information and is the precursor of the Tactical Automatic Landing System used by the US Army’s Shadow 200 UAV (Shadow 200 Tactical UAV System, 2006). The UCARS consists of two separate devices, one 1.5 kg airborne transponder and a ground subsystem. The ground subsystem will be placed on the recovery beam and
using millimeter-wave radar it can automatically locate and track the transponder. This radar platform can also sense the motion of the vessel and compensate without the use of a GPS signal. Though this system does require a separate device to be installed into the UAV and which will increase the weight by 1.5 kg, I recommend that this device be used to ensure maximum safety and reliability for the recovery of the SeaEagle.

2. **Braking System**

There are a number of techniques used to decelerate aircraft with arresting lines. The majority of these systems are commonly used for carrier jet recovery however they can be modified to recovery a UAV. Three different braking systems have been research and evaluated to determine the most appropriate for safely stopping the SeaEagle UAV.

The first system consists of a hydraulic cylinder attached to a piston and further attached to a wire cable that runs along the deck of a carrier or in between two support structures in the case of a UAV recovery device. When the aircraft arresting hook snags the cable, the wire pulls a piston within a fluid-filled chamber. The fluid is forced through a set of small holes in the end of the cylinder, thus absorbing the energy of the aircraft and resulting in deceleration (Pike, 2010). Figure 23, represents a traditional configuration of a simple hydraulic braking system on a carrier. This image demonstrate the large storage area that is required to operate this system, however due to the reduced speed and weight of a UAV the system can be reduced to better accommodate the available space.

There is a new technology coming into the market called the advanced arresting gear (AAG) which involves the use of an electric motor to replace the hydraulic system. The AAG replaces the mechanical hydraulic system with rotary engines which uses simple energy-absorbing water turbines coupled to a large induction motor (Tabour, 2010). The induction motor is used to control the arresting forces to ensure a smooth, safe recovery. This new technology allows the arrestment of a large range of aircraft, while reducing the manning and maintenance costs. By replacing the hydraulic system with the AAG system it reduces the hazards of using hydraulic fluid or oil in the braking system (Tabour, 2010). The AAG system was proven to be a successful design after prototype testing. Though this system provides a number of advantages over the traditional hydraulic system, as seen in Fig 25 there are too many components to store on the ACPB. Due to the number of components scaling them will still require a significantly larger storage space to the scaled hydraulic system.

![Figure 23. Typical Carrier Hydraulic Arresting System](Pike, 2010)

![Figure 24. ESCO’s Low Profile Friction Brake](ESCO, 2008)

![Figure 25. The numerous components that make up the AAG system](Tabor, 2010)
The final possible braking system is the low profile arresting gear designed by Engineered Arresting System Corporation (ESCO). This system uses an electronically controlled friction brake energy absorbers which allow for a variety of aircraft at different weight and engaging speeds. This system is designed for hook cables or net barrier recovery systems to arrest piloted aircraft (ESCO, 2008). As you can seen in Fig 24, this compact system eliminates the need for large foundations making it ideal for the limited space available on the ACPB. However, there is limited information available on this system and additional research must be conducted before deciding if its suitable for a UAV recovery.

As the development of a braking system is outside of the scope of this thesis it is recommended that further research is conducted before selecting a system. Additional research into all three of the systems listed will determine if they can be modified to safely arrest the SeaEagle.

3. **CATIA Modeling of Preliminary Design**

Using a computer aided drawing software called CATIA the first preliminary drawing was created CATIA is a computer aided three-dimensional interactive application used to present components or assembled products. Figure 26 demonstrates the basic configuration and size of the final design concept. The supporting beam is 4 meters long, with a triangular pattern to increase strength, an engineering drawing can be found in appendix E2. The wire is positioned along the top of the beam and using smaller slotted rollers called sheaves, is fed up into the capture area and across to the second supporting structure, and back along the top of the beam. Figure 27 shows a more detailed view of the sheaves which ensures the smooth movement of the wire. With further development of this design the wire should be connected to the braking system at the rotating base. The joints and connections of the supporting structure should be developed further.

![Figure 26. CATIA representation of the configuration of the final design](image_url)

![Figure 27. CATIA representation of the sheaves on the horizontal arresting recovery design](image_url)
4. Positioning on the ACPB

The position of the recovery system is a vital factor in ensuring a successful recovery. It is important not to interfere with the function of the ACPB. Taking this into consideration it is recommended that the recovery device be placed at the very tip of the bow. Positioning the recovery system here will allow a range of movement that will allow the UAV to be recovered regardless of the wind direction and without the vessel needing to change course to compensate. As you can see in Fig 28, the arresting beam design allows for an adjustable angle and can easily be fastened to the side of the vessel when it’s not active. The dashed red rectangles indicated the leftmost and rightmost approach position for the arresting beam, this results in approximately 180 degrees of variation of approach corridors. Having various approach corridors is a great advantage to both the captain of the vessel and the UAV operator. The UAV operator can recover the UAV in the best possible wind conditions to ensure a successful recovery and minimum damage, while the captain of the vessel has no need to change course to compensate. The only disadvantage to this positioning is the vast distance between the centre of mass of the vessel and the arresting beam. This distance could result in unwanted pitching oscillations in high sea states. However, the side positioning would be susceptible to the yaw and rolling motion of the vessel whereas at the bow this motion is significantly smaller. These considerations were taken into account and it is recommended that the recovery system be placed at the bow of the vessel.

![Diagram of various approach angles](image)

**Figure 28. A representation of the various approach angles achieved with an adjustable beam. (Naval Technology, 2010)**

5. Design Justification

After considering the customer requirements and the suitability of each design the horizontal arresting line was selected. Though the other three conceptual choices were also viable the advantages of the horizontal arresting line outweighed the advantages of the other concepts. While the final design requires modifications to both the vessel and the UAV, they were deemed appropriate and do not interfere with any of the functions of the UAV or vessel. Since the double spring model was used to model all three systems it is unclear which system has the best recovery distance. However, a governing factor towards the choice of the horizontal arresting line was its ability to adapt to various wind conditions. The advantages of each system can be seen in the literature review earlier in this report. Tabulated comparisons found in appendix C4 also justify the selection of this design. By including the modifications to this system it meets all the essential requirements and many of the desirable requirements set by the customers. In conclusion, the horizontal arresting line proved to be the safest, most reliable and effective system out of all the conceptual designs considered.
VII. Conclusion

Upon conclusion of this thesis the objectives outlined at the beginning have been met. By using project management this thesis was completed on time. By identifying the requirements and investing additional research time into developing suitable design concepts, the final design presented fulfils the needs of all the customers. Three design concepts were selected based on the results of the QFD process. These systems were further evaluated using two different spring models to determine what g loading the UAV will experience during recovery and what distance it can be recovered in. Through this evaluation processes a number of problems were highlighted. The results indicated that the UAV cannot successfully be recovered in an acceptable distance without exceeding its g limits. These results led to further investigation of the limitations on the SeaEagle. Analysing the direction of the forces acting on the UAV resulted in the assumption that the SeaEagle can withstand greater loading during recovery than recommended during manoeuvres. Further research into the fabrication of different components of the UAV justified this assumption. It was indicated that the structural limitations of the SeaEagle will be increased due to a scaling factor not considered at the start of this thesis. From these results a concept was chosen and developed into an early preliminary design. With the use of computer aided software the basic configuration of the design was presented through three-dimensional drawings. Research was conducted into the braking and navigational systems and recommendations were made for the positioning of the recovery device onboard the ACPB. Further development of this design will result in a functioning UAS capability onboard the ACPB.

VIII. Recommendations

Due to time constraints and the scope of this thesis not all aspects of this design could be developed to the preliminary stage. Through further development it is believe that the recovery system can be designed and tested to achieve a preliminary design and later a detailed design to present to the customers. There are a number of aspects that need to be researched further to ensure the success of the design.

Firstly, the UAV gravitational limits needed to be defined in the longitudinal direction, while considering the scaling factor. This would be best achieved through experimental work on the UAV to determine its structural limits. However due to the destructive nature of the testing it is recommended to use computational simulations to gain approximate results without the costs.

Secondly, the material used to construct the recovery system could be an important factor in ensuring a safe recovery and the lifecycle of the system. Due to the salt water conditions the material must be selected carefully to ensure excessive maintenance is not required and the system does not need to be frequently replaced. A stress analysis should also be conducted on the supporting structures to determine what materials should be considered.

Additionally the navigation system should be further researched for the preliminary and detailed design. The placement of this system is important during the recovery phase and could greatly affect the safety of the UAV during recovery.

Finally, a suitable braking system can only be selected after further research. With further development of the braking system maintenance hours and costs could be reduced and the recovery system will perform as effectively as possible.

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X. References


Banks, R.L., *The Integration of Unmanned Aerial Vehicles into the Function of Counter Air*, 2000, [online journal] URL:


Cameron, K., Kowalenko, V., *Portable Unmanned Aircraft System Concept Investigation*, DSTO Aeronautical and Maritime Research Laboratory, Melbourne, 1995

Cameron, K., *Unmanned Aerial Vehicle Technology*, DSTO Aeronautical and Maritime Research Laboratory, Melbourne, 1995


Effects of control, Qwerty, URL: [www.qwerty.com](http://www.qwerty.com), [accessed 20 October 2010]


Reinhardt, J., *Future Employment of UAVs*, 1999, [online journal] URL:


Trimble, S., ScanEagle Finds ‘Sweet Spot’ as Globally Ubiquitous Airborne Sensor, *Flight International* [online journal] URL: [www.insitupacific.net](http://www.insitupacific.net) [accessed: 26 April 2010]


