Conceptual Study of a USV for the Swedish Navy

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1 ABSTRACT

This thesis is an initial conceptual study of an unmanned surface vehicle (USV) for the Swedish Navy. The purpose is to highlight challenges and possibilities connected to unmanning a vessel and to suggest one specific concept.

Generating one concept meant weighing characteristics of different hull types against one another to derive a valuable compromise. The generated concept includes a feature of longitudinal bulkheads separating an inner, dry volume from outer ballast volumes. The latter fill with seawater at low velocities, causing the hull to partly submerge which in turn decreases signature and increases ballistic protection within the semi-submerged speed range. The concept measures 6.2 by 2.3 meters, weighs approximately 1800 kg and may reach a calm water top speed of 44 knots. Investigating needs and potentials of an unmanned vessel within the Swedish Navy resulted in a set of requirements, including the possibility to arm the USV. This study investigates feasibility of carrying the SAAB Trackfire remote weapon platform aboard.

Development of the initial USV concept was focused on aspects of naval architecture, including the making of a general arrangement, evaluating materials, a structural design, stability and power need analysis. Although unmanned vessels are likely to be subject to lessened structural safety factors as opposed to manned, scantling determination is based on DNV rules for classification of High Speed, Light Craft and Naval Surface Craft.
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2 INTRODUCTION

2.1 BACKGROUND
Due to a shift in political climate and national interests over post war decades the Swedish Defense has undergone a general transformation in strategy. Complete mobility and mission-specific adaptation represents current valued abilities in the change from a highly static defense against invasion. Contributing to international collaborations in peace keeping and humanitarian missions abroad are prioritized tasks. The transformation implies high demands on equipment and tactics, especially concerning operability, economic efficiency and personnel security. These requirements may be achieved through the use of unmanned vehicles. While the unmanned option is established in the air, the Swedish Defense Material Administration (FMV) is now putting effort into exploring possibilities of unmanned vessels at sea. Kristofer Gattberg at the Naval Procurement Command supervised this thesis.

2.2 OBJECTIVE
The purpose of this thesis is to provide a lead in the future work of developing an unmanned surface vessel (USV) for the Swedish Navy. This is achieved through a conceptual study that includes identifying challenges and possibilities with having no crew onboard, evaluation of design options and suggesting a technically verified concept. The final concept shall represent a well-balanced compromise between identified USV desirables and design choices are to be justified.

2.3 METHODOLOGY
The process of generating a potential USV concept has been broken down to the following fundamental elements:

1. Identify and interpret USV desirables as demanded by a future successful implementation. The following aspects need to be taken into consideration:
   a. Intended usage and capabilities
   b. Compatibility with existing Navy systems
   c. Economy in production and future operation
2. Translate design desirables to a set of requirements.
3. Conduct a market investigation in order to generate an overview perspective of existing products, successful USV applications and current efforts within the area.
4. Investigate challenges and possibilities that are unique to unmanned vessels and identify ways of successfully exploiting these.
5. Compare relevant existing products using a model of evaluation in order to pinpoint concepts relevant for further consideration.
6. On the basis of elements above, derive one compliant design. Focus is put on the aspects of naval architecture. Every design choice made need be justified by calculations or reasonable assumptions. The concept design method is further addressed in the following section.
7. Suggest methods of efficient USV integration with the Navy and society as a whole.
8. Propose areas of investigation valuable to further development.
2.3.1 **CONCEPT DESIGN METHOD**

The process of defining and developing any vessel schematically follows the well-known design spiral illustrated in Figure 1. Due to the paradox nature of ship design where sub-processes depend on each other, work may be said to start with rough estimations and a low level of detail, targeting in on higher accuracy and design improvement for every loop of the spiral until a validated final design is derived. Some of the sub-processes on the perimeter of Figure 1 specifically apply to the design of warships, while some apply to any vessel.

![Figure 1, the Design Spiral.](image)

The concept verified under section *Analysis* represents results of several loops in the design spiral, but is not to be considered a final design. As discussed in following sections, more work is favorable in order to generate a design ready for production.
3 PROJECT LIMITATIONS

3.1 DESIGN OBJECTIVES (FUNCTIONAL)

The list below has been compiled in collaboration with the Defense Material Administration and gathers features of a future USV system that have been found as valuable for future implementation in the Swedish Navy.

**Tactical capability**

- Establish and sustain control of marine areas
- Degrade hostile control of marine area
- Patrol and surveillance both in harbors and at sea
- Marine intelligence gathering
- Protect static structures at sea
- Advance into and secure coastal areas
- Fire support
- Force protection during mine clearance operations

**Compatibility**

USV deployment demands compatibility with the following current transport systems:

- Command vessel Carlskrona
- C-130/TP-84 transport aircraft
- 20 ft. standard container

**Autonomy**

The use of an unmanned vessel is only efficient if the system proves an extent of autonomy. Once deployed, direct human physical influence shall not be required in order for continuous operation within the intended time frame. Furthermore, the system must not fail due to interruption in remote contact or data link.

**Operability**

Although a vessel without crew enables operation in hazardous conditions, the choice of using it instead of a manned system should not be affected by a significant difference in operability. USV operability must therefore match that of existing Navy small high-speed crafts. Furthermore, the design needs to reflect upon the higher risk of attack in some cases of tactical operations since there is generally a higher moral and political value connected to loss of personnel as opposed to loss of equipment.

3.2 REQUIREMENTS (NON-FUNCTIONAL)

A set of requirements has been derived based on the design objectives. These are presented in Table 1 together with the limiting factor in each case.
Table 1, USV design requirements.

<table>
<thead>
<tr>
<th>Category</th>
<th>Property</th>
<th>Requirement</th>
<th>Limiting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Length overall</td>
<td>&lt; 9.2 m</td>
<td>Command vessel Carlskrona</td>
</tr>
<tr>
<td></td>
<td>Width</td>
<td>&lt; 2.34, 3.12, 3.5m</td>
<td>Container, C-130, Carlskrona</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>&lt; 2.38</td>
<td>Container</td>
</tr>
<tr>
<td>Weight</td>
<td>Maximum displacement</td>
<td>&lt; 6 tons</td>
<td>Command vessel Carlskrona</td>
</tr>
<tr>
<td></td>
<td>Payload capability</td>
<td>&gt; 250 kg</td>
<td>Weight of required equipment</td>
</tr>
<tr>
<td>Performance</td>
<td>Min. speed with max.</td>
<td>40 knots</td>
<td></td>
</tr>
<tr>
<td></td>
<td>payload</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Endurance</td>
<td>48 h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>500 NM at 10 knots</td>
<td></td>
</tr>
<tr>
<td>Tactical</td>
<td>Sensor Systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Radar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Sonar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• GPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Laser rangefinder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Color/IR camera</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Communication</td>
<td>Satellite, WLAN,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>UHF/VHF or UV-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>communication</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Armament</td>
<td>Remotely controlled</td>
<td></td>
</tr>
<tr>
<td>Operability</td>
<td>Sea keeping</td>
<td>Stay upright in sea state 4</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Lifting Device</td>
<td>Single point lift</td>
<td>Host ship cranes</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>Diesel</td>
<td>Navy standard</td>
</tr>
<tr>
<td>Structure</td>
<td>To comply with DNV HSLC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4 MARKET INVESTIGATION

The idea of making use of the unmanned option at sea is widespread, both for military and civilian applications. According to investigations such as [1], unmanned vehicles are critical components of future naval forces. While significant research has been performed on unmanned underwater vehicles (UUVs) and unmanned aerial vehicles (UAVs), relatively little effort is yet aimed towards USV development. Examples of USV usage, existing products and ongoing research are presented below to give the reader an idea of factors that have influenced the final outcome of this conceptual investigation.

4.1 USV APPLICATIONS

Historically, one of the first successful innovations of unmanned surface vehicles took place during the armament of the second world war as described by [2], when the allied forces saw the need of an expendable, self propelled vessel to lay smoke cover during amphibious landings. The COMOX torpedo represents one of the first successful USVs for military application, it is equipped with hydrofoils and capable of travelling at 60 knots, see Figure 2.

![Figure 2, the Comox torpedo & Troika multiple ship system, [3] & [2].](image)

Post war applications of unmanned vessels consisted primarily of existing ships taken out of original service and converted to minesweeping or target drones ([2]), such as the German Troika multiple ship MCM system in Figure 2. Minesweeping and target drones still represent a majority of today's USVs.

Successful missions have been carried out during modern time live combat operations such as with the Owl MK II in Figure 3 and as described in [1], from Universal Secure Applications deployed continuously in the Gulf of Persia years 1993-2000. Equipped with thermal cameras the purpose was primarily force protection through Intelligence-Surveillance-Reconnaissance (ISR) missions. The MK Owl may also be configured for sonar tow and successfully found mines in shipping lanes off Kuwait during missions in the Middle East. Some specifics on the Owl will be presented in appendix 11. Representing another modern day usage are unmanned underwater systems (UUVs) such as the one showed in Figure 4 which according to [1] were considered the main workhorses of the mine clearing effort during Operation Iraqi Freedom in 2003.
The US Navy have evidently directed a substantial amount of resources toward the development of unmanned systems and continue to do so, partly due to incidents such as the attack on a destroyer in October 2000. As described by [5], the USS Cole was exposed to a suicide attack during a routine fuel stop in the Yemeni Port of Aden, killing 17 and injuring 37. The attack was conducted by ramming a small craft with about 250 kg explosives into the side of the USS Cole as demonstrated in Figure 5. It highlights the vulnerability of naval ships as they reside in primarily civilian ports, to a high degree also significant concerning the Swedish Navy and its ships operating abroad.

Other incidents alike the Cole bombing include the French oil tanker Limburg bombing in 2002, the Philippine Super ferry 14 explosion in 2004, and Khor Al Amaya oil terminal sabotage in 2004. All are described by [7].

Ever since the Cole attack and other incidents alike, the question of force protection has been raised. Investigations such as the one presented in [8] reveal that similar situations may be efficiently prevented through the use of USVs. Unmanned systems act as force
multipliers and opens the possibility for ships and their crew to focus on their designated task to a higher degree, with less resources needed to be put into maintaining own security. As an example, Swedish Navy participating in collaborations such as the EU-common anti- pirate Operation Atlanta may present situations where force protection is a challenge. Homeport of the Swedish Navy during that specific operation was placed in Djibouti, neighboring country to Somalia where many of recent pirate attacks are believed to have their origin.

A general shift in Swedish defense strategy from static and quantitative to mobile and qualitative has created a clear place for the unmanned option in the military organization. In order to evaluate the need and explore possibilities of unmanned surface vehicles the U.S. Navy put together a team in 2007, the resulting report is named *The Navy USV Master Plan*, [1]. The Master Plan gathers a set of high pay-off USV mission categories of modern time according to the bullets below. For a detailed description of the categories refer to the original document.

- Mine countermeasures (MCM)
- Anti-submarine warfare (ASW)
- Intelligence/Surveillance/Reconnaissance (ISR)
- Maritime Security / Harbor Patrol (HP)
- Surface Warfare (SUW)
- Special Operations Forces (SOF) Support
- Electronic Warfare (EW)
- Maritime Interdiction Operations (MIO) Support

The categories above provide a picture of the wide array of potential USV use. This concept study is not aimed at deriving a design optimized towards all of these mission categories. A list of tactical tasks which the conceptual USV is expected to be able to carry out has been generated in collaboration with the Swedish Defense Materiel Administration (FMV) with current threats towards and capabilities within the Swedish Navy as background. The specific tactical tasks stipulated by FMV were used to derive the design objectives of this study and are presented under the section *Design Limitations*.

### 4.2 Unmanned Possibilities

The use of USVs is particularly relevant for missions in high threat environments, when loss of life is unacceptable or for monotonous missions extending long periods of time. According to [1], a USV may in all of these three cases present an alternative that is politically and morally viable. Furthermore, an unmanned vessel has the potential to act as a resource efficient force multiplier without putting highly trained personnel at unnecessary risk. *The Navy USV Master Plan* ([1]) states that unmanned systems make sense from several perspectives:

- **Cost** – manned systems are more expensive to operate
- **Coverage** – technological advances in sensory systems are improving enabling constant awareness of surrounding environment
• **Productivity** – manned platforms may be prioritized to objectives where they are needed. USVs are in this way efficient force multipliers.

• **Persistence** - no crew means longer continuous operation and tactical advantages

• **Vulnerability** – keeping high-value manned platforms out of harms way enables more aggressive tactics

Based on these potentials of unmanned platforms prior to manned, it is possible to determine USV features that make most use of the fact that no concern need be taken to crew. Utilizing design possibilities distinct to unmanned platforms may be a way to maximize output in terms of functional performance and amplify the advantage to manned vessels. USV advantages are presented in Table 2 together with examples of identified design features that maximizes each advantage.

<table>
<thead>
<tr>
<th>USV Advantage</th>
<th>Advantage Maximized, Suggested Feature Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>A low production and operation cost makes the USV alternative even more attractive. Could for example be achieved through modification of existing manned vessels.</td>
</tr>
<tr>
<td>Coverage</td>
<td>Payload capacity for large amount of sensory systems to make most use of rapid technological development of the area.</td>
</tr>
<tr>
<td>Productivity</td>
<td>USV adapted to multiple vessel operation makes it an even more efficient force multiplier. Also, productivity is maximized as the need for human intervention throughout the whole operational cycle is minimized.</td>
</tr>
<tr>
<td>Persistence</td>
<td>Large fuel tank/power bank and high level of autonomy enables longer time of continuous operation.</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>Equipment and design that make aggressive tactics possible, such as ballistic protection of vital systems and a powerful weapon platform.</td>
</tr>
</tbody>
</table>

Unmanning a vessel also has a direct impact on design. No onboard space need be freed for crew accommodation, no attention need be paid to sea keeping tolerance limits posted by crew, reduction in amount of gear and equipment possible and higher vulnerability acceptable. Common to these design impacts is that they lessen structural requirements and make it possible to reduce overall vessel weight, which in turn means higher general tactical and operational performance through higher payload capability or speed.

### 4.3 Challenges

Developing a vessel with the aim of unmanned operation presents a new design model with reduced constraints on the fundamentals of naval architecture such as layout, structure, crew support systems, dynamic stability and reserve buoyancy. Such a design is also subject to certain concerns solely due to the fact that the vessel is autonomously or remotely controlled. Some of these challenges are addressed below.

#### 4.3.1 Legislation

Unmanned operation is not yet specifically addressed in maritime law. Design and development of USVs must therefore be adapted to general regulations concerning any vessel at sea and as stated by [9] laws of war must also be investigated and developed for weaponized USV options. Nonetheless, current use of both armed and unarmed, unmanned aerial vehicles proves efficient usage despite legislative challenges. As indicated by Swedish
UAV-pilots recently deployed in Afghanistan ([10]) every launch of UAVs requires request for takeoff and cleared airspace by the local air traffic control. This applies to the 170 kg, ramp-launched UAV Örnen as well as the 7 kg, hand-launched Falken.

The widespread use of military application UAVs has resulted in functioning regulations that are applicable to USVs to a large extent. The Joint Authorities for Rulemaking on Unmanned Systems (JARUS) is a group of representatives from aviation authorities of America and Europe with the purpose of recommending sets of regulations for the safe integration of Unmanned Aircraft Systems into airspace. UAV requirements highly relevant to future USV legislation may be derived by scrutinizing the JARUS airworthiness publication from [11] and translating these to marine vessels. One rational conclusion from studying these regulations is that unmanned vessels may be designed with varying levels of quality as long as operation never presents danger to third party, which is to a large extent ensured by the following JARUS regulations, highly applicable to unmanned surface vessels:

**JARUS CS-LURS.1412 Emergency recovery capability**

a) a) The UAS (unmanned air system) must integrate an emergency recovery capability to prevent third party risk that consists of:
   1) a flight termination system, procedure or function that aims to immediately end the flight, or,
   2) an emergency recovery procedure that is implemented through UA crew command or by the onboard systems. This may include automatic pre-programmed course of action to reach a predefined and unpopulated forced landing area, or,
   3) any combination of CS-LURS.1412 (a) (1) and CS-LURS.1412 (a) (2).

b) The emergency recovery capability must be achievable in the whole flight envelope under the most adverse combination of environmental and operating conditions.

c) The emergency recovery capability must be safeguarded from interference leading to inadvertent or unauthorized operation.

d) The emergency recovery capability must receive its electrical power, if needed, from the bus that provides the maximum reliability for operation.

e) The emergency recovery capability must be achievable after loss of the primary electrical system.

f) Use of explosives to perform in-flight destruction of the air vehicle is not an acceptable means of compliance to this requirement

**JARUS CS-LURS.1423 Command and control data link loss**

a) The unmanned aircraft shall not present a danger to people and properties on ground following the complete loss of the data link.

b) The unmanned aircraft shall not present a danger for a mid-air collision following the complete loss of the control data link.

c) There must be an alert for the UAS crew, via a clear and distinct aural and visual signal, for any loss of the command and control data link.

d) A command and control data link loss strategy must be established, approved and presented in the UAS Flight Manual taking into account the emergency recovery capability as defined in CS-LURS.1412

e) The command and control data link loss strategy shall include a reacquisition process in order to try to re-establish in a reasonable short time the command and control data link.
Putting effort into primary and back up systems that guarantee compliance with the capabilities above should make USV operation viable in all waters. Above that, increasing specific capabilities such as data link range or structural safety factors merely implies a higher tactical value and operational efficiency. Strictly speaking, one could argue that it does not matter in terms of legislation whether the data link is poor or structural safety factors are low as long as USV system has the capability of autonomously following procedures that ensures minimized third party risks. No concern need be taken for the safety of crew onboard, highlighting one major advantage of unmanned systems. Furthermore, one advantage of surface compared to aerial systems is that structural failure is less likely to present a direct danger to third party. Wreckage falling from the sky may cause considerable damage to the area below, while a surface vessel sinking to the seabed might cause environmental concerns but presents no immediate danger.

4.3.2 Unauthorized Access
Malfunction or override of an unmanned vessel may enable unauthorized personnel to access the vessel and its contents. Depending on the type of equipment or electronics aboard this may be clearly undesirable. One example of such a situation is the Iran-U.S. RQ-170 incident in December 2011 as described by [12], where a Lockheed Martin RQ-170 unmanned aerial vehicle (UAV) (Figure 6) was captured by Iranian forces during a reconnaissance mission.

![Figure 6, the RQ-170](image)

Different sources contradict in specific details of the incident but according to the government of Iran the aircraft was brought down by a cyber warfare unit with minimum damage as a response to violation of Iranian airspace. It has not been verified whether the capture was a result of deliberate signal jamming or accidental technical issues. Some sources such as [9] state that the UAV was intact upon capture which enabled Iran to extract data collected by the drone and carry out reverse engineering on valuable pieces of technology aboard. Furthermore, it is suspected according to [14] that the RQ-170 was sold to third parties, enabling the development of the strikingly similar Chinese UAV “Lijian”. The lesson learned applies to USVs as well. One conclusion is that a higher level of sensitivity of carried equipment requires more sophisticated measures against capture, armed vessels of particular importance.

4.3.3 High Speed Control
Depending on the size of a USV, operation in high speed may cause certain problems. A vessel without crew most probably gives rise to a desire to operate in higher speed through the whole sea state spectrum since there is no risk of injury due to hard wave impacts. While crew actively stabilizes manned vessels of small size, small USVs may be limited in top speed
by its dynamic stability. In order to maximize USV operational output it is advised that measures are taken to reduce the gap between the velocity limit stipulated by structure, and the limit stipulated by the ability to stay upright in high seas and speeds. It is also advised that the USV is equipped with a self-righting device in the event of capsize. Such a precaution enables a more aggressive, and therefore efficient, use.

Another essential challenge directly coupled with vessel velocity, is the onboard camera system ability to take sharp and stable images despite rough operation. Apart from being essential to the USV capability as sensor, robust image quality is needed to give the USV operator to acquire an accurate picture of prevailing sea state through a monitor and adapt speed accordingly. According to Professor Ma Zhongli, robotic vessel expert at Harbin Engineering University in [15], USV camera technology is much more difficult and sophisticated than the ones used in normal drones, which fly more stably and predictably. Without solving these technological hurdles, robotic boats will not start mass production. She further states that a mechanical system is needed to stabilize the camera and computer software to control the lens to compensate for the boat’s motion.

Identified suggestions for overcoming the USV specific challenges described above are presented under section 7.
4.4 EXISTING PRODUCTS
Existing USV concepts and products have been investigated to provide with an idea of current progress within the area and inspiration for further developments. Investigated products are briefly presented in Appendix: Catalog of Existing USV Products & Concepts. Note that not all found products are presented in the catalog, but a selection that is thought to represent current USV diversity. Observations to be drawn from the USV selection are as follows.

- 14 out of the 24 investigated products seem to be based on existing hull models. 11 of these represent conventional, planing hull types.
- Out of the 10 concepts that represent all-new creations that are not based on existing hulls, 5 are multihulls, 2 are conventionally planing, 2 displacement hulls and 1 foiled hull.
- 3/24 products are currently equipped with a weapon platform.
- Overall length ranges from 0.5 m for the man-portable MANTAS to 16.5 m for the newly developed Piranha.
- 12/24 products are assumed to be designed for ISR as primary tactical task, 3 for SUW and the rest for target practice, mine countermeasures or civilian applications.

Based on the information given by manufacturers or second hand sources, the only existing USV of the existing USVs catalog considered a platform able to comply with the specified design limitations presented under section 2 is the Interceptor, seen in Figure 7. The Interceptor is not weaponized as standard but has a payload capacity of 400 kg, making it viable for carrying such equipment.

Figure 7, the Interceptor [53]. Complies with design requirements.
5 Concept Generation

The process of selecting a concept that suits stated needs is a matter of weighing contradicting features and capabilities of a design against each other to generate an acceptable compromise. A set of relevant concepts have been derived by combining identified USV possibilities as described in section 4.2 and the design limitations of section 3 with an evaluation of existing products.

5.1.1 Evaluation of Existing Products

An extensive compilation of existing USV products and concepts was conducted as part of the pre-study of this thesis, some of which are presented in the Appendix, section 11. These existing USV creations were evaluated in order to generate a pointer as to what types of vessels are relevant for this study. Note that not all found existing products were evaluated, but the ones that were considered to represent diversity. One of two products considered similar was excluded from evaluation, which is partly based on subjective judgments and estimates. Particular characteristics/features of each products was graded with points from 1-6, 1 meaning that the characteristic is comparatively poor in quality and 6 indicating outstanding feature, as indicated by Table 4. Each characteristic was then weighted so than the final score corresponds to valued USV capabilities. Evaluated products are listed in Table 3 together with the number corresponding to the order of appendix, section 11, Catalog of Existing Products & Prototypes. Refer to the Appendix or the relevant reference section for more information on each product. The evaluation matrix is shown by Table 5.

<table>
<thead>
<tr>
<th>Catalog no.</th>
<th>Product Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACTUV</td>
</tr>
<tr>
<td>3</td>
<td>C-Hunter</td>
</tr>
<tr>
<td>4</td>
<td>C-Target 3</td>
</tr>
<tr>
<td>6</td>
<td>Harbor Wing</td>
</tr>
<tr>
<td>7</td>
<td>Interceptor</td>
</tr>
<tr>
<td>12</td>
<td>Owl MkII</td>
</tr>
<tr>
<td>13</td>
<td>Pioneer</td>
</tr>
<tr>
<td>14</td>
<td>Piranha</td>
</tr>
<tr>
<td>15</td>
<td>Piraya</td>
</tr>
<tr>
<td>16</td>
<td>Protector</td>
</tr>
</tbody>
</table>

Table 3, existing USVs, catalog no. & names.

<table>
<thead>
<tr>
<th>Scale</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Poor</td>
</tr>
<tr>
<td>2</td>
<td>Inadequate</td>
</tr>
<tr>
<td>3</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
</tr>
<tr>
<td>5</td>
<td>Excellent</td>
</tr>
<tr>
<td>6</td>
<td>Outstanding</td>
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Table 4, weighting scale.
Table 5, existing USV evaluation matrix.

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<th>Characteristic</th>
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<th>4</th>
<th>5</th>
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<th>12</th>
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<th>14</th>
<th>15</th>
<th>16</th>
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</tr>
</thead>
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<tr>
<td>Ballistic protection</td>
<td></td>
<td>3</td>
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<td>Energy efficiency</td>
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<td>2</td>
<td>3</td>
<td>4</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
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<td></td>
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<td>5</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Suitable as weapon platform</td>
<td></td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>2</td>
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<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Suitable for autonomous control</td>
<td></td>
<td>5</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>3</td>
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<td>5</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

| Assessed tactical capabilities        |          |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |    |
| Surface Warfare                       |          | 5 | 2 | 2 | 1 | 4 | 3 | 1 | 4 | 2  |    |    |    |    |    |    |    | 3        |
| Intelligence-Surveillance-Recon       |          | 1 | 4 | 2 | 3 | 4 | 3 | 4 | 3 | 2  |    |    |    |    |    |    |    | 3        |
| Patrol/ Harbor Security               |          | 2 | 2 | 4 | 1 | 5 | 5 | 3 | 4 | 4  |    |    |    |    |    |    |    | 5        |

Weighted total: 159 186 150 125 178 179 164 176 138 182
Unweighted total: 50 56 45 41 55 54 48 55 42 56
Rank (un-weighted): 4 (7) 1 (1) 6 (8) 8 (10) 2 (4) 3 (3) 5 (6) 2 (5) 7 (9) 1 (2)

Characteristics such as endurance (range) and payload capacity have been rated based on comparison of official information from the producer, when available. Other characteristics are intuitively rated by analyzing product specifics and images. Despite the measure of uncertainty in these ratings there are some observations that may be deduced from the results of Table 5:

- The Protector (catalog no. 16) represents the most complete product, but does not fulfill FMV dimension requirements. With a top speed of 50 knots and being proven as weapon platform, it is the product with highest rating in tactical capability.
- Despite tactical capability, the Protector lacks qualities incorporated by the semi-submersible C-hunter (no. 3) which wins the overall rating. The qualities of C-hunter may be summarized as follows:
  - Excellent ballistic protection due the fact that most of the hull is submerged. According to investigations as recapitulated by (16), supersonic bullets are disintegrated by less than 90 cm of water barrier.
  - The low profile also implies an extremely low optical, thermal and radar signature.
  - Being almost fully submerged, the C-hunter is probably close to unaffected by sea state.
  - Low speed indicates energy efficient propulsion, with lessened tactical capability as downside.
  - C-hunter is not assessed as suitable as weapon platform due to the low height of structure above the static waterline and little available mounting surface.
• Largest downside of the Protector is transportability, since it is too wide to fit into a container and barely into the supports of Swedish Navy vessel Carlskrona (see section 2).
• The two products following Protector & C-hunter in ranking are represented by conventional, planning hulls that are smaller in size compared to the Protector.

One possible conclusion from evaluating existing USV products is that a conventional, planning hull best meets requirements as stated by FMV. However, a concept that combines the qualities of Protector with C-hunter might prove superior.

### 5.1.2 Potential Concepts

Based on stipulated design limitations & requirements of section 3, identified design possibilities (Table 2) and the evaluation of existing products (Table 5), a collection of potential concepts has been compiled. Focus has been put on hull types and concepts sometimes involves a high degree of unconventionality with the aim of combining qualities of different hull types and highlight possibilities of unmanned vessels. Hull types such as conventional displacing and semi-planing have been excluded from consideration due to low top speed. Potential hull type concepts are listed below.

1. Conventional Planing (P)
2. Very Slender Vessel (VSV)
3. Planing Semi-Sub (PSS)
4. Very Slender Semi-Sub (VSSS)
5. Conventional Planing, Hydrofoiled (P-H)
6. Semi-Sub, Hydrofoiled (SS-H)
7. Multihull, wave piercing (M)
8. SWATH

### 5.1.3 Concept Evaluation

Potential concepts were evaluated on the same basis as for existing USV products. Characteristics of each hull concept were subjectively rated from 1-6 with a weighting that reflects upon stated design limitations and requirements. The evaluation matrix is presented in Table 6.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>P</th>
<th>VSV</th>
<th>PSS</th>
<th>VSSS</th>
<th>P-H</th>
<th>SS-H</th>
<th>M</th>
<th>SWATH</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>General characteristics</td>
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<td></td>
<td></td>
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<td>Payload capacity</td>
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<tr>
<td>Launch &amp; recovery</td>
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<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Robustness</td>
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<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
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<td>4</td>
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<tr>
<td>Suitable as weapon platform</td>
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<td>Transportability</td>
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<td>3</td>
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<td>5</td>
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<tr>
<td>Top speed characteristics</td>
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<td></td>
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<tr>
<td>Suitable for autonomous control</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
5.2 SELECTED CONCEPT

Based on the evaluation of both existing USVs and different hull types, the planning/semi-submerged alternative was chosen as scope for this thesis. Such a concept provides the ability of high speeds common to planing crafts with the option of staying hidden and protected at low speeds. Some downsides include lessened stability and increased structural weight and complexity. These are addressed in the following analysis. An outlining illustration of the selected concept is shown in Figure 8. Final concept details and specifics are presented under section 8.

![Figure 8](image-url)
6 DESIGN ANALYSIS

6.1 GENERAL ARRANGEMENT
Structural members, equipment and propulsion system are arranged according to Figure 9 and Figure 10. Longitudinal bulkheads are placed at the minimum distance recommended for engine maintenance. Web frames are placed 1m apart of which the aft most is placed just in front of the engine. For further developments, bulkheads may replace these in order to gain intact stability. The engine is placed on two engine beams that support engine weight.

![Figure 9, general arrangement, top view.]

![Figure 10, general arrangement, side view.]

Dimensions of propulsion system and weapon platform are presented in Table 7.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Specific</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
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<tr>
<td>Engine: Volvo D3-220</td>
<td></td>
<td>702</td>
<td>718</td>
<td>750</td>
</tr>
<tr>
<td>Jet: Rolls Royce FF240</td>
<td></td>
<td>1285</td>
<td>410</td>
<td>574</td>
</tr>
<tr>
<td>Weapon Platform: SAAB Trackfire</td>
<td></td>
<td>877</td>
<td>837</td>
<td>755</td>
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</tbody>
</table>
6.2 Material Evaluation

Credible scantling determination and weight estimation is based on reliable material properties. This section presents the material data and predicted laminate properties used for calculations described in following sections. The choice of laminate and material combination is discussed, however an extensive investigation to determine an optimized material choice is left outside the scope of this study.

6.2.1 Material Properties

Predicting adequately accurate laminate properties is not straightforward. Laminate textbook theory is widely used for generating initially useful estimates. However, results vary with input values and may differ significantly from laminate properties of that used in the final product depending on production method and material quality. Steps have been taken as a part of this concept study in order to ensure reasonably accurate and conservative laminate property values for use in further calculations.

Mechanical properties of materials common in marine applications were gathered from several sources in an initial phase of this concept study. Laminate property prediction input values may in this way be somewhat verified. Gathered data is presented in Table 8 together with a reference number in the rightmost column. When sources have indicated an interval for certain properties the conservative end value of the interval presented in Table 8 and has been taken as input for further calculations.

Table 8, material properties.

<table>
<thead>
<tr>
<th>Type</th>
<th>No.</th>
<th>Name</th>
<th>Manufacturer</th>
<th>Density [kg/m²]</th>
<th>Tensile strength [MPa]</th>
<th>Tensile modulus [GPa]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>1</td>
<td>E-glass, generic</td>
<td>-</td>
<td>2540-2600</td>
<td>3450-3790</td>
<td>72.4</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Typical fiber</td>
<td>-</td>
<td>2520</td>
<td>3450</td>
<td>72.3</td>
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</tr>
<tr>
<td></td>
<td>3</td>
<td>JPSCM fabric</td>
<td>JPS Composites</td>
<td>2540-2600</td>
<td>3400-3500</td>
<td>65-75</td>
<td>24</td>
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<td>Carbon</td>
<td>4</td>
<td>Typical T300 fiber</td>
<td>-</td>
<td>1720</td>
<td>2240</td>
<td>218</td>
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<td>5</td>
<td>T300</td>
<td>Toray</td>
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<tr>
<td></td>
<td>6</td>
<td>T700s</td>
<td></td>
<td>1800</td>
<td>4900</td>
<td>230</td>
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<tr>
<td></td>
<td>7</td>
<td>Typical GY-70 fiber</td>
<td></td>
<td>1970</td>
<td>1720</td>
<td>531</td>
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<tr>
<td>Epoxy</td>
<td>8</td>
<td>Ampreg 22</td>
<td>Gurit</td>
<td>1160</td>
<td>70.3</td>
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<td></td>
<td>9</td>
<td>Typical resin</td>
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<td>1100-1200</td>
<td>60-85</td>
<td>2.6-3.8</td>
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<tr>
<td>Polyester</td>
<td>10</td>
<td>Polylite 720-M80</td>
<td>Reichold</td>
<td>1190</td>
<td>76</td>
<td>3.65</td>
<td>19</td>
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<tr>
<td></td>
<td>11</td>
<td>Typical resin</td>
<td>-</td>
<td>1100-1200</td>
<td>50-75</td>
<td>3.1-4.6</td>
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</tr>
<tr>
<td>Vinyl ester</td>
<td>12</td>
<td>1110 Resin</td>
<td>Fibre Glast</td>
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<td>82</td>
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<td>13</td>
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<td>Reichold</td>
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<td>80</td>
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<td>19</td>
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<td></td>
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<td>70-81</td>
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<td>DIAB</td>
<td>250</td>
<td>4.5 (shear)</td>
<td>97 (shear)</td>
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<td></td>
<td>16</td>
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<td>130</td>
<td>2.2 (shear)</td>
<td>50 (shear)</td>
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</tr>
</tbody>
</table>

Although the property values for each material in Table 8 may be considered as grouped within reasonable proximity to each other, it is clear that it is challenging to compare data from several sources. Methods of mechanical testing used to derive property values are not
Calculated results are presented in Table 8. Assumptions, laminate property prediction methods due to its simplicity and that it generates conservative values. Calculations were based on the following assumptions.

- Laminate lay-up sequence for every material combination: [0/90/±45]^°, i.e. laminates are assumed quasi-isotropic.
- Laminate strain to failure assumed to coincide with that of matrix.
- Laminate fiber volume fraction 55 %.
- Laminate poisons ratio = 0.2.

Calculated results are presented in Table 9 together with values from various sources.

### Table 9, laminate properties.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass/vinylest</td>
<td>2 &amp; 13</td>
<td>10%-rule</td>
<td>0.75</td>
<td>2146</td>
<td>337.85</td>
<td>13.39</td>
<td>253.39</td>
</tr>
<tr>
<td></td>
<td>1 &amp; 12</td>
<td>10%-rule</td>
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<td>2216</td>
<td>297.26</td>
<td>13.49</td>
<td>222.95</td>
</tr>
<tr>
<td></td>
<td>13 &amp; unknown</td>
<td>[19]</td>
<td>0.64</td>
<td>1982</td>
<td>132.38</td>
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<td>99.29</td>
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<td>17</td>
<td>220</td>
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<td>2162</td>
<td>41.58</td>
<td>1297.2</td>
</tr>
<tr>
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<td>6 &amp; 12</td>
<td>10%-rule</td>
<td>0.68</td>
<td>1555</td>
<td>918.24</td>
<td>41.66</td>
<td>550.94</td>
</tr>
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<td>FMV test data</td>
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<td>-</td>
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<td>427</td>
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<td>E-glass/polyester</td>
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<td>10%-rule</td>
<td>0.72</td>
<td>2149</td>
<td>280.21</td>
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<tr>
<td>E-glass/epoxy</td>
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<td>10%-rule</td>
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<td>-</td>
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<td>10%-rule</td>
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<td>41.67</td>
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<td>0.70</td>
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<td>2550</td>
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<td>1470</td>
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<td>Aluminum</td>
<td>Marine alloy</td>
<td>Ref [26]</td>
<td>-</td>
<td>2660</td>
<td>304</td>
<td>69</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5086-H34</td>
<td>Ref [25]</td>
<td>2660</td>
<td>324</td>
<td>71</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1) Lay-up unknown
2) Lay-up: V/M/M/WR/M/WR/M/M, where V = 10 mil C-Glass Veil, M = 1.5 oz./sq.ft Chopped Strand Mat, WR = 24 oz./sq.yd. Woven Roving
3) Quasi-isotropic lay-up
4) Bi-axial lay-up
5) Assumption based on DNV 3:4:3 C103
The rightmost column in Table 9 contains laminate compressive strength and the values used as input for structural requirement calculations described in section 6.3. Setting laminate compressive strength as limiting complies the fact that a structural element exposed to bending forces demonstrates tension on one side of its neutral axis and compression on the other. Some of the values representing compressive strength (footnote no. 5) have been estimated according to DNV 3:4:3 C103 stating that compression testing of laminates may not be required if the compression strength used in design does not exceed given percentages of tensile strength:

- Glass reinforcement comp. strength ≤ 75% of tensile strength
- Carbon reinforcement comp. strength ≤ 60% of tensile strength

The limit percentages were used in the structural requirement calculations of following sections. Data from the source referred to as FMV test data in Table 9 are a result of mechanical testing of laminates used in earlier projects at FMV. The tests were conducted in cooperation with a specific supplier and are to be considered as reliable.

The laminate data of Table 9 may be used for investigating USV material concepts, the final concept of this thesis however is based on the glass fiber/Vinyl ester laminate alternative highlighted in Table 9. As described in following sections, DNV stipulates laminate areal reinforcement requirements in DNV 3:4:5 table A2. This requirement was found to be ruling for the USV concept and is expressed as laminate fiber weight per area, meaning that a lighter fiber type is not credited. The relatively cheap glass fiber is therefore favorable.

6.2.1.1 Composites vs. Aluminum

Vessels recently delivered to the Swedish Navy testify for a shift in acceptance of laminate constructions as opposed to metallic. Examples are Combat Boat 90E and the Visby-class Corvette built with a Vinyl ester-carbon-glass fiber combination and sandwich construction. As described by Eric Greene in [26] safety factors for metallic constructions are generally lower since composite laminates do not exhibit the classic elastic to plastic stress-strain behavior that metals do, especially for compressive failure modes. Greene states that the safety margin in extreme load cases for properly designed composite structures is higher nonetheless. Although metals may in some cases be considered more robust and cost efficient, laminate repair and construction techniques are improving. This study will for these reasons focus on comparing composite laminate concepts and leave metal ones for further studies.
6.3 STRUCTURAL DESIGN

A semi-submersible concept demands an unconventional structural design. This section describes the process of determining structural scantlings. The structure has been analyzed by bottom, deck and vertical structures separately based on the classification society Det Norske Veritas (DNV) specific high speed craft requirements ([27]). Different laminate alternatives have been considered according to the previous section and a sandwich structure has been considered as well. Every design choice has been made based on the FMV design limitations described in section 3. Calculations for all structural members are based on the assumptions listed below.

Structural design - assumptions:

I. Design pressures differ depending on at what position on the hull is considered. Pressure values presented in tables of following sections represent the highest calculated pressure for that specific member. In other words, the highest occurring pressure along each member is considered limiting.

II. In order to facilitate design pressure calculations, panels are assumed rectangular with a width equal to the maximum width of the actual panel.

III. Web frame, girder and longitudinal bulkhead span is assumed the maximum occurring over the whole length of each structural member.

IV. The chine dividing panel no. 1 in Figure 11 is not taken into consideration when calculating design areas or as contributing to stiffness. Panel no.1 is also assumed rectangular according to above.

V. The V-bottom in itself is considered to contribute to longitudinal stiffness.

VI. For use in DNV pressure calculations, the static waterline is assumed to coincide with that of empty ballast volumes.

VII. Sandwich panels assumed as thin faced with weak core.

VIII. Deck panel taken as simply supported along all sides, deck frame and stiffener modeled as clamped.

6.3.1 HULL BOTTOM

A perspective view of the bottom and side structure is shown in Figure 11. Longitudinal bulkheads run from aft to bow in order to achieve watertight separation between outer ballast volumes and center dry volume. Two beams support the engine and coincide aft of the web frame just in front of the engine. Two web frames support bottom panels, beams and the deck structure. The bottom of the ballast compartments are kept clear of transverse beams in order to ensure unobstructed flow of water from these compartments out through the open parts of the transom.
6.3.1.1 Bottom Design Pressure

Deriving design pressures for all structural members is a prerequisite for scantling determination. Design pressures presented in Table 10 have been calculated according to DNV 3:1 for each structural member of the hull bottom. Figure 11 shows the three bottom panels, one web frame, and two parts of the longitudinal bulkheads that were considered separately. Table 10 shows geometrical data used for calculating design pressure acting on bottom structural members. The pressure type referred to as slamming by DNV represents the highest pressure acting on the web frame, while pitching slamming is represents design pressure for all bottom panels. Slamming increases at a constant rate from aft up to $x = 2.57$ m (half the static waterline length) and keeps the same value from that point to the bow, it also increases for lower deadrise angles. In order to assure conservative values, the slamming pressure was therefore evaluated at a point closest to $x = 2.57$ m longitudinal distance from the transom for each structural member. DNV Slamming and pitching slamming pressures and are independent of the vertical distance between the evaluation point and waterline ($z$-direction).

![Figure 11, bottom structure members identified.](image)

### Table 10, bottom design pressures.

<table>
<thead>
<tr>
<th>Span/short side [mm]</th>
<th>Length [mm]</th>
<th>Load Area $[m^2]$</th>
<th>Evaluation point, $x/z$ [m]</th>
<th>Design pressure [kPa]</th>
<th>Pressure type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web frame</td>
<td>2.59</td>
<td>1000</td>
<td>2.19</td>
<td>2.69/0.49</td>
<td>10.93 Slamming</td>
</tr>
<tr>
<td>Panel no.1</td>
<td>558</td>
<td>6215</td>
<td>3.15</td>
<td>0/0.26</td>
<td>19.78 Pitching</td>
</tr>
<tr>
<td>Panel no.2</td>
<td>500</td>
<td>2695</td>
<td>1.40</td>
<td>0/0.49</td>
<td>21.12 Slamming</td>
</tr>
<tr>
<td>Panel no.3</td>
<td>500</td>
<td>2584</td>
<td>0.95</td>
<td>0/0.46</td>
<td>21.12 Slamming</td>
</tr>
<tr>
<td>Engine beam</td>
<td>-</td>
<td>1.38</td>
<td>-</td>
<td>2.57</td>
<td>3.28 kN Point load</td>
</tr>
</tbody>
</table>

The values of Table 10 have been used for determining bottom structure scantlings according to the following sections.
6.3.1.2 Bottom Panel Design

Bottom panel scantlings have been derived for both sandwich and single skin construction with the aim of comparing the final structural weight of the two. There are several parameters to consider when establishing which construction type represents the best overall compromise, these results might however provide a pointer. Although a single skin construction might be better represented by a structure with more structural members, single skin and sandwich scantling determination are based on the same design pressures and areas. Comparison of the two alternatives is discussed further under section 6.3.4.

The sandwich alternative has been optimized according to equation 1 using a sequential quadratic programming algorithm (SQP), an iterative method for nonlinear optimization implemented in Matlab. Allowable deflection and stresses are stipulated by DNV 3:4:5 B500, actual plate response with the design pressures as input was calculated using expressions in the same DNV section which in turn is based on textbook plate theory as described by [29].

\[
\min \rho^*(x), \text{considering}\begin{cases}
\rho_R > \rho_{R,DNV} \\
\sigma_f^{\text{max}} < \sigma_{\text{allow}} \\
W_{\text{max}} < W_{\text{allow}} \\
\tau_{c,\text{max}} < \tau_{\text{allow}}
\end{cases}
\]

\[\rho^*(x)\] – plate areal density as a function of face & core thickness
\[\rho_R\] – areal reinforcement density
\[\sigma_f\] – face compressive stress
\[\sigma_{\text{allow}}\] – wrinkling or ultimate face stress, whichever smallest
\[\tau_c\] – core shear stress
\[w\] – midpoint deflection

Required single skin laminate thickness was similarly derived by DNV 3:4:6. As mentioned earlier, all calculations are based on the assumption of quasi-isotropic laminates. It must also be noted that panel membrane effects have not been taken into consideration. Results are presented in Table 11 for the glass/vinyl ester material concept.

Table 11, bottom panel optimization together single skin analysis results. Laminate: Glass/Vinyl ester.

<table>
<thead>
<tr>
<th>Panel type</th>
<th>Sandwich</th>
<th>Single skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel no.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Laminate thickness [mm]</td>
<td>1.43</td>
<td>1.43</td>
</tr>
<tr>
<td>Core thickness [mm]</td>
<td>8.77</td>
<td>7.56</td>
</tr>
<tr>
<td>Deflection req. [mm]</td>
<td>11.16</td>
<td>10.00</td>
</tr>
<tr>
<td>Resulting deflection [mm]</td>
<td>11.16</td>
<td>10.00</td>
</tr>
<tr>
<td>Face stress req. [MPa]</td>
<td>73.57</td>
<td>73.57</td>
</tr>
<tr>
<td>Resulting face stress [MPa]</td>
<td>30.34</td>
<td>28.37</td>
</tr>
<tr>
<td>Core shear stress req. [MPa]</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Resulting shear stress [MPa]</td>
<td>0.54</td>
<td>0.59</td>
</tr>
<tr>
<td>Areal reinforcement req. [kg/m²]</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>Resulting areal reinforcement [kg/m²]</td>
<td>2.40</td>
<td>2.40</td>
</tr>
<tr>
<td>Resulting areal weight [kg/m²]</td>
<td>7.50</td>
<td>7.34</td>
</tr>
</tbody>
</table>

The sandwich alternative for every panel is limited by stiffness with DNV areal reinforcement requirement as active constraint, whilst the single skin option is limited by strength in each
case. The values in Table 11 might not be appropriate for the final construction depending on available lamina thicknesses and production methods.

6.3.1.3 Web frame & Beam Design

Beams and web frame were designed according to the strength requirement of DNV 3:4:7 and the following criteria.

Prerequisites:

I. The engine beams are limited to a minimum height of 270 mm for fitting the Volvo D3 engine.
II. A deflection of less than 0.5% of member length is tolerated except for the engine beams where the limit is set to 0.2%.
III. Effective bond area (DNV 3:4:7 B500) not taken into consideration
IV. Same laminate lay-up as for panels in web and flange, no “built-up” beams (DNV 3:4:7 B602).
V. Holes in beams not taken into consideration.
VI. Engine beams were modeled as freely supported exposed to two point loads. These point loads represent the engine weight acting on 4 engine supports and was determined according to DNV 3:1:2 C800, heavy units. Setting up equilibrium results in a maximum torque of 4.05 kNm at the aft engine support.

Resulting web frame and engine beam scantlings are presented in Table 12 together with underlying requirements.

Table 12, resulting bottom frame and engine beam scantlings.

<table>
<thead>
<tr>
<th>Structural member</th>
<th>Web frame</th>
<th>Engine beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>240</td>
<td>290</td>
</tr>
<tr>
<td>Width</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Laminate thickness</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Deflection req.</td>
<td>6.67</td>
<td>6.38</td>
</tr>
<tr>
<td>Resulting deflection</td>
<td>0.88</td>
<td>5.92</td>
</tr>
<tr>
<td>Section modulus requirement [mm 10$^{-4}$]</td>
<td>3.02</td>
<td>1.96</td>
</tr>
<tr>
<td>Resulting section modulus</td>
<td>4.74</td>
<td>3.51</td>
</tr>
</tbody>
</table>

6.3.2 DECK

The USV deck layout includes large hatches at the rear for engine maintenance and a cutout close to the web frame adapted to the weapon system. Web frame and stiffener are placed symmetrically on opposite sides of the weapon platform cutout, see Figure 12.

6.3.2.1 Weapon Platform Interface

The weapon system, in this case SAAB Trackfire, and it’s mounting requires particular consideration. SAAB interface specifications from [28] state that Trackfire servos are optimized for each installation but stipulate requirements on the platform bed plane as guidance, these are listed below.

- Bed plane natural frequency $\geq 30$ Hz
- Bed plane need be able to withstand 8 kN vertical force and 5 kN horizontal. This corresponds to the maximum exerted force when firing.
- Vertical stiffness $\geq 9.6 \times 10^6$ N/m
Required deck panel scantlings have been estimated by utilizing textbook sandwich theory as described in [29] based on the assumptions listed in the introduction of section 6.3.

6.3.2.2 Design Pressure

The maximum vertical force when firing is assumed to be distributed evenly along the mounting surface as illustrated in Figure 12. The design load used for panel scantling requirement calculations equals the pressure acting on the mounting surface but is in turn assumed to act over the whole area of the panel.

\[
q = \frac{F_y}{\pi(R^2 - r^2)}
\]

Figure 12, assumed deck design pressure.

The deck panel of Figure 12 above measures 1 by 1 m. Panel design pressure was calculated to \(q_p = 6.69 \text{ kN/m}^2\). Web frame and deck stiffener are assumed to carry half of the maximum vertical force each, distributed as a uniform load across each beam, i.e. \(q_{w,f} = \frac{F_z}{2l} = 4 \text{ kN/m}\). The ends of each deck beam are firmly jointed to adjacent longitudinal bulkheads and were therefore modeled as clamped. Assuming an evenly distributed load is assumed to generate conservative results. However, localized loads at the interface between deck panel and mounting surface have not been taken into consideration.

Sandwich structures are according to [29] known for being sensitive to localized loads due to significant induced local deflection of the face into the core. A complex state of stress is obtained near the vicinity of these load areas and may result in premature failure. Additional reinforcement is therefore recommended close to the mounting surface but is left outside the scope of this study.

6.3.2.3 Panel Stiffness

Sandwich plate deflection may be expressed as the sum of deflection due to bending and shear. The maximum partial deflections may be calculated by assuming thin faces, a weak core, isotropic plate and that the maximum deflection occurs at the geometrical center of the plate. Results from [29] (table 9.1) gives a maximum deflection according to eq. 2 for the deck panel.
Eq. 2 is valid for plates with side aspect ratio \( a/b = 1.0 \). Assuming linear elasticity the stipulated bed plane vertical stiffness requirement may be expressed by eq. 3.

\[
k = \frac{F_z}{w_{\text{max}}} \geq 9.6 \times 10^6 \ [N/m]
\]

Resulting deflection and vertical stiffness is presented in Table 13 for final deck panel scantlings.

### 6.3.2.4 Platform Bed Plane – Natural Frequency

A bed plane natural frequency that is in the magnitude of weapon rate of fire increases the risk of malfunction due to altered relative velocity of the machine gun mechanisms. According to sandwich theory as described in [29] the vibrational behavior of sandwich plates depends strongly on the plate shear factor of eq. 4:

\[
\phi = \frac{D}{b^2 S}
\]

In the case of thin faces and assuming free harmonic excitation of the deck panels the shear factor \( \phi < 0.01 \), implying that the effect of shear deformation is negligible. According to [29] the natural frequency of a sandwich plate may then be expressed according to eq. 5.

\[
\omega_{mn} = \pi^2 \left[ \frac{mb}{a} \right]^2 \left\{ \sqrt{\frac{D}{\rho^* b^4 (1 - v^2)}} \right\}
\]

\( m, n \) - plate modes
\( b \) - width
\( a \) - length
\( \rho^* \) - areal density
\( v \) - Poisson’s ratio

The natural frequency requirement was found to be limiting for the deck panel, as seen in Table 13.

### 6.3.2.5 Deck Design

Accepted deck scantlings were derived by taking weapon platform interface and DNV requirements into consideration. Results are presented in Table 13. Panel scantlings are ruled by required natural frequency and stiffeners by required section modulus. Both designs are constrained by required areal reinforcement.

<table>
<thead>
<tr>
<th>Table 13, resulting deck scantlings.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deck member</strong></td>
</tr>
<tr>
<td>Laminate thickness [mm]</td>
</tr>
<tr>
<td>Core thickness [mm]</td>
</tr>
<tr>
<td>Beam width [mm]</td>
</tr>
<tr>
<td>Maximum torque [Nm]</td>
</tr>
<tr>
<td>Face stress req. [MPa]</td>
</tr>
<tr>
<td>Resulting face stress [MPa]</td>
</tr>
<tr>
<td>Core shear stress req. [MPa]</td>
</tr>
</tbody>
</table>
6.3.3 **VERTICAL STRUCTURES**

### 6.3.3.1 Design Pressure

Side panels and longitudinal bulkheads are exposed to bending forces from static and dynamic water pressure and slamming induced in buckling forces. Buckling of sides and bulkheads was evaluated by assuming that the slamming pressure acts uniformly over the panel area supported by the bulkhead/side in question and the resulting in plane compressive stress was calculated. This stress was in turn compared with the panels critical global buckling stress according to standard textbook formulas and DNV 3:4:10 C103.

\[
P_{Stamming} = \frac{F_{Stamming}}{A}
\]

\[
\sigma_{Stamming} = \frac{F_{Stamming}}{d \cdot L} = \frac{P_{Stamming} \cdot A}{d \cdot L}
\]

![Figure 13, bulkhead and side panel pressures.](image)

The sea pressure acting on sides and bulkheads was evaluated by DNV 3:1:2 C500. As for other pressure calculations, the static waterline is assumed to coincide with that of emptied ballast volumes and the highest occurring pressure acting on each structure was taken as design pressure. The pressure referred to as forebody side and impact pressure was also taken into consideration, but was found to have limited effect due to the small size of the vessel. The lengths of the longitudinal bulkheads were split in two by the web frame while the side panels are seen as continuous along the whole craft length since no transverse structure connects to them except at the ends. Resulting design pressures are presented in Table 14.
6.3.3.2 Vertical Structures – Design

Table 15 reveals required scantlings of vertical structures together with resulting stresses. It is clear that panel buckling strength is not limiting for any of the structures. The panels were instead optimized against bending in the same way as described above for bottom panels.

Table 14, vertical structures - design pressure.

<table>
<thead>
<tr>
<th>Structural Member</th>
<th>Span/short side [mm]</th>
<th>Length [mm]</th>
<th>Design area [m²]</th>
<th>Evaluation point, x, z [m]</th>
<th>Design pressure [kPa]</th>
<th>Pressure type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal bulkhead bow</td>
<td>500</td>
<td>2584</td>
<td>0.95</td>
<td>2.69/0.26</td>
<td>21.12</td>
<td>Slamming</td>
</tr>
<tr>
<td></td>
<td>612</td>
<td></td>
<td>0.34</td>
<td>0 / 0.40</td>
<td>4</td>
<td>Sea pressure</td>
</tr>
<tr>
<td>Longitudinal bulkhead aft</td>
<td>500</td>
<td>2695</td>
<td>1.40</td>
<td>2.69/0.34</td>
<td>21.12</td>
<td>Slamming</td>
</tr>
<tr>
<td></td>
<td>781</td>
<td></td>
<td>0.38</td>
<td>0 / 0.4</td>
<td>4</td>
<td>Sea pressure</td>
</tr>
<tr>
<td>Side panel</td>
<td>558</td>
<td>6215</td>
<td>3.15</td>
<td>0/0.26</td>
<td>19.28</td>
<td>Pitching slamming</td>
</tr>
<tr>
<td></td>
<td>431</td>
<td></td>
<td>2.28</td>
<td>5.14/0.26</td>
<td>8.07</td>
<td>Sea pressure</td>
</tr>
</tbody>
</table>

Both the sides and the bulkheads of Table 15 are limited in stiffness and by the DNV minimum requirement for amount of skin reinforcement, which is lower for internal structures such as bulkheads. Resulting core thickness of side panels differs from that of bottom panel no. 1 by 3.6 mm, laminate thickness equal. One option for facilitating production is to adopt bottom panel scantlings to the side panels. The scantlings of the thickest panel (no.1) are then applied to all panels, including the sides. The areal weight would then increase by 0.39 kg/m². Another option is making use of a single skin laminate at the sides. Required single skin thickness is 6 mm, equivalent to 13.29 kg/m².

6.3.4 Sandwich vs Single Skin

The choice of constructing using sandwich or single skin is not obvious. Among other things, the choice depends on target lifetime, area of operation and amount of units to be produced. As mentioned earlier, the weight comparison between sandwich and single skin construction presented here is based on the same bottom layout, which is misleading to some extent. A single skin construction might demand a larger amount of structural members in order to reduce panel span and weight. Comparing the two alternatives in this way nonetheless provides a pointer as to the magnitude of weight difference.
Deriving required panel scantlings with E-glass/Vinyl ester as material choice according the procedure described above yields a bottom panel weight of 116 kg for sandwich and 290 kg for single skin, where total laminate area is estimated to 15.4 m². The difference in weight need be taken into consideration when assessing which alternative provides the best compromise, along with the sandwich features listed below.

**Sandwich – advantages:**

- **Structural.** Due to the need of keeping the bottom panels between the longitudinal bulkheads and outer sides free from structure, sandwich presents an advantage in stiffness per weight compared to single skin.
- **Damage tolerance.** The sandwich core absorbs impact loads such as slamming to a higher extent, reducing the risk of matrix cracking.
- **Silence.** Sandwich construction reduces structure born vibrations and noise. A feature of clear importance intended for covert reconnaissance.
- **Environment.** Single skin construction produces more volatile emissions compared to sandwich. Single skin construction is therefore restricted by environmental regulations to a higher extent. The higher emissions are partly due to the increase of exposed laminate surface in production, which increases for every added ply. Furthermore, the amount of resin used is generally higher for single skin constructions.

**Sandwich - disadvantages:**

- **Operating temperature.** A sandwich core may soften or outgas due to high temperature as opposed to a single skin construction that is only limited by the relatively high resin distortion temperature. DIAB recommends an external skin temperature up to 85°C for their marine application foams H130 & H250. This poses a concern if a dark gelcoat color is applied in order to reduce optical signature, which under the sun may develop temperatures close to 85°C.
- **Production costs and cycle time.** Sandwich construction requires specific equipment, higher expertise and longer production cycle time. Single skin construction is an open contact-mold process that enables less complicated and thus cheaper production. In the event of future production of the USV concept it is likely that a single unit is produced. One-off production stipulates a clear advantage in single skin since sandwich construction is difficult using a male framework instead of a female mold.

The statements above are recapitulated from [30]. Sandwich advantages are thought to outweigh the disadvantages for this concept, especially considering the structural advantage.
6.4 **Weight Estimation**

Accurate vessel weight estimation is significant for predicting power need and stability. Structural weight was estimated based on the scantlings of each structural member as presented in section 6.3. Centroids for each structural member was calculated through a model in a CAD-software named Rhinoceros. Weight and center of gravity for separate components were compiled through information provided by each supplier when possible and was otherwise estimated. Engine center of gravity was assumed to coincide with the geometric center. Structural and component weight is listed in Table 16 below together with their centers of gravity in a global coordinate system with origin at the bottom center of the transom. Values are rounded up to nearest integer.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight [kg]</th>
<th>Share of total weight [%]</th>
<th>Longitudinal COG [mm]</th>
<th>Vertical COG [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>400</td>
<td>22</td>
<td>2314</td>
<td>619</td>
</tr>
<tr>
<td>Engine</td>
<td>260</td>
<td>14</td>
<td>1051</td>
<td>450</td>
</tr>
<tr>
<td>Jet</td>
<td>155</td>
<td>9</td>
<td>0</td>
<td>231</td>
</tr>
<tr>
<td>Fuel tank</td>
<td>60</td>
<td>4</td>
<td>2886</td>
<td>268</td>
</tr>
<tr>
<td>Fuel, 100% fill</td>
<td>422</td>
<td>23</td>
<td>2886</td>
<td>268</td>
</tr>
<tr>
<td>Weapon platform</td>
<td>245</td>
<td>13</td>
<td>2200</td>
<td>1118</td>
</tr>
<tr>
<td>Heavy weapon alternative</td>
<td>38</td>
<td>2</td>
<td>2200</td>
<td>1523</td>
</tr>
<tr>
<td>Ammunition</td>
<td>80</td>
<td>4</td>
<td>2200</td>
<td>400</td>
</tr>
<tr>
<td>Sensors</td>
<td>20</td>
<td>1</td>
<td>500</td>
<td>1368</td>
</tr>
<tr>
<td>Battery pack, weapon sys.</td>
<td>50</td>
<td>3</td>
<td>3400</td>
<td>250</td>
</tr>
<tr>
<td>Battery pack, start &amp; service</td>
<td>50</td>
<td>3</td>
<td>190</td>
<td>232</td>
</tr>
<tr>
<td>Remote ctrl gear</td>
<td>30</td>
<td>2</td>
<td>1000</td>
<td>500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1810</strong></td>
<td><strong>100</strong></td>
<td><strong>1996</strong></td>
<td><strong>530</strong></td>
</tr>
</tbody>
</table>
6.5 Hydrostatics & Stability

6.5.1 Method
USV concept hydrostatics and stability were evaluated using Maxsurf Modeler and Maxsurf Stability software, developed by Formation Design Systems. Analysis in Maxsurf Stability is based on an iterative procedure of finding trim, heel and draft that satisfy static equilibrium, and the righting lever arm that varies with shift of center of gravity and center of buoyancy due to heel.

Having in mind that the concept includes the feature of keeping the transom part of ballast volumes open or closed with a hatch, hydrostatics and stability were evaluated for the hull in both semi-submerged and light state of flotation. Due to the significant weight of a filled fuel tank compared to the total USV mass (23%), analysis was also done for filled and emptied fuel tank. Here, the free movement of the fluid in the fuel tank is not considered since the load cases represent 0% or 100% fill, and nothing in between. The four load cases are summarized by Table 17. Every load case includes the weight of 500 HMG rounds of ammunition according to Table 16, representing the most critical weapon alternative in terms of stability.

Table 17, load cases.

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Condition</th>
<th>Fuel Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Semi-submerged</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>Transom hatched</td>
<td>100%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0%</td>
</tr>
</tbody>
</table>

Calculations for upright hydrostatics, large angle stability and static equilibrium were conducted in Maxsurf for every load case. Input values for each calculation is coordinates of vessel center of gravity, i.e. longitudinal, vertical and transverse position. The procedure of finding these is described in section 6.4. The amount of water entrained inside the waterjet (28 liters) was not taken into consideration. In order to facilitate calculations, the semi-submerged hull was modeled without ballast volume bottom panels as shown in Figure 14. It is assumed that this assumption makes calculations conservative since water will leave and enter the ballast volumes without any delay. In other words, the dampening effect due to water passing through the open transom is not taken into consideration.

Figure 14, static stability model.
6.5.2 HYDROSTATICS – RESULTS

Table 18 shows static specifics for each load case as specified in Table 17. Figure 15 & Figure 16 illustrates the waterline position and angle along the hull for load case 1 & 3 respectively.

Table 18, vessel hydrostatics.

<table>
<thead>
<tr>
<th>Static Specific</th>
<th>Load Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement - $\Delta$</td>
<td>[kg]</td>
<td>1810</td>
<td>1390</td>
<td>1810</td>
<td>1390</td>
</tr>
<tr>
<td>Long. Center of Gravity - LCG</td>
<td>[m]</td>
<td>1.996</td>
<td>1.726</td>
<td>1.996</td>
<td>1.726</td>
</tr>
<tr>
<td>Vertical Center of Gravity - VCG</td>
<td>[m]</td>
<td>0.530</td>
<td>0.609</td>
<td>0.530</td>
<td>0.609</td>
</tr>
<tr>
<td>Waterline length - $L_{WL}$</td>
<td>[m]</td>
<td>5.289</td>
<td>5.138</td>
<td>5.585</td>
<td>5.269</td>
</tr>
<tr>
<td>Block coefficient - $C_B$</td>
<td>[1]</td>
<td>0.379</td>
<td>0333</td>
<td>0.379</td>
<td>0.333</td>
</tr>
<tr>
<td>Initial metacentric height - $G_{M_0}$</td>
<td>[m]</td>
<td>0.625</td>
<td>0.528</td>
<td>1.719</td>
<td>1.747</td>
</tr>
<tr>
<td>Maximum lever arm - $GZ_{Max}$</td>
<td>[m]</td>
<td>0.269</td>
<td>0.258</td>
<td>0.382</td>
<td>0.383</td>
</tr>
<tr>
<td>Angle at $GZ_{Max}$</td>
<td>[$'$]</td>
<td>37.5</td>
<td>37.3</td>
<td>32.7</td>
<td>32.2</td>
</tr>
<tr>
<td>Trim - $\epsilon$</td>
<td>[$'$]</td>
<td>2.478</td>
<td>4.493</td>
<td>1.169</td>
<td>2.403</td>
</tr>
<tr>
<td>Draft AP - $T_{AP}$</td>
<td>[m]</td>
<td>0.483</td>
<td>0.483</td>
<td>0.411</td>
<td>0.333</td>
</tr>
<tr>
<td>Draft FP - $T_{FP}$</td>
<td>[m]</td>
<td>0.335</td>
<td>0.148</td>
<td>0.292</td>
<td>0.168</td>
</tr>
</tbody>
</table>

Figure 15, static flotation load case 1.

Figure 16, static flotation load case 3.
6.5.3 Static Stability - Results

Figure 17 shows the righting lever arm GZ as function of heel angle for the different load cases.

Despite the absence of crew, USV stability was compared to prevailing stability requirements for manned vessels in order to evaluate whether stability is satisfactory. It was found that the concept fulfills all stability requirements stated by the International Maritime Organization (IMO) as described in [30]. Table 19 presents relevant IMO criteria together with actual values of the concept for the load cases with highest vertical center of gravity.

Table 19, IMO criteria & actual values.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unit</th>
<th>IMO requirement</th>
<th>Actual, load case 2</th>
<th>Actual, load case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area under GZ-curve 0° - 30° or GZmax</td>
<td>m²</td>
<td>&gt; 3.1513</td>
<td>1.9354</td>
<td>7.8144</td>
</tr>
<tr>
<td>Area 30° to 40°</td>
<td>m</td>
<td>&gt; 1.7189</td>
<td>2.5537</td>
<td>3.7801</td>
</tr>
<tr>
<td>Max GZ at 30° or greater</td>
<td>m</td>
<td>&gt; 0.200</td>
<td>0.258</td>
<td>0.383</td>
</tr>
<tr>
<td>Heel at GZmax</td>
<td>°</td>
<td>&gt; 15.0</td>
<td>37.3°</td>
<td>32.2</td>
</tr>
<tr>
<td>GM0</td>
<td>m</td>
<td>&gt; 0.150</td>
<td>0.528</td>
<td>1.747</td>
</tr>
</tbody>
</table>

6.5.4 Legacy Design Stability Problem

As stated earlier, the final USV design is a result of several design spiral iterations. One legacy design meant an unsatisfactory hydrostatic characteristic that might be of interest for further USV concept exploration. The main difference in this legacy design compared to the final one was that volume was added horizontally just beneath the deck instead of vertically in the outmost flotation volumes as seen in Figure 14. The legacy design is schematically...
shown in Figure 18. The aim was a simple design to facilitate production and also the feature of large displacement increase for a small increase in vessel weight, to keep draft variations with different payload or load cases to a minimum. This could be achieved by leveling the waterline with the ballast volume “roofs”. This was in turn found to be difficult without decreasing the internal height of the ballast volumes and thus waiving the semi-sub feature.

The legacy design resulted in a static flotation with approximately 15° heel and was considered inappropriate due to the difficulties of operating onboard equipment such as radar, weapon platform and cameras in the low speeds as the hull would demonstrate unstable behavior. The legacy design also implies lessened overall stability.

![Figure 18, legacy design.](image)

Figure 19 shows legacy design GZ-curve. The initial metacentric height $GM_0$ may be read out as approximately -0.29 m.

![Figure 19, legacy GZ-curve.](image)
Changing the design to house vertical flotation elements meant decreasing center volume buoyancy by decreasing its width. This implies a more narrow engine compartment that obstructs maintenance and vertical flotation volumes that may complicate production. The fuel tank is also narrowed and heightened however, lessening the free surface effect on transverse stability.

6.6 POWER & PROPULSION

This section describes the methods of predicting resistance and identifying a suitable propulsion system within the USV concept study. The results presented herein are products of several cycles of the design spiral.

6.6.1 RESISTANCE

Resistance has been predicted through the semi-empirical method presented by D. Savitsky 1964 from [32] and a following development in 1976 from [33]. The method combines theory from fluid mechanics such as predicting friction of viscous flow around plates with empirical data for a range of different hull types. Furthermore, resistance in the pre-planing range has been evaluated through a similarly semi-empirical method developed by Compton as described in [34]. Calculating resistance by these methods requires geometrical input, which were measured from a drawing or CAD model in every loop of the design spiral. Final inputs are presented in Table 22. Table 20 gathers validity ranges for the methods used for evaluating resistance.

<table>
<thead>
<tr>
<th>Method</th>
<th>Range of validity [knots]</th>
<th>Constraining Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savitsky</td>
<td>$9.2 \leq V_s \leq 16.2$</td>
<td>$C_{vu}$, beam Froude’s no.</td>
</tr>
<tr>
<td>Savitsky pre-plan</td>
<td>$0.7 \leq V_s \leq 18.5$</td>
<td>$F_{ku}$, volume Froude’s no.</td>
</tr>
<tr>
<td>Savitsky added wave</td>
<td>$5.0 \leq V_s \leq 15.0$</td>
<td>$V_s / V_L$, applicability range</td>
</tr>
<tr>
<td>Compton</td>
<td>$2.0 \leq V_s \leq 10.2$</td>
<td>$F_{ku}$ lower &amp; $F_{hiL}$, length Froude’s no. upper boundary</td>
</tr>
</tbody>
</table>

Method applicability is also limited to certain factors of hull geometry. Savitsky’s method is based on several series of hull shapes, where the evaluated hull is assumed to be represented by Series 62 and the method is therefore valid within the specified speed range in Table 20. Compton and Savitsky pre-plan methods are based on hulls with center of gravity more or less centered over hull length. The evaluated hull has a center of gravity 14.2% aft of amidships for load case 1 & 3, whereas the boundary for Savitsky pre-plan is 7% and 13% for Compton. Other parameters of hull geometry fall within ranges of method validity. Resistances for the heavy load cases (1 & 3) according to the different methods are presented in Figure 20. Results are based on vessel weight and waterline geometry corresponding to emptied ballast volumes. Savitsky pre-plan, added wave resistance & Compton in Figure 20 represent interpolated results using second-degree curves, interpolation points are marked with circles.
The drop in Savitsky resistance at 5.5 knots represents an estimate of the transition from semi-submerged to surfaced, the subject is discussed under section 6.6.2.1. According to [33] the added wave resistance in Figure 20 has a precision of +20% and is unaffected by deadrise angle. Figure 21 shows trim and wetted length to beam ratio according to Savitsky. Worth mentioning is that trim steadily decreases for higher velocities, indicating that a shift in center of gravity more aft might be relevant for further developments. Note that Figure 21 is based on the Savitsky planing method and is therefore not valid for velocities below 9.2 knots.
Figure 21, Savitsky trim and wetted length to beam ratio.

6.6.2 POWER

Required output power has been calculated based on the resistance curves of previous subsection and is presented in Figure 22 for the different resistance prediction methods. Added required power due to waves according to Savitsky has a local maximum around hump speed, minimum at 24 knots, and then increases. Note that the part of the added wave power curve right of 27 knots is an interpolated extension of Savistky added wave power that is outside method range of validity. The extension was done to generate an idea of added wave power at higher velocities and is marked by a different curve shading. The curve labeled max. possible waterjet output in Figure 22 represents an estimation of feasible output power and is based on the assumption that the engine is able to deliver it’s maximum power (162 kW) throughout all velocities and a waterjet efficiency estimation as described under section 6.6.3.
Reason for the difference in magnitude between the pre-planing power predictions and Savitsky planing is unknown. It might be a result of the slight offset in longitudinal center of gravity between method validity and concept actual. Furthermore, the Compton method is according to [34] mainly intended for significantly larger and heavier vessels. The intersection between Savitsky planing and possible power output curves at 44.5 knots represents the maximum speed provided that the engine is geared and adapted for maximum output here. The intersection of added wave power interpolation in the same region is thought to be coincidental.

6.6.2.1 Submerged to Surfaced – Transition
A swift transition from zero velocity to planing may be credited by situations such as extraction from reconnaissance after unintentional opponent detection or rapid interception of an identified threat after static surveillance, refer to the Cole incident described under section 4. The transition gives rise to several physical phenomena that effect required time and power need for the transition. These were investigated in an attempt to determine whether power is sufficient and transition time acceptable.

The transition may be discretized and simplified according to the following phases:

1. $V = 0$. The hull floats statically, ballast volumes are filled.
2. $V < V_{\text{ventilation}}$. Viscous flow of water that follows the hull generates a swirl at the transom, containing water inside the ballast volumes, which are partly filled. The decrease in ballast water volume is replaced by air from the bow inlets. Flow of water through the ballast volumes gives rise to added friction due to the internal wetted surface and a pressure decrease inside the volumes as water exits at a higher
rate than replaced by air. The mass of the remaining ballast water also effects the rate of acceleration by inertia.

3. \( V = V_{\text{ventilation}} \). Viscous flow of water that follows the hull separates completely at the transom. Water exits without obstruction through the open transom. Total resistance is assumed to coincide with that for an emptied hull once ballast volumes are emptied. According to observations made by Savitsky in [33], complete transom ventilation occurs at \( C_V = 0.6 \), corresponding to approximately 5.5 knots.

The effect of ballast water inertia and ballast volume pressure decrease is left for further studies. Considering the added frictional resistance of phase 2, the internal wetted ballast volume surface was calculated to approximately 20 m\(^2\) for the hull completely submerged. This may be compared to the external wetted surface when the hull is submerged of 10.9 m\(^2\). The conservative assumption that the internal wetted surface remains constant up to \( V = V_{\text{ventilation}} \) yields an added friction with maximum of 75 N at 5.5 knots. After \( V_{\text{ventilation}} \), water is assumed to have left the ballast volumes, leading to the small drop in frictional resistance as seen in Figure 20. The difference in frictional resistance due to a higher wetted surface barely affects the required power curve. Neglecting the effect of ballast water inertia and ballast volume pressure decrease leads to the conclusion that required power for transition is much smaller than that of higher velocities. Time elapsed before ballast volumes are emptied is dependent on propulsion efficiency and the design of bow inlets. Considering the comparatively low speed at which complete transom ventilation occurs, it may be reasonable to assume that the increase in time from zero to planing is in the same order of magnitude as that of a conventional boat of same size and weight.

### 6.6.3 Propulsion

Volvo D3-220 is the suggested engine for this concept. It runs on diesel, has a maximum output power of 162 kW and represents one of Volvos special light duty commercial engines. Recommendations state that full power is not to be utilized more than 1 hour per 12-hour operation period. It was found that engines for more heavy duty and continuous operation from several manufacturers are unreasonably heavy compared to light duty engines such as the D3-220, making them unsuitable for the USV concept. For further engine specifications refer to [35].

Waterjet was chosen over sterndrive as propulsion unit for this concept for two reasons.

- **Dimensions.** Waterjet does not add to the overall height of the vessel and therefore facilitates transport and storage. The boat may be placed on a deck or flat surface without the need for cradles provided that the hull is sufficiently reinforced, a feature of significant interest to a boat of small size intended for host ship transport. Furthermore, sterndrive would require special consideration to ensure that the drive remains intact during launch and recovery using a sled as described in section 7.4.
- **Maneuvering.** Jet propulsion enables excellent maneuvering capabilities and provides the option of powerful deceleration by reversing the jet stream at full throttle. Such a feature could prove especially valuable for the USV concept since it enables a swift transition from surfaced to submerged, which could be useful in certain situations.
According to [36] an estimation for initial design phases for waterjet propulsion efficiency is given by equation 6.

\[ \eta = \frac{1}{1 + 8.64/V} \]

\[ V \] - vessel velocity in m/s  

(6)

Maximum possible propulsive power based on efficiency of equation 6 and D3-220 engine output power of 162 kW is plotted in Figure 22 of section 6.6.2. Suggested waterjet unit is Rolls Royce FF240.

Although waterjet propulsion reduces the need for a gear connected to the driveshaft, it is advised that the option of installing either a centrifugal clutch or reverse gearbox is taken into consideration. Centrifugal clutch has advantage in that it needs no direct control to connect engine driveshaft and propulsion unit at appropriate throttle increase. Such simplicity is valuable when considering the increase in communications bandwidth and the need for servos and automation for every mechanical motion. A reverse gearbox however, gives the possibility of shifting to neutral and engine number of revolutions may be increased while keeping the vessel still, allowing for more electric power during e.g. static surveillance. Shifting to reverse also enables debris such as plastic bags that has choked the jet inlet to be blown out. A reverse gear may furthermore feature a built in reduction gear to synchronize engine and jet unit optimum number of revolutions.

The USV concept range of operation for different speeds are presented in Table 21 and is based on fuel consumption rates given by Volvo.

**Table 21, Range and operating hours at different speeds with 500L fuel capacity.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>9</td>
<td>26</td>
<td>8</td>
<td>62.5</td>
<td>500</td>
</tr>
<tr>
<td>19</td>
<td>25.5</td>
<td>48</td>
<td>13.6</td>
<td>36.7</td>
<td>697</td>
</tr>
<tr>
<td>33</td>
<td>59</td>
<td>89</td>
<td>23.9</td>
<td>20.9</td>
<td>689</td>
</tr>
<tr>
<td>38</td>
<td>81</td>
<td>117</td>
<td>30.2</td>
<td>16.5</td>
<td>627</td>
</tr>
<tr>
<td>41</td>
<td>96.5</td>
<td>136</td>
<td>34.9</td>
<td>14.3</td>
<td>586</td>
</tr>
<tr>
<td>44.5</td>
<td>117.5</td>
<td>162</td>
<td>46.7</td>
<td>10.7</td>
<td>476</td>
</tr>
</tbody>
</table>
6.7 PRODUCTION

A suggested production process is briefly addressed below. The process is conventional apart from the phase of joining longitudinal bulkheads and ballast volume roofs to bottom & deck structure, seen in Figure 23.

![Figure 23, structural elements, exploded view.](image)

It is suggested that lamination takes place by vacuum injection using separate female moulds of hull and deck. An example view of such a mould is seen in Figure 24.

![Figure 24, hull bottom female mould.](image)
Sandwich material of engine beams and deck reinforcements are laid out and laminated in the same process. The longitudinal bulkheads need also be manufactured using a mould that coincides with the shape of bottom and deck moulds. By preparing the final hull bottom and deck laminates according to Figure 25 the parts may be joined together using e.g. Crestomer 1152PA/1153PA, a glue approved by DNV for joining vital structural elements. Crestomer may also be used to join longitudinal bulkheads to bottom and deck and to attach the roof of the ballast volumes, seen in Figure 23, to the outer side structure. Here, it is suggested that the sides are prepared to form a shelf for these roofs to rest on once side and roof are to be joined together. A final phase of the production process would be to glue a material such as Trekollan on to prepared surfaces as shown in Figure 23. Attaching such a durable material would add to the overall robustness of the vessel.
7 IDENTIFIED DESIRABLES

The work included in different phases of this conceptual study has led to spin-offs in distinguishing specific opportunities to overcome the challenges coupled with unmanned vessels. This section is aimed at suggesting ways of USV usage and equipment of particular value for maximizing strategic, economic and operational output. For background information on USV specific challenges the reader is referred to section 4.3. This section applies to the final concept of this study or any other unmanned vessel alike and might aid the development of future USV design specifications.

7.1 ENSURING AUTONOMY & LEGISLATIVE COMPLIANCE

The following underlined topics summarize suggested USV features for ensuring legislative and ethical compliance.

Emergency recovery capability: the USV needs to feature both stable remote control and autonomous control should the remote link fail. Appropriate procedures for link failure need be programmed prior to deploying the vessel and adapted to mission type and environment. The vessel might for example be programmed to head for the closest communication node should it lose connection to the operator station, and the speed it does so in may depend on the urgency of the mission.

Autonomous mission planning: a USV with the ability of operating independently of constant operator supervision realizes the benefits of an unmanned platform. It is advised that any future USV development has the capability of autonomous route planning through input from operator, radar, GPS, digital charts, AIS and an inertial navigation system. The latter a type of dead reckoning through the use of accelerometers and gyroscopes. Equipping a future USV with many sources of navigational feedback enables a high degree of autonomy and system safety. Investigations such as [9] by J. Colito prove the feasibility of efficient USV autonomous mission planning. The planning algorithm described by Colito is a procedure of selecting the route with maximum fitness from a population of alternatives. Route fitness is evaluated with named navigational systems, set mission goals, any mission constraints, and vessel capabilities as input.

Preventing unauthorized access: considering past incidents with UAV cyber attacks as the one in section 4, measures for preventing unauthorized USV operation is required. The demanded quality of such a feature need be higher for any weapon platform. An option of complicating unauthorized acquisition might also be relevant. Such a feature could for example be achieved through a valve at the bottom of the hull that may be autonomously or remotely opened to deliberately sink the vessel.

Minimizing environmental damage: considering the probability that unmanned vessels are more likely to be operated aggressively compared to manned, it is desirable that containers, pipes and battery packs be designed so that no fuel or chemicals leak should the vessel capsize.
7.2 **BOOSTING COMMUNICATIONS**
In order to enable over-the-horizon operation, it is suggested that techniques for extending communications range are developed parallel to future USV development. One appropriate measure is ensuring future unmanned aerial or surface platform have the capability of relaying signals between control station and USV. Another suggested procedure is adaptive bandwidth use. Not all functions of the USV need be controlled at all times. Choosing to set some functions to autonomous control makes more bandwidth available and extends range depending on required frequency of function specific transmission.

7.3 **EXTENDING ENDURANCE**
As highlighted in Table 2, endurance is one of the main advantages of unmanned platforms. The underlined topics below address some USV features that may amplify the advantage.

*Alternate power source.* In order to extend the period of time that the USV is capable to conduct static surveillance it is desirable that it be fitted with solar panels on any available area of the deck structure.

*Sea refueling capability.* Some navy missions, typically recent ones conducted by the Swedish Navy abroad, do not offer the opportunity of land based refueling. Such circumstances demand the option of refueling at sea for both manned and unmanned platforms. “Providing the host ship the capability to refuel USVs without the need to bring them aboard enhances mission efficiency and reduces host ship exposure. This works to improve the effectiveness of naval USV missions and decrease risks to personnel and potential damage to vessels and equipment”, according to Dr. Henshaw, representative from Rapid Autonomous Fuel Transfer (RAFT) project as described by [37] The project provides a solution to autonomous refueling via a transfer arm with a magnetic fitting, hanging over the bow section during trials shown in Figure 26. Approximately 60 trial refueling attempts at sea states ranging from 0 to 3.25 were completed with a high rate of success.

Figure 26, autonomous refueling demonstrated [37].
The vessel in Figure 26 used to conduct autonomous refueling trials is named Sea Fox, a USV development described in the USV catalog in the appendix.

**Dynamic stability.** Depending on the level of ambition to operate the USV in rough sea states, ways of increasing dynamic stability might be subject to consideration. Fitting a gyroscope is one practical option. Shallow revision of products of the main suppliers of gyroscopes for marine use concludes that no gyros are available for fitting into a vessel of displacement and size corresponding to the USV concept. As reference, the M7000a represents the smallest gyro from Seakeeper Inc. ([38]) and was installed in the Piranha USV, described in the appendix. The Piranha installation is shown in Figure 27.

![Figure 27, example gyroscope USV installation [39].](image)

M7000a weighs 455 kg and delivers an angular momentum of 7000 Nms, equivalent to 15000 Nm of anti-rolling torque. Although the efficiency of such a product is proven, a smaller and lighter development is needed for a USV corresponding to the concept.

**Capsize recovery.** A system for turning the vessel upright after capsize increases the possibility of aggressive USV operation even further. Such a system is used by the Canadian Coast Guard for smaller boats as shown in Figure 28. It consists of a bladder mounted on top of a frame and is filled with air from a 4000 PSI pressurized container by pulling a floating rope, causing the boat to swiftly right itself.

![Figure 28, capsize recovery system [40].](image)
7.4 Launch & Recovery

Efficient USV operation involves reliable ways for launch and recovery. An unmanned vessel has the advantage that no attention need be paid to the safety of crew during launch and recovery, making the durability of USV, onboard equipment or host ship limiting factors instead.

**One point lift.** The most common launch and recovery technique involve a davits, where the vessel is simply hoisted along the side of the host ship. Another common launch and recovery technique involves stern ramps, where the vessel speeds up a fixed or moveable ramp placed at the host ship stern. A study in collaboration with Thyssen Krupp Marine investigates [41] other ways of launch and recovery systems adapted to unmanned vehicles, and concludes stern ramp in combination with a sled as suitable, see Figure 29. Despite future launch and recovery technique, it is advisable that the USV be equipped with a lifting hook located above vessel center of gravity, and a bow loop for line or sled attachment. Figure 30 below exemplifies one method of transportation that complies with Navy standard 20 ft. containers.

Autonomous docking station. Productivity, coverage and economic efficiency of a future USV development would be greatly amplified through a system that enables autonomous launch and recovery. Envisioned in Figure 31, such a docking station could consist of a floating sled similar to the one in Figure 29 that is moored at a spot of strategic value. While in stationary readiness, the vessel may be connected to land power to keep battery charge at maximum and systems at appropriate temperature during cold weather. A radio mast or other communication node in vicinity to the docking station extends the range of feasible transmission to the USV. Even though docking stations were to be placed all along the coast of Sweden, the transmission to deploy any vessel could be sent from one geographic location. Upon launch, land power connection could be torn from its socket as the vessel propels off the sled. Here, water jet over stern drive propulsion is expected to simplify the procedure. Recovery may be facilitated by floating rims that lets the USV glide into place. Maintenance and refueling would be facilitated by a certain level of infrastructure around the docking station and could also be run by a central organization to minimize costs.
Placing autonomous docking stations at suitable geographic locations would also cause a significant reduction in response time, credited by missions such as responding to territorial violations, intercepting suspicious crafts or search and rescue operations. The latter an application discussed in section 7.5. In a large perspective, a docking station network could consist of several USVs with different modular payloads. Some may be equipped for search and rescue, some for surveillance and some for surface warfare depending on prioritized network capacity.
7.5 CIVILIAN APPLICATIONS

According to Swedish constitution, civil authorities in Sweden such as police, coast guard or fire brigade has the right to request assistance of military resources under certain circumstances. As an example, there is a tradition in Navy helicopter teams leading or assisting search and rescue operations. Potential civilian applications are identified below together with suggested modifications and equipment modules that might establish the USV as a valuable asset to civilian activities. A USV is particularly suitable for such tasks if it is incorporated into a network of autonomous docking stations as described in section 7.4 since that would imply a exceptionally quick response time.

Search And Rescue. A USV could prove a valuable resource in situations where the distressed are conscious. After being guided to the location from a ground station, aerial or manned vessel platform, the USV could simply serve as a flotation device and transport distressed to an area where further aid is accessible. This resembles the ambition with an existing product named SEAL as described in the appendix. The USV concept might in some cases prove suitable for the task due the low freeboard level, facilitating for distressed to climb aboard. The USV may also provide with close up images from an onboard camera with infrared capability, particularly valuable for e.g. assessing accidents with involving large passenger ships, and assist towing operations.

Fire fighting. By replacing the weapon station with a water cannon the USV could assist fire fighting aboard ships or static structures. The Swedish company Unifire specializes on water cannons for a wide variety of applications. The smallest of which is named Force 50 and is seen in Figure 32 mounted on a mobile robotic platform. The cannon is adapted to remote or autonomous control and may be modified with a variety of difference nozzles depending on application, adding foam is also possible. According to [42], maximum flow of the Force 50 is 2000 liters/min at 10 bars, implying the need for powerful pumps is a cannon to be installed on a USV.

Maritime Security & Harbor patrol. A USV could be an efficient force multiplier for long and monotonous assignments such as surveying fishery and border patrol. These tasks are under Coast Guard responsibility but even so thought to represent the most common in national waters during peace time operation should USVs be put into service. Another aspect of maritime security is anti-piracy. A USV equipped with non-lethal weapons is could be extremely effective in protecting merchant vessels from pirates. During international anti-
piracy missions the Swedish Navy could aid with continuous USV operation with the command vessel Karlskrona as host ship. In order to extend mission range, merchant vessels may act as communication nodes so that the USV may still be operated from the host ship, or USV control could be temporarily handed over to any merchant vessel travelling through dangerous waters. An LRAD (Long Range Acoustic Device) is an appropriate piece of modular equipment for maritime security missions. Capable of generating 143 dB at close distances and stable 100 dB at up to 500 meters the LRAD 300X-RA of Figure 33 is an efficient non-lethal weapon and hailing device appropriate for small vessel mount [44]. It weighs about 13 kg and consumes 25 W of power.

![Figure 33, the LRAD 300X-RA (44).](image)

Environmental protection. USVs may be equipped with sensors to collect radiological, chemical, biological and geophysical data. Connected to maritime security, such features could aid in determining contaminant spread and could also imply a valuable resource for protecting and surveying the nuclear power plants situated at the shorelines of Sweden. Another identified USV application is quick reaction to environmental disasters such as oil spills. A USV may be controlled from any aircraft from where oil spills are more easily detected and aid in mechanically removing oil from the surface as shown in Figure 34, a personnel demanding task with a high degree of simplicity, making it suitable for semi-autonomous USV insertion.

![Figure 34, detaining oil spill (45).](image)
8 Resulting Concept

The final suggested USV concept is presented below. It is a result of the market investigation, concept generation procedure and design iterations as described in this thesis. Figure 36 summarizes features and details of the concept and Table 22 gathers main particulars. When two values are given for a specific particular, they refer to the USV being partly submerged and the case where transoms are hatched. The concept USV meets all design requirements specified by Table 1.

Figure 37 illustrates the semi-submerged level of flotation of the concept USV. The reduced signature and increased ballistic protection obtained in this way for low velocities ensures
two out of three fundamental factors of efficient warfare always are fulfilled; cover, fire and movement. Cover from surrounding water and reduced signature is achieved at the cost of speed, and vice versa. A conventionally hulled vessel may only have this ability by adding structural ballistic protection at the cost of weight.

Table 22, main particulars.

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<tr>
<td>Length overall [m]</td>
<td>6.7</td>
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<td>Waterline length [m]</td>
<td>6.2</td>
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<tr>
<td>Beam [m]</td>
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<tr>
<td>Draft [m]</td>
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<tr>
<td>Height, antenna excluded [m]</td>
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<tr>
<td>Height, keel to deck [m]</td>
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<tr>
<td>Power [kW]</td>
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<tr>
<td>Max. speed [knots]</td>
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<td>476</td>
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</table>
9 CONCLUSIONS

One conclusion to be drawn based on investigations and analyses conducted as part of this study, concerns the unconventional aspect of the suggested concept. Considering the outcome of the semi-submersible feature at cost of decreased simplicity compared to a conventional design, the feature may easily be rejected as not worth the effort. Although the market investigation and concept generation phase of this study pointed toward such a feature as highly appropriate for a USV, the achieved increase in ballistic protection and stealthy signature for low velocities corresponds to an increase in maximum draft of approximately 7 cm (refer to Table 18). The increase in draft due to the ballast volume feature may be seen as significant relative to the overall height of the hull, but less significant when considering the overall height of the concept including weapon station and sensors.

In order to lower the static profile and signature of the concept further, one measure could be to add weight and move the center of gravity forwards. As seen in Figure 36, lowering the static trim would submerge a large portion of the bow. Moving the center of gravity forwards might on the other hand give rise to negative trim at high velocities, a tendency seen in Figure 21. Negative trim could to part be prevented by installing sterndrive propulsion but to cost of complications in transport and lessened maneuverability.

Another conclusion includes structural aspects of the concept. For a vessel of such small size, the level of robustness may be considered limiting. As highlighted by classification societies, global and local loads acting on the vessel once in operation are not as structurally demanding as the loads that may potentially arise during e.g. deploying or beaching the vessel. Despite the fact that the vessel is unmanned and may theoretically be subject to lessened structural safety factors, one may reason that an acceptable level of robustness is only achieved through the use of constructions similar to that of manned vessels, the possible decrease in structural weight therefore not substantial. Further USV developments of similar size may consequently be facilitated by making use of existing hulls, while larger USV developments may be credited by novel designs.

Despite the degree of applicability of the specific concept derived herein, it is clear that both the need for an unmanned option at sea and required technical prerequisites are highly present.
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11 APPENDIX: CATALOG OF EXISTING USV PRODUCTS & CONCEPTS
Catalog of Existing USV Products & Prototypes

- Gathered as part of conceptual study market investigation -

2014-03-04

Note:
- Contains images and description of 24 products.
- Alphabetical order by product name.
- Info taken from manufacturers or second hand sources.
- Stated displacement/speed is for fully equipped hull without additional payload.
1. ACTUV

**Anti-Submarine Warfare Continuous Trail Unmanned Vessel.**

**Key features:** DARPA (USA’s equivalence to FMV) funded project launched in 2010. Optimized towards offshore submarine tracking for up to 90 days. Full autonomy with wide array of tactics adopted from gamers simulator and compliance with maritime laws. Project budget: $58. Pictures shows one of the concepts by SAIC.

**Length/beam/draft:**

**Displacement/ top speed:**

**Equipment:** mid- & high frequency, active & passive sonars, total field magnetometer

2. Barracuda

**Producer:** Meggit Training Systems.

**Application:** target drone

**Key features:** Previously used by the Swedish Navy. Line-of-sight control using VHF. Operator control camera and impact detection camera images transmitted via shark fin antenna. May also be configured for mine sweeping operations. Based on Navy standard RIB.

**Length/beam/draft:** 7.24/2.75/0.84 m

**Displacement/top speed:** 2074 kg/56 knots

**Equipment:** Scanning Projectile Impact Evaluation System, active / passive radar augmentation, winch.

3. C-Hunter

**Producer:** ASV Global

**Applications:** hydrographic survey, mine countermeasures, underwater surveillance

**Key features:** semi-submerged hull and low speed enables long endurance and exceptional seakeeping. Diesel-electric.

**Length/beam/draft:** 6.3/0.65/2.0 m

**Displacement/top speed:** 2000 kg/6 knots

**Equipment:** multi-beam, echo sounder & sidescan sonar
4. C-target 3
Producer: ASV Global
Applications: target drone
Key features: light weight and easily deployed with single point lift. Can operate individually or as part of swarm. Rugged aluminum hull, and protected outboard engine makes drone robust.
Length/beam/draft: 3.25/1.4/0.6 m
Displacement/top speed: 325 kg/25 knots
Equipment: UHF communications, real time video link and Missed Distance Indicators (MDI).

5. Project: Espadon, concept Sterenn Du
Producer: DNCS, Thales & ECA collaboration, together with the French Navy. Hull by Pech’Alu International
Application: mine clearance
Key features: the demonstrator Sterenn Du is optionally manned and capable of deploying both a towed array sonar and mine disposal vehicle. Weight of such equipment motivates size of Sterenn Du. Able to launch and recover in sea state 4.
Length/beam/draft: 17 m/7.5/unknown
Displacement/top speed: ≈25 000 kg/unknown
Equipment: AUV and ROV for mine detection and clearance. System for deploying these.

6. HWT X-3
Producer: Harbor Wing
Applications: surveillance
Key features: vertical wing sail and complementing diesel-electric hybrid drive ensures endurance up to 3+ months. Retractable foil option for high top speed. American coast guard has placed an order for cost efficient surveillance of natural reserves.
Length/beam/draft: 15.2/12.2/3 m
Payload cap./top speed: 680 kg/25 knots
Equipment: powerful radar & telemetry capabilities

7. Interceptor
Producer: 5G Marine
Applications: harbor patrol & force protection
Key features: conventional hull modified with stealthy top structure. Fitted with multi-fuel engine. Control system compatible with same protocol as UAVs for seamless integration.
Length/beam/draft: 7/2.5/0.41 m
Weight/top speed: 1590 kg/47 knots
Equipment: day- and night vision camera, generator, underwater sensors.
8. MANTAS
Producer: MARTAC
Applications: surface & sub-surface coverage.
Key features: Man-portable Tactical Autonomous System. Scalable hull from 0.5 to 25 m. High speed surface and submerged operation. Combines hybrid propulsion with underwater glide for endurance. Designed for air drop and self-righting.
Length/beam/draft: unknown
Displacement/top speed: unknown
Equipment: Iridium & 4G communications, variety of sensors, solar re-charge.

10. Mistral
Producer: M Ship Co.
Applications: wide array missions with modular payloads
Key features: the Mistral USV is a concept based on MShipCo’s Stiletto M-hull (fig 10.1) with an open systems architecture that provides large onboard area for a variety of payloads. Optionally manned
Length/beam/draft: 14.6/6.1/unknown
Displacement/top speed: 11 340 kg/35 + knots (light load)
Equipment: Pre-programmed loss-of-comms plan, convoy auto-follow, self-tuning autonomous control, UHF RF link.

9. MiniVAMP
Producer: ACSA, France
Application: virtual mooring of GPS-tracking buoy
Key features: Virtually Anchored Multipurpose Platform, represents a low-cost version of limited autonomy. Intended to carry ACSAs GIB-technology, where the exact 3D metric position of an underwater vehicle nearby may be determined using synched GPS-time between surface platform submersible.
Length/beam/draft: unknown/unknown/0.75 m
Displacement/top speed: 60 kg/3 knots
Equipment: GIB-transmitter/receiver, solar panels, electric motor.
11. MUSCL  
**Producer:** U.S. Naval Surface Warfare Center  
**Applications:** Intelligence-Surveillance-Reconnaissance (ISR)  
**Key features:** Modular Unmanned Surface Craft Littoral. Simple design to be carried onboard riverine patrol boats and act as "point", investigating threat before the manned platforms arrive. Based on conventional planing hull. First 3 delivered to US Navy in 2012 to a cost of $700 each. Rolls Royce awarded contract to develop 100mm water jet for MUSCL.  
**Length/beam/draft:** 1.5 m/unknown/unknown  
**Displacement/top speed:** 39 kg/unknown

12. Owl MkII  
**Producer:** DRS Technologies  
**Application:** ISR / force protection  
**Key features:** compact size, low profile and high stability Jet-ski hull. Wide array of modular payloads. The first US Navy operational USV, successfully deployed in the Middle East 1993-2000, then with towed side-scan sonar. Publicly available footage testifies for ability to keep high speed despite rough water and small size.  
**Length/beam/draft:** 3/1.65/0.2 m  
**Displacement/top speed:** 500 kg/30 knots (dry)  
**Equipment:** LRAD, cameras, noise-silencing system, radar

13. Pioneer  
**Producer:** Njordworks  
**Applications:** water testing, oil spill cleanup, survey  
**Key features:** highly portable, semi-autonomous control. Air propeller pod driven by electric engine enables operation despite debris or ice and high maneuverability.  
**Length/beam/draft:** 1.07/0.64/0.1 m  
**Displacement/top speed:** 13 kg/2.8 knots  
**Equipment:** WiFi control, different cameras, sonar, mission specific configuration by changing nose part.

14. Pirahna  
**Producer:** Zyvex Marine  
**Applications:** long range ISR, patrol & anti-piracy missions  
**Key features:** largest nano-enhanced carbon fiber structure at time of sea trials 2010. Lightweight hull gives fuel efficiency of 45 l/h and payload capability of 6.8 tonnes, making it capable to carry torpedoes and over-the-horizon missiles.  
**Length/beam/draft:** 16.5/unknown/unknown  
**Displacement/top speed:** 3630 kg/24 knots cruising  
**Equipment:** gyro stabilized (Seakeeper)
15. **Piraya**

**Producer:** Kockums  
**Applications:** Coastal patrol & forward early warning system  
**Key features:** a demonstrator for USV group control, where 3 units may be controlled from one single operations console. USVs with different modular payloads may be teamed up in groups with composed capabilities. Integrated with legacy communication systems and other unmanned vehicles it may provide an efficient force multiplier.  
**Length/beam/draft:** 4/1.4/unknown  
**Displacement/top speed:** 400 kg/20+ knots  
**Equipment:** TV/IR cameras, radar, CBRN sensors, small fire arms

16. **Protector**

**Producer:** Rafael  
**Application:** ISR/Naval Warfare/Port Security  
**Key features:** probably the most complete USV product with 20 built units. Used frequently by Israeli, US and Singapore navies. Based on RIB hull, CAT diesel engine, jet propulsion, remotely controlled weapon. Two versions: 9m (fig 16.1) & 11m (fig. 16.2)  
**Length/beam/height:** 9/3.5/4.5 m  
**Displacement/top speed:** 4000 kg/50+ knots  
**Equipment:** LRAD, TOPLITE targeting system, weapon & boat stabilizer, water cannon (11m), laser rangefinders, missile armament demonstrated.

17. **SEAL**

**Producer:** International Submarine Engineering  
**Applications:** Search & Rescue  
**Key features:** fits inside a 76 cm pod that may be dropped from any aircraft at high altitudes using a parachute. Once in the water it inflates and navigates semi-autonomously to any distressed in the water. Extra deep keel for stability and aft ramp for easy climb aboard.  
**Length/beam/height:** 14.2/1.52/1.8 m  
**Displacement/top speed:** ≈1100 kg/5 knots  
**Equipment:** IR camera, bilge pumps, AIS, hinged hull

18. **Sea Fox**

**Producer:** Northwind Marine Inc. for Center for Autonomous Vehicle Research at U.S. Naval Postgraduate School  
**Application:** ISR/Port Security  
**Key features:** a proof-of-concept platform with several modular options including swimmer detection, radar, sonar and listen/talk capability. Aluminum RIB hull with 250 hp, jet fueled Mercury racing engine.  
**Length/beam/height:** 5.2/2.1/4.9 (w/ mast extended) m  
**Displacement/top speed:** 1100 kg/35 knots  
**Equipment:** Inertial Measurement Unit, 2D sonar, IR & EO cam.
Other USVs – Image Gallery
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