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Autonomous Systems Design

An Exploratory Research Study in the Context of Maritime Shipping

Torgeir Fjelldal

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Supervisor: Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

Preface

This master's thesis is part of the Master of Science degree in Marine Technology with a specialization in Marine Systems Design at the Norwegian University of Science and Technology (NTNU) in Trondheim. The following thesis was written in its entirety by Torgeir Fjelldal during the spring of 2018, and the work load is equivalent to 30 ECTS. The thesis is an exploratory research study focusing on the concept of autonomy and its influence on ship design within the maritime shipping industry.

The master thesis builds on the preceding project thesis written in the fall of 2017 with the topic "Proposed Methodologies for Autonomous System Design".

I would like to thank my supervisor Bjørn Egil Asbjørnslett for providing relevant literature and useful comments. I would also like to express my thanks and gratitude to
Jason McFarlane, Principle Architect at Kongsberg Maritime for helpful guidance and valuable insights into state-of-the-art developments within the Yara Birkeland project.

Finally, I would like to thank PhD Candidate Sigurd Solheim Pettersen, at the Department of Marine Technology at NTNU, for great inputs and discussions along the way.

So long, and thanks for all the fish,

Torgeir Fjelldal

Abstract

The maritime shipping industry is experiencing a rapid development towards utilizing autonomous systems to a greater extent. These systems are capable of decision-making and executing actions on behalf of or in cooperation with humans, rendering conventional shipping operations to be performed by unmanned vessels possible. The disruptive effects of autonomy will challenge conventional methods for designing and operating ships. Most marine systems can be fundamentally redefined, opening up possibilities for new ideas and innovation.

The objective of the master's thesis was to investigate how autonomy will affect the existing systems on board a conventional container ship as it is expected that many functions previously carried out on the vessel itself can be performed at remote locations or be proven redundant. This was the foundation for the first research question: *Which physical system changes will result from including autonomous capabilities in ship design of a conventional container vessel?* Due to the novelty and disruptiveness of autonomy it is important to explore how existing approaches can be adapted to assess the uncertainty and complexity associated with including autonomy in the design of future marine systems. This leads to the second research question: *Which methodologies exist that can provide decision support for autonomous systems design?*

To answer the research questions, an exploratory research study was carried out by reviewing available literature on autonomous visions and projects to identify trends in the systems architecture needed for achieving autonomous capabilities as well as highlighting design challenges and potential barriers from different relevant aspects. This became the foundation for the case study where a selection of applicable design methodologies were used to gain insights in the relationships and interactions between the various on-board systems of a container ship and a proposal for a functional breakdown and changes to the on-board systems for an autonomous container ship was developed. Further, a demonstration of the autonomous job analysis method was applied to investigate if it could uncover additional design challenges and functional requirements related to autonomous operations.

Due to limitations in available information and the early phase of development in autonomous systems design within the maritime shipping industry, reaching a quantitative conclusion to the research questions was not an objective for this exploratory research study. The thesis concluded on the first research question that determining *which* physical systems on board the vessel are going to change was not achievable at this stage of development. This is because of the disruptive effects and uncertainties related to autonomy as well as the immense amounts of possibilities in the systems design. However, generic ways of *how* the mapping between functional requirements and design parameters was identified, which is valuable to understand from a systems design point of view as it gives insights into how the physical systems is affected by autonomy.

Finally, the autonomous job analysis was proven as an efficient method to provide decision support for uncovering additional functional requirements for the autonomous capabilities needed for different parts of the voyage. Thus answering the second research question. For further work it would be desirable to perform a more comprehensive analysis on the presented case study. However, that would require a multitude of expertise from disciplines such as marine systems design, information and communications technology (ICT) architecture and cybernetics. The author believes that the combination of different areas of competencies is a key factor for achieving a more holistic autonomous systems design.

Sammendrag

Sjøfartsnæringen opplever en rask utvikling mot å benytte seg av autonome systemer i en større grad enn før. Disse systemene er i stand til å ta avgjørelser og gjennomføre oppgaver på vegne av eller i samarbeid med mennesker. Dette gjør at konvensjonelle skipsfraktsoperasjoner kan bli utført av ubemannede fartøy. Effektene av autonomi vil utfordre konvensjonelle metoder for å prosjektere og operere skip. I tillegg kanl de fleste marine systemer bli fundamentalt omdefinert noe som gir muligheter for nye ideer og innovasjon.

Målet med masteroppgaven var å undersøke hvordan autonomi vil påvirke eksisterende systemer ombord et konvensjonelt containerskip, da det forventes at mange funksjoner tidligere utført på selve fartøyet kan utføres på land eller blir unødvendige å inkludere i skipsdesignet. Dette var grunnlaget for det første forskningsspørsmålet: *Hvilke endringer i fysiske ombordsystemer vil oppstå som følge av å inkludere autonome evner i skipsdesign av et konvensjonelt container-fartøy?* Det vil også være viktig å undersøke hvordan eksisterende prosjekteringsmetoder kan tilpasses for å vurdere usikkerheten og kompleksiteten forbundet med å inkludere autonomi i utformingen av fremtidige marine systemer. Dette fører til det andre forskningsspørsmålet: *Hvilke metoder kan gi beslutningsstøtte for prosjektering av autonome systemer?*

For å svare på forskningsspørsmålene ble det gjennomført en forskningsstudie der tilgjengelig litteratur om autonome visjoner og prosjekter ble brukt for å identifisere trender innen systemarkitektur for autonomi, samt å fremheve utfordringer og potensielle barrierer fra ulike relevante aspekter i den maritime næringen. Dette ble grunnlaget for case-studien hvor et utvalg av anvendelige prosjekteringsmetoder ble brukt for å få innblikk i samspillet mellom de ulike ombordsystemene til et containerskip. I tillegg ble det laget et forslag til systemendringer for et autonomt containerskip. Videre ble prosjekteringsmetoden *autonomous job analysis* anvendt for å undersøke om den kunne avdekke ytterligere designutfordringer og funksjonelle krav knyttet til autonome operasjoner.

På grunn av begrensninger i tilgjengelig informasjon og den tidlige utviklingsfasen av autonome systemer innen sjøfartsnæringen var det ikke et mål for denne forskningsstudien å nå en kvantitativ konklusjon på forskningsspørsmålene. Masteroppgaven konkluderte på det første forskningsspørsmålet at det ikke var mulig å bestemme *hvilke* av de fysiske systemene ombord på skipet som kom til å måtte endres. Dette skyldes at autonome skip fortsatt er i utviklingsstadiet og at det er enorme endringsmuligheter i ombordsystemene. Imidlertid ble det identifisert generiske måter om *hvordan* endringene i relasjonene mellom funksjonelle krav og designparametere vil komme til å være som forfatteren av denne masteroppgaven mener er verdifullt å forstå fra et prosjekteringssynspunkt.

Til slutt ble *autonomous job analysis* vist som en effektiv metode for å gi beslutningsstøtte i å avdekke funksjonskrav til autonome evner som trengs for ulike deler av operasjonen til containerskipet som besvarer det andre forskningsspørsmålet. For videre arbeid ville det vært ønskelig å utføre en mer omfattende analyse av den presenterte casestudien, men forfatteren av denne masteroppgaven vil påpeke at det ville kreve en rekke ekspertise fra disipliner som marin prosjektering, informasjon og kommunikasjonsteknologi (IKT) arkitektur og kybernetikk. Forfatteren av denne masteroppgaven tror at å kombinere forskjellige kompetanseområder er en nøkkelfaktor for å oppnå en mer helhetlig løsning ved prosjektering av autonome systemer.

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Chapter 1

Introduction

1.1 Background

In 2013, the German government released a memo containing a state-of-the-art technology strategy document which outlined a plan for a fully computerized and unmanned manufacturing industry. The memo referred to the implications of this plan to be a paradigm shift in industrial manufacturing and it was coined *Industry 4.0*. This is also commonly referred to as the fourth industrial revolution (Kagermann et al., 2013). While there are many technologies related to the new industrial advances, Hermann et al., 2016 denotes four main design principles for Industry 4.0:

1. Interoperability - meaning that machines, devices and sensors are able to connect and communicate via the Internet of Things (IoT) and exchange data
2. Information transparency - using sensor data to create virtual copies of physical objects for analysis and to achieve higher-value context information. More frequently referred to as digital twins
3. Technical assistance - supporting humans by aggregating and visualizing information to aid in decision-making as well as relieving humans from difficult or unsafe tasks by the use of cyber-physical systems
4. Decentralized decisions - the ability of cyber-physical systems to make own decisions at various levels of autonomy

The intention with these four design principles is to clarify the basic understanding of the term Industry 4.0 and can be used for identifying and implementing Industry 4.0 scenarios. These design principles also opens up for new possibilities in other industries apart from manufacturing as well and is becoming a revolutionary factor for new developments within the shipping industry.

Figure 3.12 below shows an illustration of technological areas adopted from Industry 4.0 presented in Berge et al., 2017 which are relevant for the shipping industry:

Figure 1.1: Technological Areas Adopted From Industry 4.0 (Berge et al., 2017)

As the vessel becomes smarter in terms of an increased number of connected sensors on board, they will produce massive amounts of data. This will no longer only be data related to the vessels position, but also information regarding weather, surrounding elements, status of onboard equipment and cargo (Berge et al., 2017). To comply with the increased data produced by the vessels, several actors within the maritime shipping industry have now developed digital ecosystem platforms to integrate all the different kinds of information that is obtained and provide advanced data analytics from vessel data which can be used to predict, plan, simulate and optimize the maritime assets performance throughout the entire life-cycle for the stakeholders.

Berge et al., 2017 considers that both Internet of Services at Sea (IoSS) and Robotics and Autonomy will be possible game changers for the shipping industry. The article points out that Internet of Services at Sea will allow an increased amount of services to be performed on shore, such as planning and optimization of the vessels route, technical and commercial performance monitoring and maintenance planning. Further, developments within robotics and autonomy opens up the possibility of implementing autonomous systems into vessels which are capable of decision-making and executing actions on behalf of or in cooperation with humans. These two key technological areas combined are essential factors for rendering conventional shipping operations to be performed by unmanned vessels possibly by reducing the need for human presence on board. Autonomous and unmanned ships will challenge conventional methods for designing and operating ships, and most marine systems can be fundamentally redefined, opening up possibilities for new ideas and innovation.

1.2 Research Questions

The basis for the problem lies in the disruptive effects autonomy will have on ship design and the various design challenges that occurs, which must be identified and considered as a part of the design process. A goal of this master's thesis is to investigate how autonomy will affect the existing systems on board a conventional container ship as it is expected that many functions previously carried out on the vessel itself can be performed at remote locations or be proven redundant. The introduction of new functional requirements may also occur as an effect of including autonomous capabilities in ship design. Thus, the first research question for this master's thesis becomes:

1. *Which physical system changes will result from including autonomous capabilities in ship design of a conventional container vessel?*

The idea of autonomy has existed for quite some time but has traditionally only been used to some extent in the maritime industry so far. A reason for this may be the fragmented systematic knowledge of designing autonomous systems for maritime applications. Due to the novelty and disruptiveness associated with autonomy it is important that new methodologies tailored for autonomous systems are developed, as well as exploring how existing approaches can be adapted to include autonomy in the design of future marine systems. This leads to the second research question:

2. *Which methodologies exist that can provide decision support for autonomous systems design?*

1.3 Objective

To address the research questions earlier stated the following objectives will be covered:

1. Present a literature review by documenting the following:
    (a) An introduction to the concept of autonomy.
    (b) The state-of-the-art applications, visions and developments of autonomy within the maritime shipping industry.
    (c) Design challenges associated with autonomous vessels within maritime shipping.
2. Document relevant approaches and methods dedicated and/or applicable for autonomous systems design.
3. Create a high-level functional breakdown for container ships with the intent to:
    (a) Identify system components that may be proven redundant when introducing autonomous capabilities.
    (b) Propose new system components required to achieve autonomous operation.
4. Develop an illustrative case study on a short-sea shipping operation with the goal of identifying the vessel operational modes and determine functional requirements for different parts of the voyage.
5. Discuss and conclude on how autonomy affects ship design in the context of maritime shipping.

1.4 Structure of the Master's Thesis

The structure of this report is laid out in the following way:

- **Introduction**
  Chapter 1 starts by stating the background for this thesis along with the problem statement and the coherent objectives that will serve as an introduction to this master's thesis.

- **Literature Review**
  Chapter 2 defines the concept of autonomy and relevant taxonomies for levels of autonomy. Chapter 4 is dedicated to give an introduction to the different envisions of autonomous systems in the maritime industry as well as highlighting some of the implications and design challenges that occurs by introducing autonomy to a marine system within maritime shipping from different relevant aspects.

- **Methodology**
  Chapter 3 presents various methods, approaches and methodologies relevant for the design of autonomous systems.

- **Case Study**
  Chapter 5 presents a selection of design methodologies which are applied to a case regarding an autonomous container ship with the primary intention of demonstrating the methods applicability, as well as gaining insights into the systems design and uncover functional requirements related to the operations of the vessel.

- **Discussions**
  Chapter 6 gives a reflection on the various topics specified in the literature review on the concept of autonomy and the various design challenges related to autonomous systems design is first presented before a discussion on to the research questions.

- **Conclusion and Further Work**
  Chapter 7 concludes on the research questions posed in Chapter 1 and gives recommendations for further work to be done within this topic.

Chapter 2

Autonomy

> *"I am putting myself to the fullest possible use, which is all, I think, that any conscious entity can ever hope to do"* – HAL 9000, 2001: Space Odyssey

The word "autonomy" originates from the Greek words *auto* and *nomos* meaning "self" and "law" respectively. The concept of autonomy also has its roots in ancient Greek philosophy in the idea of self-mastery where it was first used to characterize self governing city states (Dryden, 2017). It was not until the Enlightenment Age of the 18th century that autonomy was considered as a moral action determined by a person's free will through the work of the philosopher Immanual Kant (Zweig, 1967). However, autonomy as a concept of a persons own free will only encompasses one way in which the term is used. Throughout history there has been developed several interpretations of this terminology within areas such as philosophy, psychology and most relevant to this master's thesis; technology.

When referring to technological autonomy one speaks of a technology-based system that is able to demonstrate some level of artificial free will by making its own decisions about its actions while performing different tasks, without the need for the involvement of an exogenous system or operator (Albus et al., 1998). The next sections will provide a further introduction to understanding the concept of autonomy.

2.1 Autonomy vs. Automation

Both *automation* and *autonomy* are often used interchangeably and it is difficult to distinguish one from another. In fact, there exists many different definitions and taxonomies for both concepts making it challenging to draw a clear line between the two. This subsection will present characteristics of automation and autonomy and how these two concepts compliment one another.

The term automation is usually associated with industry, manufacturing and robots with many of the available definitions being related specificly to industrial applications. Groover, 2014 refers to automation as:

> *"A set of related functions performed automatically by equipment. Automation assumes that the operator performs any requirements before or after the automated sequence in order to complete the task."*

While T. Sheridan et al., 2000 provides a more generic definition focusing less on the tangible embodiment of automation as:

> *"A device or systems that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator".*

An industrial example of automation could be a conveyor belt that has replaced human operators by installing an automated system. The system detects the size and position of various objects with a vision system and correctly adjusts the grasp of a robotic arm by using a look-up table to for instance sort the objects. However, if an unfamiliar object is identified by the vision system it would most likely not be able to adjust the grasp correctly causing a deviation from the operational goal of sorting objects in a non-damaging and correct manner (Garcia et al., 1989).

More generally, an automated system is characterized by having well-defined functions with a pre-programmed link between sensor input and system output and operates in structured, often repetitive, known environments. While the task is performed more or less without any human intervention, the systems input and response are designed by an operator ahead of time, giving the system limited capabilities to handle unforeseen situations (Ekornsæter et al., 2012).

The first distinction between the two concepts is that a fully autonomous system has the capability to handle unforeseen situations by performing problem solving operations without human intervention. With that being said, automated functions are often embedded in autonomous systems. Referring to the previous example, when encountering an unfamiliar object the robot manipulator system uses the same automated functions such as vision-based object detection and sensor-based collision avoidance. However, the system can then adjust the grasp correctly to handle the unknown object by using methods that enables system learning, providing the system with autonomous capabilities (Sutton et al., 1998).

(Ekornsæter et al., 2012) argues in their article that in order for a system to be autonomous it must possess one or more of the following capabilities:

- *Learning:* Improvement through practice, experience or by teaching
- *Reasoning:* Generate conclusions from available knowledge
- *Planning:* Construct a sequence of actions to achieve a goal
- *Decision making:* Select a course of action among several alternative scenarios - includes a notion of expected action outcome
- *Situation awareness:* The ability a system has to perceive its surroundings
- *Actuation:* The ability to physically interact with its environment
- *Human Machine Interfaces (HMI):* How the autonomous systems interact with humans

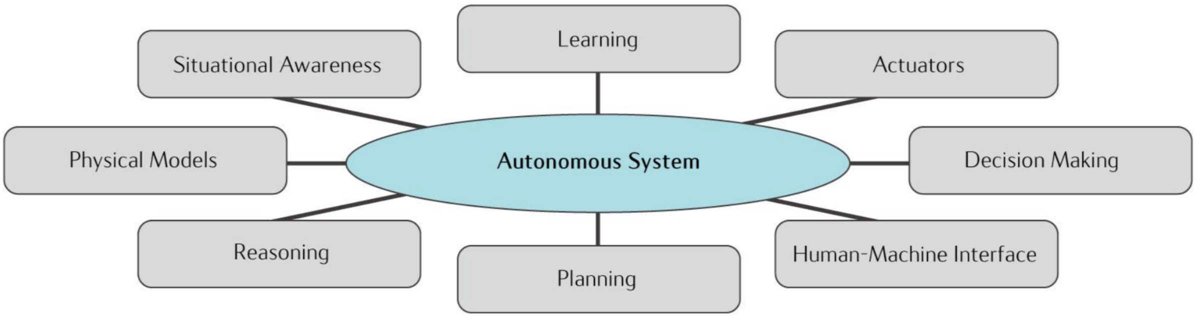


Figure 2.1: Capabilities of an Autonomous System (Ekornsæter et al., 2012)

Figure 2.1 gives a descriptive overview of the capabilities associated with autonomous systems. However, conceptualizing autonomy is not a straight forward process and most of the definitions are found within robotics literature. This is due to the fact that robots usually are the physical embodiment of an autonomous system that are capable of performing physical actions. Beer et al., 2014 have carried out an extensive literature study regarding various definitions of autonomy found in robotics literature. In addition, the article provides its own general definition of autonomy more suitable for the purpose of this master's thesis as:

> *"The extent to which a system can carry out its own processes and operations without external control."*

Note that the definition begins with the phrase, *"The extent to which..."*. This indicates an important assumption regarding autonomy. It is a common misconception to think of autonomy as concept that is either *all* or *nothing* while it should rather be considered as continuously ranging from no autonomy to full autonomy. This emphasizes the need for a proper taxonomy that describes the extent of autonomous capabilities for a system. Thus, the next subsection is dedicated to present various taxonomy for autonomy.

2.2 Levels of Autonomy

Various taxonomies have been proposed as a classification system to model the levels of automation and autonomy. During the literature search for taxonomies it is observed that many authors tends to use the term automation over autonomy even when referring to systems that is indeed *"free to make own choices"*. This is also brought up and discussed in Vagia, Transeth, et al., 2016. Hence, the taxonomies in this master's thesis will be presented the same way as the authors do it in their respective articles.

Sheridan and Verplank (1978) proposed a 10-point scale that specified function allocation between the automated system and humans as well as what information is communicated. The taxonomy is among the oldest that can be found in the literature and has been the basis for many others taxonomies (Vagia, Transeth, et al., 2016).

Table 2.1: Levels of Automation (T. B. Sheridan et al., 1978)

Level of Automation	**Description**
1.	Fully manual control
2.	The computer offers a complete set of decision/action alternatives
3.	The computer narrows the selection down to a few
4.	The computer suggests one alternative
5.	The computer executes that suggestion if the human approves
6.	The computer allows the human a restricted time to veto before automatic execution
7.	The computer executes automatically, then necessarily informs the human
8.	The computer informs the human only if asked
9.	The computer informs the human only if it decides to
10.	Fully autonomous Control

The scale has some shortcomings worth mentioning. The various levels in Table 2.1 focuses on the output functions of decision-making and action selection while lacking description regarding input functions such as information acquisition, i.e. perception of the environment. M. R. Endsley et al., 1999 proposed a revised taxonomy of 10 levels to be used in the context of teleoperations that laid more emphasis on the input functions and has a clear distinction in who has the greater authority at each level.

Table 2.2: Levels of Automation (M. R. Endsley et al., 1999)

Level of Automation	**Description**
1. Manual Control	The human performs all tasks including monitoring the state of the system and holds the main role.
2. Action Support	The human still holds a main role and the system assists with performance of the selected action. Some human action might be required.
3. Batch Processing	Human generates and selects the options to be performed, which are later on turned over to the system to be carried out automatically.
4. Shared Control	Both the human and the computer generate possible decision options. The human retains full control over the selection of which option to implement, however, carrying out the actions is shared between the human and the system.
5. Decision Support	The computer generates a list of decision options, which the human can select from. The operator may generate his or her own options. Once the human has selected an option, it is turned over to the computer to implement.
6. Blended Decision Making	The computer generates a list of decision, which selects from and carries out if the human consents. The human may approve of the option or select another one from the computer or operator.
7. Rigid System	The system presents only a limited set of actions to the operator and the option is restricted to them. The operator has little discretion on the option.
8. Automated Decision Making	The system selects the best option to implement and carries out that action, based upon a list of alternatives it generates.
9. Supervisory Control	The system generates options, selects the option to implement and carries out that action. The human mainly monitors the system and intervenes if necessary.
10. Full Automation	The system carries out all actions. The human is completely out of the control loop and cannot intervene.

A conceptual model for types of levels of automation was proposed by Parasuraman et al., 2000. The model starts with defining the process that should be automated before breaking up the process of deciding the level of automation by identifying types of automation required divided into four stages. Automation categorized within *information acquisition* stage relates to the sensing and registering of input data necessary to perform the activity. The automated functions needed to assess the various input data is identified in the *information analysis* stage which creates the basis for the automation needed in the *decision selection* stage to select from decision alternatives. Finally, the automation needed to execute the entire or parts of the chosen action is identified in the *action implementation* stage. This model differs from the others in the way that the initial level of autonomy is evaluated by primary and secondary criteria to identify potential design issues which may lead to a re-evaluation of the chosen level of automation.

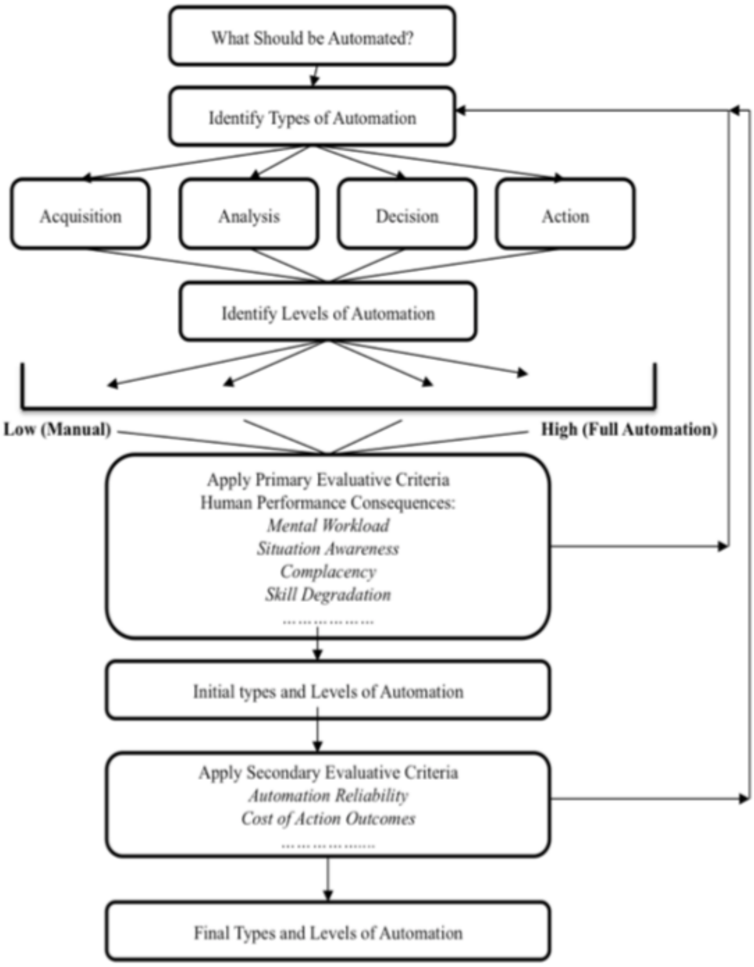


Figure 2.2: Flow Chart of the Model of Types and Levels of Automation (Parasuraman et al., 2000)

Another taxonomy that is commonly referred to in the literature is given in Table 2.3 and consists of 6 different levels varying from fully manual to autonomous control given by the US Navy Office of Naval Research (Williams, 2016).

Table 2.3: Levels of Automation (Williams, 2016)

Level of Automation	**Description**
1. Human Operated	**All activity within the system is the direct result of human-initiated control inputs.** The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
2. Human Assisted	**The system can perform activity in parallel with human input**, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input. An example is automobile automatic transmission and anti-skid brakes.
3. Human Delegated	**The system can perform limited control activity on a delegated basis.** This level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
4. Human Supervised	**The system can perform a wide variety of activities given top-level permissions or direction by a human.** The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviors that are not within the scope of its current directed task
5. Mixed Initiative	**Both the human and the system can initiate behaviors based on sensed data.** The system can coordinate its behavior with the human behaviors both explicitly and implicitly. The human can understand behaviors of the system in the same way that he understands his own behaviors. A variety of means are provided to regulate the authority of the system w.r.t. human operations.
6. Fully Autonomous	**The system requires no human intervention to perform any of its designated activities** across all planned ranges of environmental conditions.

A more simplistic taxonomy by NTNUs Centre for Autonomous Marine Operations and Systems (AMOS) given in A. J. Sørensen et al., 2017 is presented in Table 2.4 below which only considers four varying levels of autonomy.

Table 2.4: Levels of Autonomy (A. J. Sørensen et al., 2017)

Level of Automation	**Description**
1. Automatic operation (Remote control)	System operates automatically. Human operator directs and controls all functions; some functions are preprogrammed. System states, environmental conditions and sensor data are presented to operator through human-machine-interface (HMI) (human-in-the-loop/human operated).
2. Management by consent	System automatically makes recommendations for mission or process actions related to specific functions, where system prompts human operator at important points for information or decisions. At this level, system may have limited communication bandwidth, including time delay due to, e.g., physical remoteness. System can perform many functions independently of human control, when delegated to do so (human-delegated).
3. Semi- autonomous operation or management by exception	System automatically executes mission-related functions when and where response times are too short for human intervention. Human operator may override or change parameters and cancel/redirect actions within defined time lines. Operator s attention is only brought to exceptions for certain decisions (human-supervisory control).
4. Highly autonomous operation	System automatically executes mission- or process-related functions in unstructured environment with capability to plan and re-plan mission or process. Human operator may be informed about progress, but the system is independent and “intelligent” (“human-out-of-the loop”). In manned systems the human operator is in the loop, has a more supervisory role, and may intervene.

There are many factors that contributes to the requirement for autonomy and it might be difficult to determine the appropriate level of autonomy for a system. Huang, 2007 highlights that the notion of autonomy addresses only the human interaction aspect and suggests that an unmanned system required level of autonomy or as they define it, Contextual Autonomous Capability (CAC), should be:

> *"[...] characterized by the missions that the system is capable of performing, the environments within which the missions are performed, and human independence that can be allowed in the performance of the missions (Huang et al., 2007)."*

The three aspects is defined as: human independence, environmental complexity and mission complexity which are depict in the Autonomy Levels For Unmanned Systems (ALFUS) framework illustration presented in Figure 2.3 below:

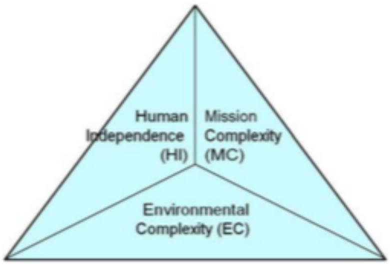


Figure 2.3: The Three Aspects for ALFUS (Huang et al., 2007)

Further, (Huang, 2007) proposes that the unmanned system is scored for the three aspects and presented in a three axis model as shown in Figure 2.4 below:

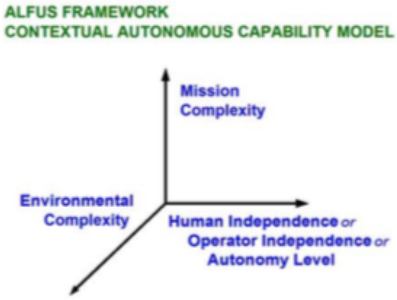


Figure 2.4: The Three-axis Model for ALFUS (Huang, 2007)

Presenting the required level of autonomy from different aspects may give better insights into the nature of the challenges facing the autonomous system and can be beneficial in terms of achieving a better system design.

While this section has only presented a few of the available taxonomies created for autonomous systems, it can be stated that it is not possible to determine a taxonomy that is best suited for all types of applications. When choosing or creating a taxonomy for levels of autonomy one need to prioritize the needs and requirements for the given application and choose a taxonomy accordingly. Further, it is usually concluded that a specific level of autonomy might not be applicable to an entire operation and will vary from different sub-tasks by the degree of complexity involved. This type of *dynamic* autonomy is highly relevant for autonomous vessels as the required amount of human interaction will depend on the state of the vessel and the sub-task that is being executed. For instance, it is believed that tasks such as navigation in the open sea can be performed fully autonomous, while more complicated parts of the voyage may require closer supervision or even be remotely controlled by the human operator. The concept of having dynamic levels of autonomy during different parts of a vessels operation will be further investigated in the following chapters.

Chapter 3

Design Methodologies Applicable for Autonomous System Design

This chapter will present different methods, approaches and methodologies relevant for the design of autonomous systems. The intention of presenting these design methodologies is to highlight important guidelines and mindsets for how to approach a design process for developing autonomous systems and elements from some of these methodologies will be used for the case study later in this master's thesis. A discussion on the applicability of the following design methodologies as decision support for autonomous systems design is found in Chapter 6.

3.1 Axiomatic Design

Axiomatic Design is a design theory developed by the Massachusetts Institute of Technology (MIT) Professor Suh Nam-pyo. The essence of this theory is that in order for a design to be considered good it must satisfy two design axioms referred to as the *Information Axiom* and *Independence Axiom*. While axioms has differences in definition when used in the context of different fields of study, it is generally referred to as something that is taken to be true and can serve as a starting point for further reasoning (Sue, 1998). Sue, 2000 describes design as the interplay between *what we want to achieve* and *how we want to achieve it*. The objective of a design is always stated in the functional domain through specific functional requirements (FR) and the physical solution are generated in the physical domain built up in terms of design parameters (DP). Sue, 2000 further defines the design process as the mapping between these two domains, satisfying the designer-made functional requirements as illustrated in Figure 3.1 below:

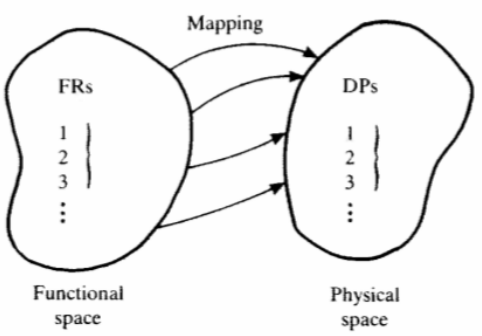


Figure 3.1: Mapping Between Functional and Physical Space (Sue, 2000)

3.1.1 Independence Axiom

The intention with the Independence Axiom is to maintain the independence of the functional requirements (FRs) of the design. In other words, to comply with the independence axiom the relationship between a DP and FR should be defined in such a way that an adjustment in DP can be done to satisfy its corresponding FR without affecting other FRs. This can be expressed by the following equation:

$$\boldsymbol{FR} = [\boldsymbol{A}]\boldsymbol{DP} \tag{3.1}$$

The notion of goodness of a design is based on the shape of the design matrix $\boldsymbol{A}$. There are three characteristics of the design matrix found in Suh's axiomatic design theory. If the matrix is a diagonal matrix, as shown in the equation below, it is defined as a uncoupled design thus satisfying the Independence Axiom.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{3.2}$$

The second characteristic of a design matrix is when it is triangular as shown in the matrix below:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{3.3}$$

This is referred to as a decoupled design matrix and will only satisfy the Independence Axiom if the design sequence is correct. Finally, the following design matrix represents what is defined as a coupled design:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{3.4}$$

This design does not comply with the independence axiom as a change in DP will affect more than one FR. This indicates that new DPs must be found to satisfy the FRs. Sue, 2000 states that the definition of a simple FR-DP may not be sufficient when considering complicated systems and proposes to decompose the system with a zigzagging process between the functional and physical domain.

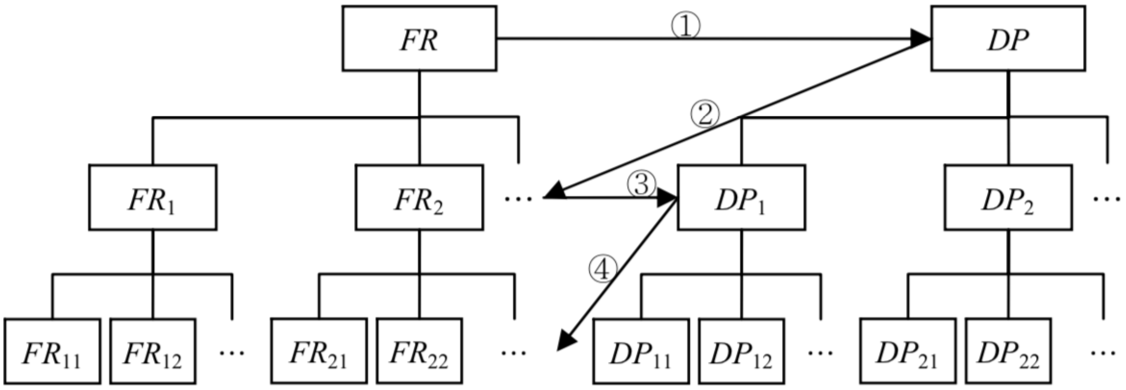


Figure 3.2: Illustration of Zigzagging between the Functional and Physical Domain (Park, 2007)

It can be seen in Figure 3.2 that the DPs are defined at the same level as the FRs while lower level FRs are based on the characteristics of the DPs in the level above.

3.1.2 Information Axiom

The second axiom of Park, 2007 is the Information Axiom which intends to minimize the information content of the design. When multiple feasible designs are found from the Independence Axiom, the most favourable design can be selected based on the Information Axiom. That is, the best design has minimum information content that is usually quantified by the probability of success. Generally, the amount of information for a design is closely related to its complexity. However, Sue, 1998 expresses that quantifying a design's level of information and measuring complexity varies according to the situation but is usually quantified by the probability of success, i.e. the probability of satisfying FR_i with DP_i.

3.1.3 Application of Axiomatic Design

Although both axioms seems to be expressed simply the real application can be difficult according to Pahl et al., 2007 and greatly depends on the expertise and experience of the designer that carries out the design process. Sue, 2000 states that axiomatic design is suitable for the following areas:

1. Creative design
2. Analysis of existing designs
3. Design improvement

When considering creative design there might be a situation where some functional requirements are defined where there does not exist a feasible product to satisfy the FR. This forces the designer to try and create a new idea for a new product and axiomatic design can then be applied to materialize the design idea by allocating and selection suitable parts. However, Park, 2007 emphasizes that the creation of an entirely new idea is very difficult and rare in machine design.

Axiomatic design can also be applied to analyzing existing products from a designers viewpoint. According to Park, 2007 a better product can be selected by referring to the Independence Axiom. If multiple products satisfies the Independence Axiom, the best design can be found from the Information Axiom.

In order to make design improvements on a design that may not be sufficiently good, the FRs and DPs are mapped out before applying the Independence Axiom. This will give answers to whether the design is considered good and can be improved by satisfying the Independence Axiom. Further, the DPs is then defined to minimize the information content, satisfying the Information Axiom. Generally, the application of axiomatic design follows a flow illustrated in Figure 3.3 below:

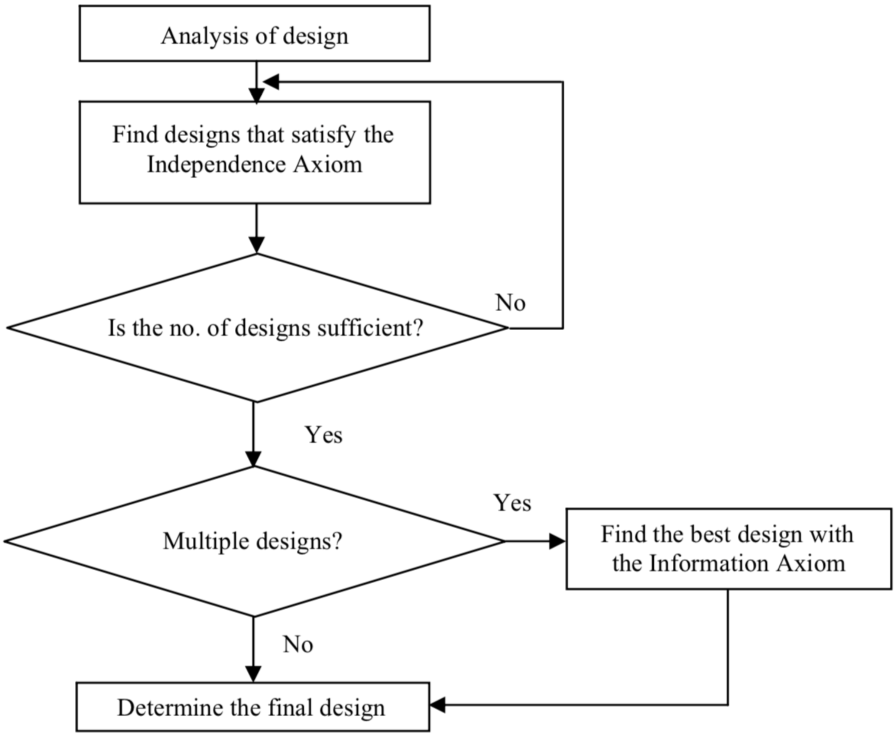


Figure 3.3: Illustration of Applying Axiomatic Design (Park, 2007)

3.2 System Based Ship Design

The System Based Ship Design (SBSD) approach is a method described in Levander, 2012 which is an alternative to the traditional design spiral model which is based upon an iterative and rather industrious *design-evaluate-redesign* structure presented in Evans, 1959. Figure 3.4 below illustrates the design process flow of the System Based Ship Design approach:

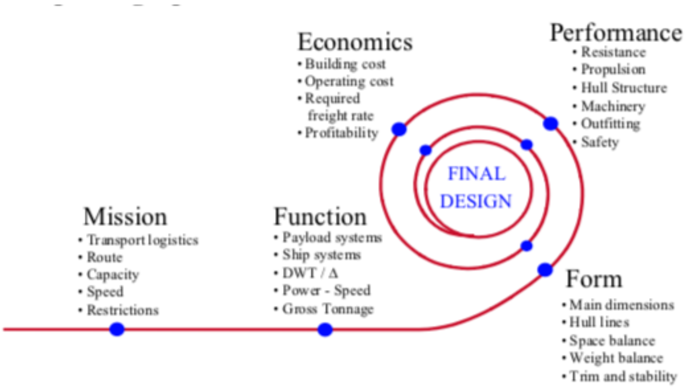


Figure 3.4: The System Based Ship Design Process (Levander, 2012)

The design process is initiated by determining the vessels mission statement before a set of functional requirements are defined in accordance with the mission which is fulfilled by a variety of systems. This creates a functional breakdown structure that displays all systems required in the vessel and are most often categorized into *payload systems* and *ship systems* and gives a structured overview of the various capabilities of the vessel. Ship systems are functions that are needed to operate the ship, independent of the cargo on board while the payload systems describes functions and requirements that generate cash flow for the vessel (Kawser, 2012). The required volumes or form of the various systems on-board the vessel is determined from a database of existing generic vessels in the same segment which together gives the required gross tonnage of the vessel before the design of the hull and general arrangement of the vessel can commence.

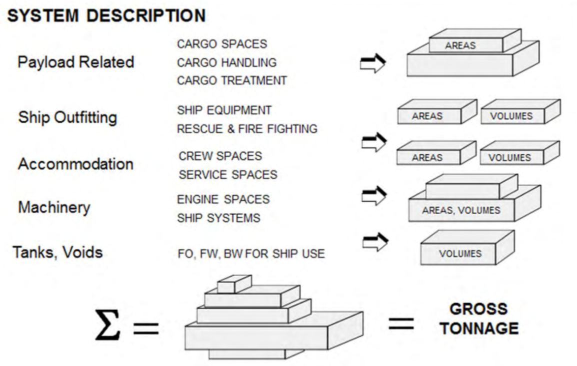


Figure 3.5: Illustration of Function-to-form Mapping in SBSD (Levander, 2012)

By preventing the designer to be locked into their first assumptions the System Based Ship Design approach facilitates for creative, novel solutions to be found in early stages of the design process as well as reducing the number of iterations needed to reach the final design. This frees up more time to improving and evaluating the design and finding alternative solutions.

3.3 Catalogue Design

This section will give a brief description of a conceptual design approach popularly referred to as catalogue design. The approach is explained in detail in Pahl et al., 2007 and provides a different way of viewing function-form mapping by the use of a database. The database could either be based on existing, previously made solutions defined on a sub-functional level and/or based on fundamental knowledge from natural science. When carrying out the design approach one develops a hierarchy of functions before generating working principles between the sub-functions, starting from the bottom of the function structure. The database should also contain knowledge of the interrelationships between the various sub-functions to ensure a working functional structure. Depending on the fidelity of the database a number of different concepts variants can be developed using this approach. This type of function-form mapping bears resemblance to the system based ship design approach as earlier presented. Figure 3.6 illustrates the mapping between the functional and physical domain as given in Pettersen, 2017.

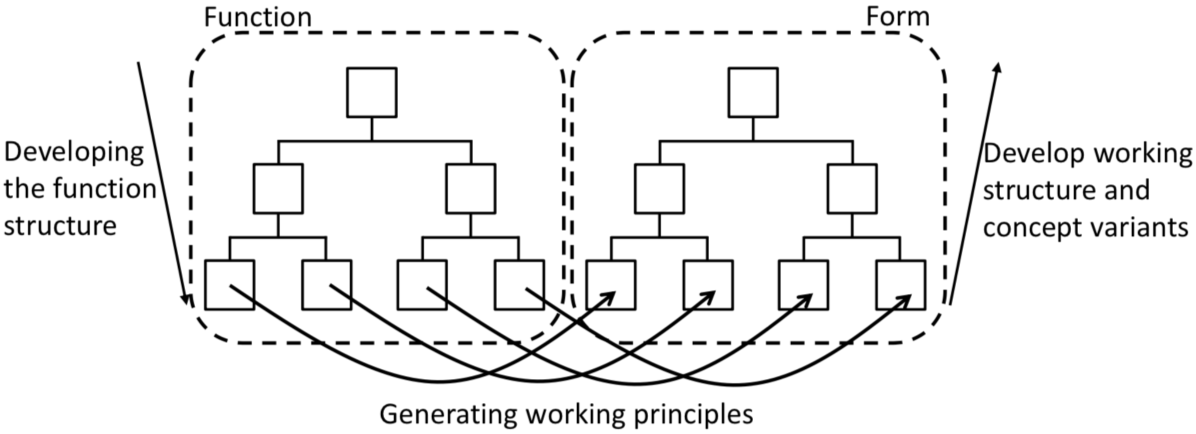


Figure 3.6: Illustration of Mapping in *Catalogue Design* (Pettersen, 2017)

3.3.1 First Principles

Closely related to defining knowledge based on natural science is first principles thinking. A first principle is a foundational assumption that cannot be deduced any further. In physics, a calculation is from first principles if it does not make empirical assumptions but begins at established laws of physics (Irwin, 1988). Applying this to human reasoning it is about boiling things down to a fundamental truth that one is sure is true and building up the reasoning from there. While first principles is trivial in its definition it is difficult to practice and is contradictory to natural human analogical reasoning. One of the primary obstacles to first principles thinking is the human tendency to optimize form rather than function. This becomes evident when reviewing developments that claims to be innovative but really is just an iteration of a previous form rather than an improvement of the core function of the product. The following excerpt from the New York Time article titled *Reinventing the Suitcase by Adding the Wheel* provides a suitable example:

> *In ancient Rome, soldiers used leather messenger bags and satchels to carry food while riding across the countryside. At the same time, the Romans had many vehicles with wheels like chariots, carriages, and wagons. And yet, for thousands of years, nobody thought to combine the bag and the wheel. The first rolling suitcase wasn't invented*

> *until 1970 when Bernard Sadow was hauling his luggage through an airport and saw a worker rolling a heavy machine on a wheeled skid. (Sharkey, 2017)*

The story highlights the human tendency to *live life by analogy* (Musk, 2015) focusing on designing a better bag (form), while Sadow considered how to more efficiently store and transport objects(function). Hence, one needs be wary of inherited ideas due to the fact that old conventions and previous forms are often accepted without question and, once accepted, can be a limiting factor for creativity (Clear, 2017).

3.4 Modularization

The term *Modularity* and *Modularization* is generally referred to the degree to which a system's components may be separated and recombined (Coltheart, 1999). However, the meaning varies with which field of study it is used in such as software development, engineering, mathematics or biology. This section will give an introduction to the concept of modularization and present a modeling technique applicable for the design of complex systems that is based on modularization.

3.4.1 Defining Modularization

(Erikstad, 2009) highlights three basic commonalities that applies for the various contexts that modularity is applicable:

1. *The division of larger systems into smaller parts or components*
2. *The principle of (relative) self-sufficiency of the individual parts*
3. *The recombination of the parts into multiple end products, according to a set of "rules" given by an overall systems architecture*

A common theme is observable in the following two definition. First, Baldwin, 2000 with the definition of modularity as:

> *"...the conscious splitting apart of a design into independent sub-units. After a modularization, a user can mix and match modules and construct different combinations"*

and in Schilling, 2000 where modularity is defined as:

> *"A general systems concept: It is a continuum describing the degree to which a system's components can be separated and re-combined."*

All three definitions brings up the possibility of mixing and matching various components as a central part of modularization rather than only splitting up a product for later assembly. This introduces a certain degree of flexibility in the way components of a system are combined. However, the reader should note that the use of a modularization methodology alone is not sufficient in order to derive a complete design solution. It is in the combination with conceptual design methodologies that modularization proves useful by extending the design space and reducing complexity in a design (Pettersen, 2017).

3.4.2 Systems Architecture

According to Tripathy et al., 2007 the architecture of a system can be looked at in many ways such as product architecture, process architecture, organizational architecture, etc. Further, Eppinger et al., 2012 defines system architecture as:

> *"The structure of a system – embodied in its elements, their relationships to each other (and to the system's environment), and the principles guiding its design and evolution – that gives rise to its functions and behaviours."*

Jankovic et al., 2016 refers to this definition by stating that in general the term *"system"* can be applied to product, process and organization, or embodiment of the three at the same time.

Generally, system architecture describes the structure of a system and can be found, to some degree, in all types of designs by defining the relationship between the systems main functions and entities. System architecture design emerged from the World War II as a part of the System Engineering Methodology which tackles the problems of complexity in a system by decomposing it into sub-systems (Blanchard, 2004). Central to the System Engineering methodology is the *Systems Engineering V-model* illustrated in Figure 3.7 below:

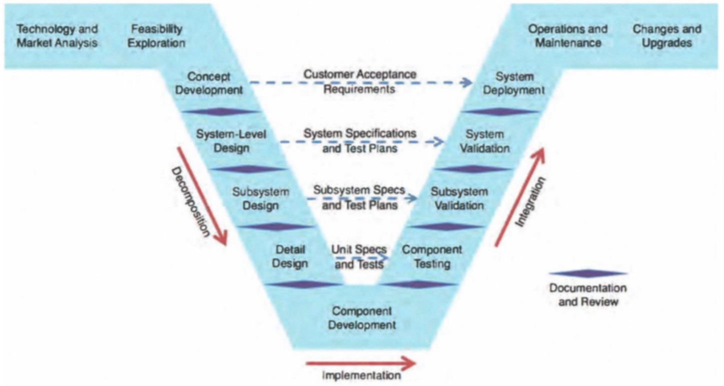


Figure 3.7: System Engineering V-model (Eppinger et al., 2012)

The V-model gives a graphical representation of a systems development life-cycle and depicts the tasks needed to be performed during a development process (Forsberg et al., 1991). The left side of the "V" represents the decomposition of the system into sub-systems along with a definition of system specifications while gradually reaching a more detailed design. The bottom and right side of the "V" relates to the implementation, integration and validation of the various sub-systems. The V-model is a frequently used model that comes in many variations within other disciplines and methodologies.

Visualizing a systems architecture can also be done by using a hierarchical tree structure presented in Figure 3.8:

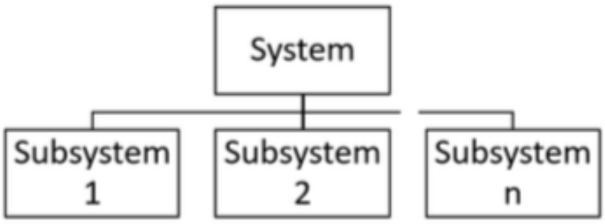


Figure 3.8: Hierarchical Tree Structure (Hölttä-Otto, 2005).

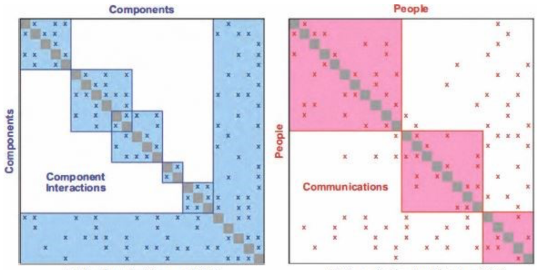
Such a structure gives a clear illustration of the relationships of the various sub-systems and enables a better understanding of the modular design (Hölttä-Otto, 2005). Another way of displaying a system's architecture is by using a Design Structure Matrix (DSM) which is presented in the next section.

3.4.3 Design Structure Matrix

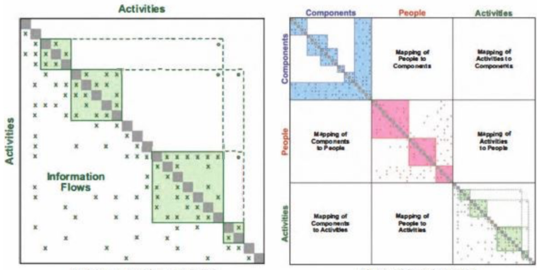
Design Structure Matrix (DSM) is a flexible modeling technique that can be used for designing, developing, and managing complex systems. The technique was first introduced by (Steward 1981) as an approach to managing the design of complex systems. More recently, in Eppinger et al., 2012 a DSM is defined as:

> *"... a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture (or designed structure)."*

Further, Eppinger et al., 2012 distinguishes between four main types of DSMs; the product architecture DSM, the process architecture DSM, the organization architecture DSM, and the Multidomain MDM. Usually, a product architecture DSM is regarding the interactions between various components in the system, an organizational DSM takes human communication into consideration while the process architecture analyses the information flow for different activities in a system. The multi domain matrix (**MDM!** combines the forementioned DSM's.



(a) Product Architecture DSM (b) Organization Architecture DSM



(c) Process Architecture DSM (d) Multidomain MDM

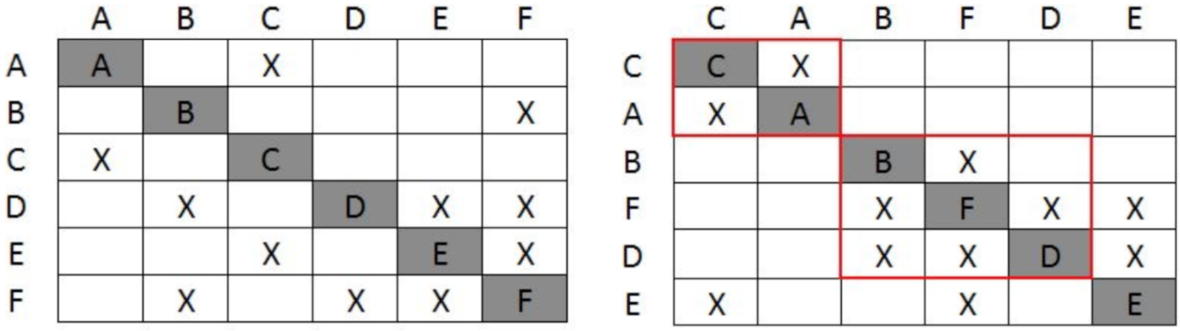
Figure 3.9: Illustration of the Four Main Types of Design Structure Matrix (Eppinger et al., 2012)

While these types of Design Structure Matrix's represents different elements the procedure of creating the DSM is similar for each type by following an analytic approach illustrated in Figure 3.10 below:

Figure 3.10: Flow of a Design Structure Matrix (Pettersen, 2017)

First the system is decomposed into a component level hierarchical system where the relationships between the system elements is identified and documented. These elements and relationships are then analyzed for structural patterns and influence on system behaviour. The findings are displayed in the DSM model, highlighting the most prominent features. Finally, actions is made based on the analysis to improve the system.

After having identified and mapped interactions, relationships and dependencies between the elements in a system, a clustering algorithm or similar can be applied to group components and/or functions together to gain insight into the possibility to establish modules in the system to increase flexibility.



	A	B	C	D	E	F
A	A		X			
B		B				X
C	X		C			
D		X		D	X	X
E			X		E	X
F		X		X	X	F

	C	A	B	F	D	E
C	C	X				
A	X	A				
B			B	X		
F			X	F	X	X
D			X	X	D	X
E	X			X		E

Figure 3.11: Example of Partitioning Components with the Use of Clustering Algorithm (Hölttä-Otto, 2005)

Figure 3.11 depicts the interactions between components with a "X" marking in the DSM. However, there are other ways to illustrate the interactions, dependencies and relationships of the system. Hölttä-Otto, 2005 presents coupling coefficients ranging from -2, -1, 0, 1, 2 to underline the strength of the interaction and/or relation between components. Another way is presented by Eppinger et al., 2012 by using colors, symbols and shadings to represent the level of interactions, dependencies and relationship within a system. This master's thesis will not discuss the displaying techniques for DSM's any further.

Advantages by using a DSM is that it can represent large complex systems in a compact and concise form. The DSM displays the system in a intuitive way and highlights relationship patterns of interest which makes it a efficient communication tool. Due to the information being presented in a matrix form there is also possible to apply powerful analytical tools. Another advantage with the matrix-format is that it is easy to extend and modify the DSM model which facilitates for flexibility. However, possessing extensive expertise and knowledge of the system is of paramount importance in order to obtain feasible results when using a Design Structure Matrix approach.

3.5 SEATONOMY

The SEATONOMY methodology is product of strategic research collaboration between various parts of SINTEF to meet the demand for coherent, structured and scientifically rooted methods and tools for designing autonomous technologies for industrial use. The intention of SEATONOMY is to provide suitable guidelines, principles, best practices and tools for developing autonomous systems. SINTEF defines an industrial autonomous system as an autonomous unit that can operate safe and efficient in a real world environment at an acceptable cost relative to the value it provides, thus distinguishing it from other academic, space and military autonomous projects (Grøtli, Vagia, Rødseth, et al., 2015).

There will be various design challenges specially related to autonomous system design and SEATONOMY provides three main high level challenges that a design methodology for industrial autonomous systems must be able to address:

- To determine a set the *right* degree of autonomy for a given application
- Ensure that all relevant critical situations have been identified, assessed and handled
- Ensure a predictable behaviour within predefined boundaries for all relevant operational scenarios

The SEATONOMY methodology assesses these challenges from three different viewpoints illustrated in the figure below:

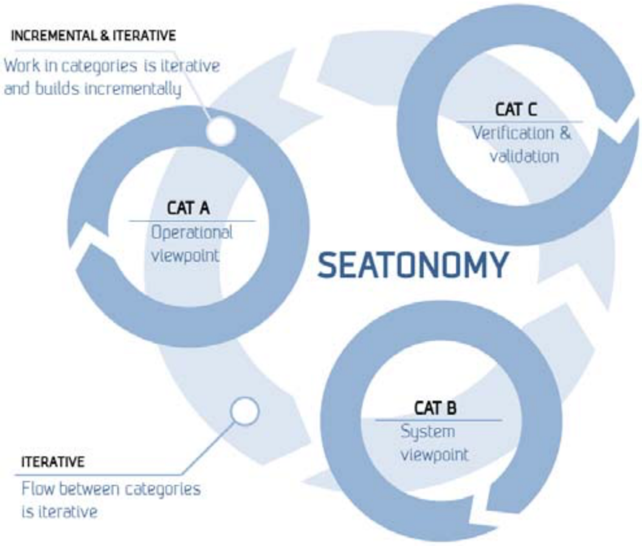


Figure 3.12: SEATONOMY Work Flow (Grøtli, Vagia, Rødseth, et al., 2015)

The reader should note that SEATONOMY illustrates the work flow as an incremental and iterative process. By doing this, one takes into account that the results from one viewpoint may lead to redesign of the next. In addition, every aspect of a design is rarely covered during the first iteration due to uncertainty and lack of detailed information at an early stage of the design process.

The next subsections will provide an in-depth explanation of the three different viewpoints.

3.5.1 Category A: The Operational Viewpoint

The operational viewpoint's purpose is to determine the performance aspects of the autonomous system without considering the physical system. This would be similar to only consider the functional space of axiomatic design while leaving out the form-space. The objective of this viewpoint is to establish an understanding of the autonomous operation that is going to be designed by identifying the problem/problems that is going to be solved. SEATONOMY proposes the following work flow to correctly assess this viewpoint:

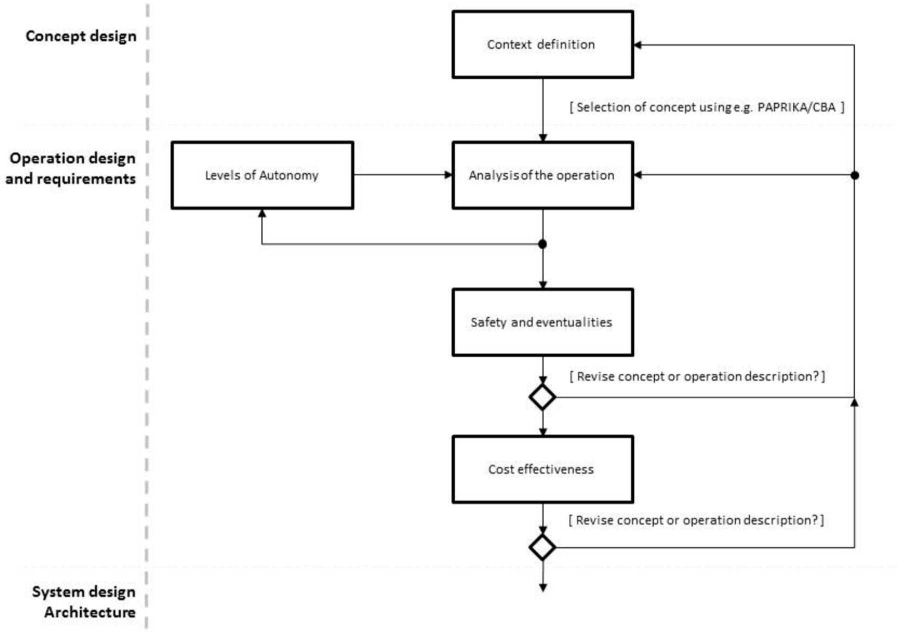


Figure 3.13: Flow Chart of Work Flow in Operational Viewpoint (Vagia, Haugli, et al., 2015)

The assessment starts by defining an initial operational context that the system will be exposed to before designing and selecting a potential feasible concept. The operation will then be analyzed with regards to operational modes, requirements and design challenges along with autonomous needs and limitations. An appropriate level of human-machine interaction will then be specified and evaluated against safety requirements to ensure that an acceptable level of safety is achieved. The concept is revised if it fails to meet the safety requirements and will only be economically assessed before having reached a satisfactory level of safety. A repetition of the process is necessary if the concept fails to meet the safety or cost requirements.

According to Vagia, Haugli, et al., 2015, there already exists a well-established framework for choosing between design alternatives and assessing the level of safety and economical feasibility of a design with methods such as:

- Analytical Hierarchy Process (AHP)
- Hazard Operability Analysis (HAZOP)
- Job Safety Analysis (JSA)
- Return On Investment (ROI)
- Life Cycle Costing (LCC)

However, methods for breaking down and analyzing an operation with regards to its autonomous requirements is limited. The next section is dedicated to give an introduction to the Autonomous Job Analysis method which was created to be a part of the SEATONOMY methodology and will be used for the case study found later in this master's thesis..

3.5.2 Autonomous Job Analysis

The intended use of the Autonomous Job Analysis (AJA) method is to uncover operational modes, design challenges and requirements to autonomous behaviour. The method sub-divides the operation before analyzing each sub-operation individually similar to other task analysis techniques such as the Hierarchy Task Analysis (HTA) method (Stanton, 2006) which (Grøtli, Vagia, Fjerdingen, et al., 2015) states that the AJA method uses elements from. AJA is a team based effort and requires co-operation from a multi-disciplinary selection of stakeholders to achieve an optimal result. The method is performed early in the design process as illustrated in Figure 3.14 below:

Figure 3.14: Illustration of when to Perform AJA in a Project (Vagia, Haugli, et al., 2015)

To facilitate for better communication and understanding between stakeholders the AJA method proposes that a *AJA meeting* is conducted and presents an agenda that the stakeholders should follow. The Autonomous Job Analysis also gives a guideline to follow when performing the method:

1. Describe the main goal of the operation
2. Divide into sub-goals, based on e.g. sequence, parallel behaviour or choices
3. Answer the list of AJA question described in the AJA table
4. For each sub-goal, go to step 2 and repeat until goals become trivial tasks

The guideline refers to an AJA table which is a generalized table of goals and sub-goals along with questions that will aid in the analysis of an autonomous operation. The table can be modified by adding or removing questions depending on the type of operation. The AJA table is presented in Table 3.1 as it is given in Grøtli, Vagia, Fjerdingen, et al., 2015.

Table 3.1: Autonomous Job Analysis Table (Grøtli, Vagia, Fjerdingen, et al., 2015)

ID	Name	Description
1	Description of the sub-goal	Give a short description of the sub-goal, focusing on the objective without too much technical detail. Achievement of the sub-goal should contribute to the achievement of a goal at a higher level and eventually the main goal of the operation
2	Communication	Communication flow: What key information needs to be communicated and when? Communication restrictions: What are the limitations?
3	Perception	Which information about the environment and the system itself must be available?
4	What are the criteria for success?	List design criteria which specify whether the sub-goal has been achieved. This can, for instance, be performance specifications related to accuracy or time.
5	What can go wrong?	Is there anything that can prevent the sub-goal from being successfully accomplished? Be specific about what characterizes abnormal behavior.
6	What is the operational safe state?	Define what state or mode the system should go to in order to maintain the safety of the operation in the best possible way
7	What is the human machine interaction?	Describe the human-machine interaction. The interaction can be described in words, or with reference to some taxonomy; Levels of Autonomy
8	Are there other premises or requirements for successful execution?	Describe other relevant premises for successful execution of the sub-goal
9	Notes and comments	Add comments that are relevant for the sub-goal, but are not captured by the previous questions or table

By performing the AJA method according to the fore-mentioned guidelines one is left with a detailed description of the operation that has ideally all of its sub-operations analyzed based on operational and technical constraints.

The AJA Canvas Tool

The AJA Canvas Tool was presented in Grøtli, Vagia, Haugli, et al., 2017 as a collaboration tool to facilitate the use of the AJA method within a group of people and for individuals. The canvas itself contains all the categories of the AJA method on a single page and is supported with questions to ask during the design and some example answers. The purpose of the canvas is to make the application of the method more user-friendly and efficient to increase the likelihood of AJA actually being used as a part of the design process of an autonomous operation. Grøtli, Vagia, Haugli, et al., 2017 suggests that one should print out a copy of the canvas for every sub-operation and used in meetings between customers, operation designers and field experts. As the authors conducts this master's thesis alone the AJA Table was used instead during the case study.

3.5.3 Category B: The System Viewpoint

The system viewpoint is initiated after the first iteration of category A is completed and handles issues related to the design of the system itself focusing on both software and hardware by using the problem formulation that was created in the operational viewpoint. SEATONOMY also provides a workflow of the system analysis that is presented in Figure 3.15.

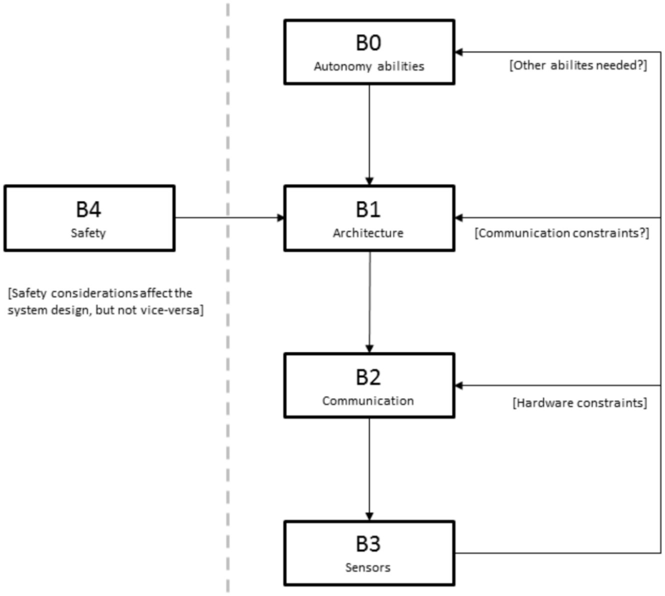


Figure 3.15: Flow Chart of Work Flow in System Viewpoint (Grøtli, Vagia, Rødseth, et al., 2015)

The viewpoint starts by reviewing the autonomy abilities of the system by defining which functional requirements the system needs in order to perform each of the sub-operations. Then suitable software architecture is developed to implement the autonomous abilities into the system. Furthermore, the system is assessed by how safe it is and if there is need for redundancy or diversity in the system. Once a safe system is ensured the design of how the system should communicate is reviewed. This design is depends on what level of autonomy is required by the system, the operational conditions the system is going to operate and level of interaction with other external vehicles during operation. This will affect what kind of sensors is chosen to be installed in the system. When choosing sensors there is of course important to find out what are the right sensors, but also to not use more sensors than what is necessary. Naturally, there will be limitations to which autonomous abilities is possible to achieve by today's standard of hardware which creates an iterative behaviour of the whole work flow of category B.

This master's thesis will not go any further in technical depth on the system viewpoint of the SEATONOMY methodology.

3.5.4 Category C: The Verification and Validation Viewpoint

While category A and B is meant to focus on designing various aspects of the autonomous system the verification and validation viewpoint carries out the process of integrating and testing the system to make sure they behaves according to the performance requirements sat to the system. This may lead to redesign of some elements in the autonomous system. This way off assessing a design process resembles a more traditional V-model of the systems engineering approach. Figure 3.16 below illustrates the how the SEATONOMY methodology fits into the V-model:

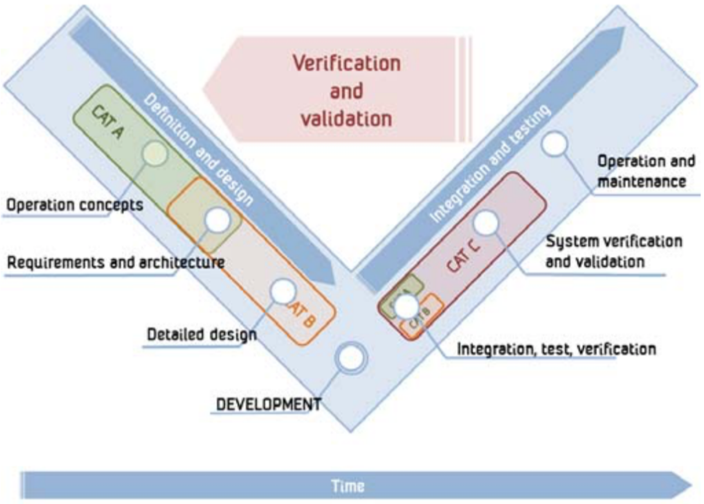


Figure 3.16: Relationship between V-model and the SEATONOMY Methodology (Grøtli, Vagia, Rødseth, et al., 2015)

It can be seen that category A and B represents the process of decomposing the system into sub-systems and reaching a gradually more detailed design by defining operational concepts as well as requirements and architecture. The integration and testing of the system would require assessment from all three viewpoint before the final system is verified, validated and operational.

Chapter 4

Autonomy in the Maritime Shipping Industry

> *"Technologies for realizing remote and autonomous ships exist. The task is to find the optimum way to combine them reliably and cost effectively* - Esa Jokioinen, Rolls-Royce Marine

Applications of autonomy has started to become more prevalent within the major transportation industries. Most automotive vehicles today possesses anti-collision, lane-control and self-parking capabilities and fully autonomously driven cars is close to be realized on a commercial level. The aviation industry has already a long history of utilizing features such as autopilot, automatic landing systems and drones. However, autonomy has only to a limited degree been applied in industrial marine systems causing the marine application of autonomy to fall behind compared to other industries (Grøtli, Vagia, Rødseth, et al., 2015). While there has been done substantial research within academia and the military it is generally based on expensive technology and fragmented systematic knowledge which is not ideal for re-use. These factors contributes to the maritime industry choosing traditional and less efficient solutions and rather adapt a wait-and-see attitude towards autonomy (Grøtli, Vagia, Rødseth, et al., 2015). With that being said there are segments within in the maritime industry today that recently has put significantly amounts of efforts into the development of autonomous systems

The underwater robotics industry is considered the most prominent in terms of applying autonomous capabilities on a commercial level whereas autonomous underwater vehicles (AUV) have been a great enabler for underwater inspection and exploration for industries such as oil & gas and aquaculture. Schjølberg et al., 2016 introduces in their article on the Norwegian offshore industry's ambition to increase the amount of subsea-processes in deep waters and arctic areas, highlighting that the current state of Norwegian subsea developments consists of aging equipment and expects a significantly rise in demand for inspection, maintenance and repairs (IMR) in the future. Schjølberg et al., 2016 proposes that by implementing certain autonomous functionalities to these operations (Shared Control) and deciding the best degree of autonomy and human- machine interaction in operations would optimizes factors such as efficiency, safety, cost and reliability in IMR operations. Concluding remarks of the article is that advances in sensor technology, communication, ICT architecture design, localization methods, robotics and task-planning opens new possibilities to bridge the gap between manual control and autonomy which is also applicable for operations in aquaculture and deep sea mining.

Bringing autonomy to any marine application is different from other industries as it introduces some additional challenges that needs to be assessed. Autonomy in the marine section will according to Grøtli, Vagia, Rødseth, et al., 2015 be constrained by the following:

1. Always on - no "safe state"
2. High reliability - the system must behave according to the operations intentions
3. Unreliable communication - handle limited communication or drop-outs in communication with operator
4. Unstructured environment - must be able to avoid collisions in complex environments
5. Own energy-supply - be in control of own energy production and consumption
6. Cost focus - solutions must be efficient and have low risk in development and use
7. Time focus - well known methods that work now are better than unknown that might not work

When designing autonomous systems for marine applications constraints like these becomes important to consider. While these constraints refers mostly to a technical point of view on the challenges associated with autonomous systems it is important to be aware of other areas relevant to the maritime shipping industry where other challenges may occur as well.

The following sections is dedicated to give an introduction to the different envisions of autonomous systems in the maritime industry as well as highlighting some of the implications and design challenges that occurs by introducing autonomy to a marine system within maritime shipping from different relevant aspects. The literature presented in this section will serve as the foundation for the case study found later in this master's thesis.

4.1 Autonomous Visions and Projects

From a historical point of view there is a clear industrial trend that work previously done by humans have been tried to be replaced with technical solutions which is either performed mechanically or in more recent times; digitally. The maritime shipping industry is no different and has seen a massive reduction in necessary crews for various types of vessels for the past two centuries. (Hochhaus, 2000) presented the development of machinery crews for ocean-going cargo ships extending from year 1860 to 2000 shown in Table 4.1 below:

Table 4.1: Developments of Machinery Crews for Ocean-going Cargo Ships (Hochhaus, 2000)

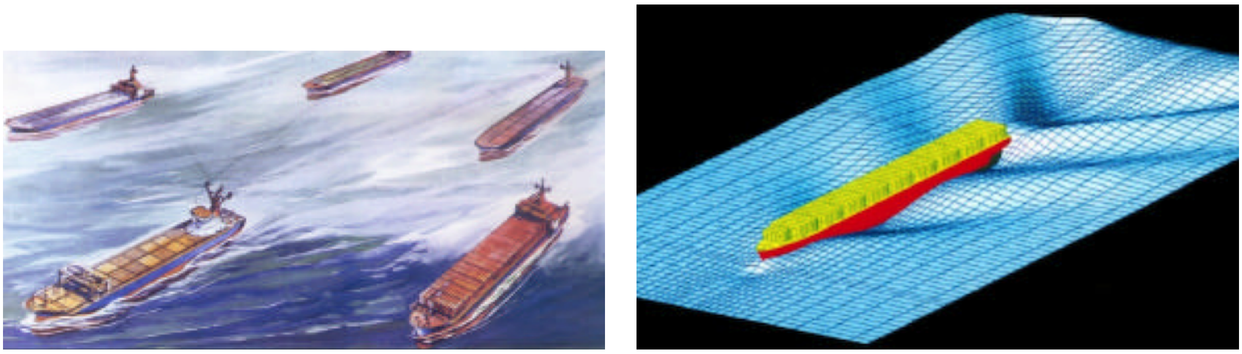
Year	**1860**	**1880**	**1900**	**1910**	**1920**	**1930**	**1950**	**1960**	**2000**
Machinery Crew	230	115	85	75	18	18	12	12	5

The manual labor intensive steamships needed hundreds of men as crew for feeding coal to the steam boilers but due to technological developments in systems such as machinery and navigation equipment there has been less requirements for manpower in the recent years. Today, the largest container vessels are nearly 400 meters in length and 60 meters in width with a cargo capacity of close to 20 000 containers at a time, but would usually only require a crew of 16 people (Bertram, 2002).

The strive for improvements in automation technology to reduce the need for manpower has never stopped and the idea of unmanned vessels have been envisioned and matured for at least four decades. One of the earliest known vision of unmanned vessels was described in Schönknecht et al., 1973 as a master-slave concept with the following excerpt:

> *"In this age of rationalization and automation it would not be difficult to imagine a ship without a crew. [...] It is indeed quite possible that at some distant future date the captain will perform his duties in an office building on shore. In his place he will leave a computer on board the ship which will undertake all the tasks of the navigator's art, [...] controlling the ship, and will in fact perform the task much more effectively."*

A Japanese ship project described in Lin, 1989 had a similar vision during the 1980s about having a convoy of unmanned "slave" ships being remotely controlled by a highly automated "master" escort vessel without a "shore captain" but were discarded due to the availability of cheaper, foreign crews (Andrews, 2016).



(a) Vision for master-slave concept (Schönknecht et al., 1973)

(b) Unmanned Container Vessel Vision (Kasai et al., 1996)

Figure 4.1: Early Visions of Unmanned Concepts (Andrews, 2016)

The Finnish ship designer, Kai Levander, stated in 1994 that:

> *"A ship with no crew on board could travel aided by the GPS chain and guided from the traffic stations. Pilots could board near the harbor and take the ship into port. An automated mooring system secures the ship to the quay without help from the crew."*

Further, Kasai et al., 1996 envisioned an unmanned container vessel concept that combined artificial intelligence (AI) and tele-operation in 1996. While the concept itself was believed to be feasible, it was discarded due to not being economically attractive because of the high maintenance costs (Bertram, 2002).

In the 2000's the vision of intelligent vessels re-emerged in a 2007 paper published by a cluster of European maritime stakeholders named Waterborne Technology Platform on future developments of the maritime industry regarding competitiveness and innovation. The maritime European research agenda named *Autonomous Vessel* as one of the key exploitation outcomes. The vision described the vessel as being equipped with modular control systems and communication technology to enable wireless monitoring and control, including advanced decision support systems and the capabilities for remote and autonomous operation (Waterborne Technology Platform, 2007). This paper laid the foundations for the origin of the MUNIN project which is further described in the next paragraphs.

4.1.1 MUNIN

The MUNIN research project was a project co-funded by European Union (EU) in 2012, which consisted of eight partners from scientific and industrial backgrounds located in Germany, Norway, Sweden, Iceland and Ireland (MUNIN, 2016). The aim of the project was to develop a technical concept for the operation of an unmanned merchant ship and assess the feasibility of the technical, economic and legal aspects of the project. The name, MUNIN is an acronym for *Maritime Unmanned Navigation through Intelligence in Networks* and refers to the Odin's ravens from Norse mythology which was flying around the world gathering information without any guidance and then returned the information, or "cargo", to its master. This is symbolic for the vision of the MUNIN project.

The MUNIN project investigated the benefits of autonomous capabilities on a dry bulk carrier performing intercontinental, deep-sea voyages. The rational behind the choice of intercontinental dry bulk shipping was the attractiveness of the simple cargo requirements and savings from the possibility of slow steaming which today is economically infeasible due to the additional crew costs. Other benefits apart from reduced operational costs and environmental impact would be related to social sustainability in terms of seamen being able to monitor and control the vessel from ashore and remain connected to family, friends and their social life. This could benefit the maritime industry by attracting new, highly qualified professionals.

The resulting paper of the MUNIN project deemed the solution of simply remote controlling the vessels at all times as unattractive due to the limitations in satellite bandwidth in certain regions and the high communication costs. The proposed solution was to implement new systems on board the vessel allowing for the ship to be autonomously operated. Figure 4.2 below shows the proposed systems of the MUNIN concept and the main functionalities of the system components will be briefly explained in the following paragraphs.

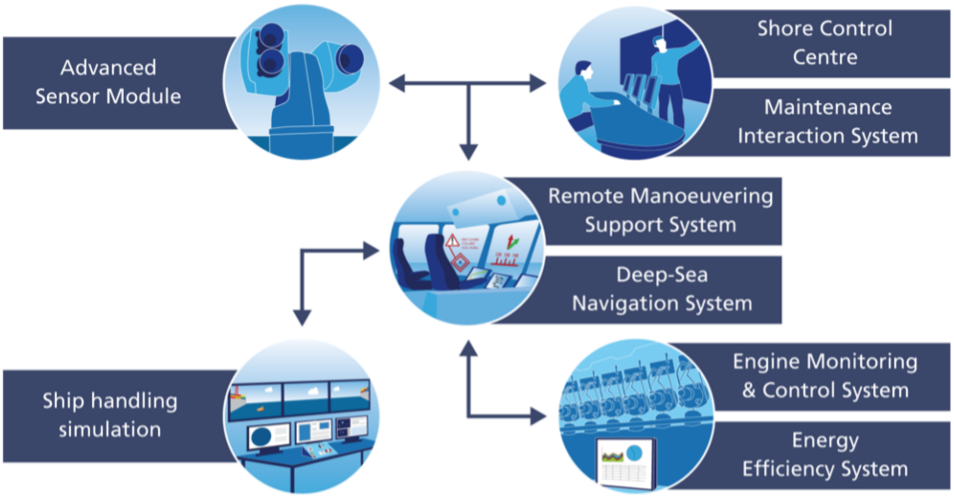


Figure 4.2: System Components of The MUNIN Concept (MUNIN, 2016)

Advanced Sensor Module

The advanced sensor module is responsible for object detection, classification and environmental perception by fusing together sensor data from infrared and visual spectrum cameras as well as radar and AIS data. The assessed sensor information of potential hazards and nearby objects serves as input for the autonomous navigation system and the shore control centre. A more detailed explanation of the advanced sensor module is given later in this chapter.

Autonomous Navigation System

The main function of the autonomous navigation system is to ensure that the vessel follows its planned route and acts according to governing rules and regulations. The system uses meteorological forecasts and sensor input to optimize the voyage plan and potentially perform allowable deviations from the original planned route to ensure safety. The autonomous navigation system can perform fully autonomously or allow shore control centre operators to intervene and remotely control the vessel. A detailed description of the autonomous navigation system along with the system awareness system is given later in this chapter.

Remote Manoeuvring Support System

To have accurate estimates of the vessels movements and manoeuvring ability is a necessity to ensure safe autonomous operations, especially related to collision avoidance and other critical maneuvers. Thus, the remote manoeuvring support system calculates and estimates the vessels movements and aids in providing the anticipated vessel motion trajectory.

Autonomous Engine and Monitoring Control System

Having a fully autonomously operated vessel means that maintenance and repairs cannot be performed during transit. Hence, advanced condition monitoring and predictive diagnostics of critical technical systems will be crucial to prevent breakdowns during deep sea voyages. The functional state of the various on-board technical systems will be important input for the shore control centre operators which can plan and schedule necessary maintenance.

Maintenance Interaction System

(Grøtli, Vagia, Rødseth, et al., 2015) argues that technical operations will be the most complex part of shifting from conventional ships due to most on-board systems being designed and built with the availability of crew in mind. As the systems itself needs to be redesigned for autonomous vessels it will also be necessary to incorporate a new maintenance strategy. The MUNIN project proposes that functions such as extended equipment monitoring and condition aggregation intended to minimize satellite communication bandwidth must be implemented in the on-board systems to achieve a successful maintenance interaction system between the vessel and the shore control centre.

Energy Efficiency System

The MUNIN project states that one of the main differences induced by going from conventional to autonomous vessels will be within the engine and propulsion systems. An unmanned vessel would in addition no longer require accommodation and the increased demand for reliability would require a duplication of engine, propulsion and steering systems which allows for new types of energy management strategies to be implemented. This will drastically change the vessels power demand thus creating the necessity for an energy efficiency system to optimize the energy management and fuel consumption of the vessel.

Shore Control Centre

Many of the functions previously being located on-board a vessel is envisioned to be transferred to a dedicated shore control centre when implementing autonomous capabilities on a vessel. While the autonomous vessels are going to be operated without any need for intervention from shore, certain events can occur which is outside the defined operational constraints that the various systems cannot safely handle. In that case, the shore control centre will assist by changing its operational mode from autonomous to remotely controlled. In case of an emergency the ship is envisioned to activate the fail-to-safe mode if loss of communication prevents the shore control centre from intervene. Other tasks that will be performed by the shore control centre includes on-board energy management, condition monitoring and maintenance planning.

MUNIN's Operational Modes

Together with defining the required systems needed to perform autonomous operations, (MUNIN, 2016) also defined five different operational modes for the unmanned vessel which is shown in Figure 4.3 below:

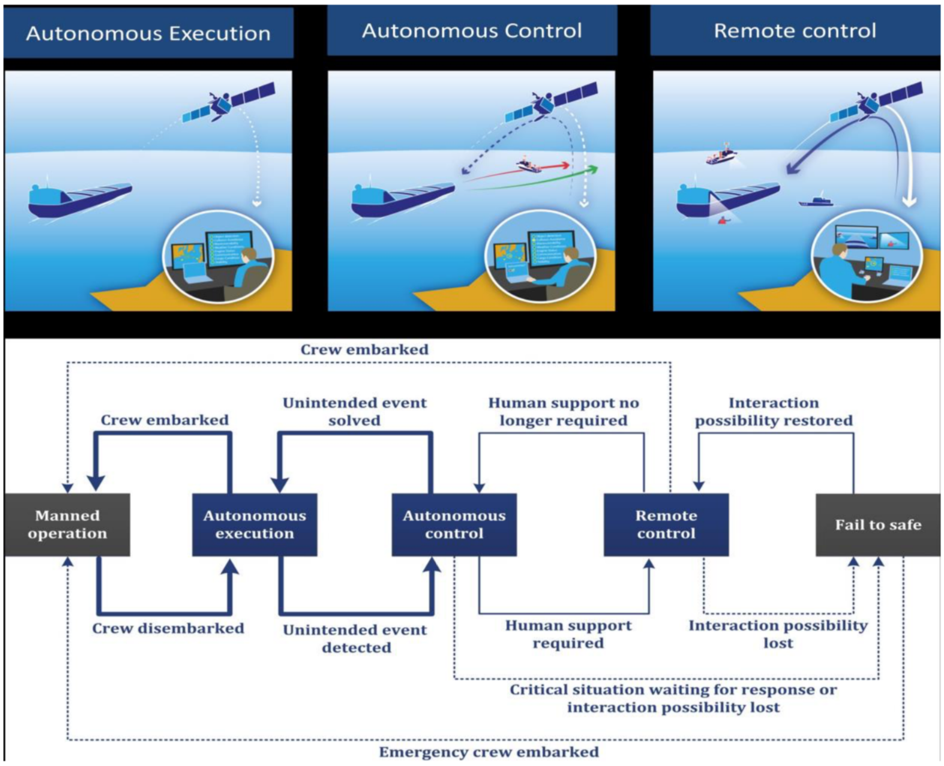


Figure 4.3: The MUNIN projects Operational Modes (MUNIN, 2016)

The manned operation mode represents the mode where the vessel is controlled normally by a crew. Removing the crew from the vessel changes the operational mode for the vessel to autonomous execution mode where all operational decisions are performed by the autonomous systems itself according to the predefined voyage plan and only monitored by the crew on shore. However, if an event occurs that forces the vessel to deviate from the voyage plan, for example due to another vessel or a change in weather conditions, it changes to the autonomous control mode allowing the systems to make changes in the voyage plan to ensure safety. If the event cannot be solved by the autonomous systems, the shore control centre can remotely take control over the vessel to handle the situation by switching off the autonomous capabilities. Such an intervention requires steady and reliable data communication link between the vessel and shore control centre. If this is not the case, the fail-to-safe mode will be activated with certain procedure to minimize the risk of potential collision or grounding.

There is no doubt that autonomy will induce more uncertainty in terms of how an operation is performed. However, it is important to note that an autonomous operation will not be carried out at a fixed level of autonomy. There is much more likely that the first implementations of autonomous capabilities will be made by operating with a dynamic level of autonomy, going back and forth between various operational modes.

4.1.2 ReVolt

The ReVolt project is a battery powered unmanned vessel that Det Norske Veritas Germanischer Lloyd (DNV GL) began developing in 2014 intended for short-sea shipping. One of the main drivers for this project was to reduce the operating costs the vessel by installing a 3000 kWh battery to minimize the amount of high maintenance parts related to the on-board machinery. Designed to be fully electric, the 60-meter container feeder has a range of 100 nautical miles and a capacity of 100 TEU (Adams, 2014). Being a fully unmanned vessel has also allowed for the design speed of the vessel to be reduced to 6 knots and the vessels hull is designed specifically for this speed which greatly reduces the water resistance (Adams, 2014). ReVolt is also designed without any crew facilities to maximize the loading capacity which can be seen in the illustration below:

Figure 4.4: The DNV GL ReVolt Concept, (Adams, 2014)

The ReVolt concept is stated to merely be a vision of the future and DNV GL has as far as the author knows any plans of actually building the vessel any time soon. However, a 1:20 scaled model has been built in collaboration with the Norwegian University of Science and Technology (NTNU), with the intention of being a research platform for testing sensor fusion and collision avoidance for autonomous surface vehicles (Adams, 2014).

4.1.3 Electric Blue

Electric Blue is a vision concept developed by Rolls-Royce which is based on an industry-standard 1000 TEU container vessel. The concept is a response to an increasingly dynamic and unpredictable shipping market caused by rapid development in technology, fluctuating fuel costs and stricter environmental regulations that complicates the decision process of investing in new vessels intended for future operations. By offering *maximum modularity* in the design allows the shipowner to reconfigure essential functions on-board the vessel such as changing from diesel to electric propulsion or removing crew facilities and control bridge for autonomous operation by simply exchanging modular blocks from the vessel (Rolls-Royce, 2017).

(a) Modular Accommodation Sections

(b) Modular Power Configuration

Figure 4.5: Illustration of the Modularity of the Electric Blue Concept (Rolls-Royce, 2017)

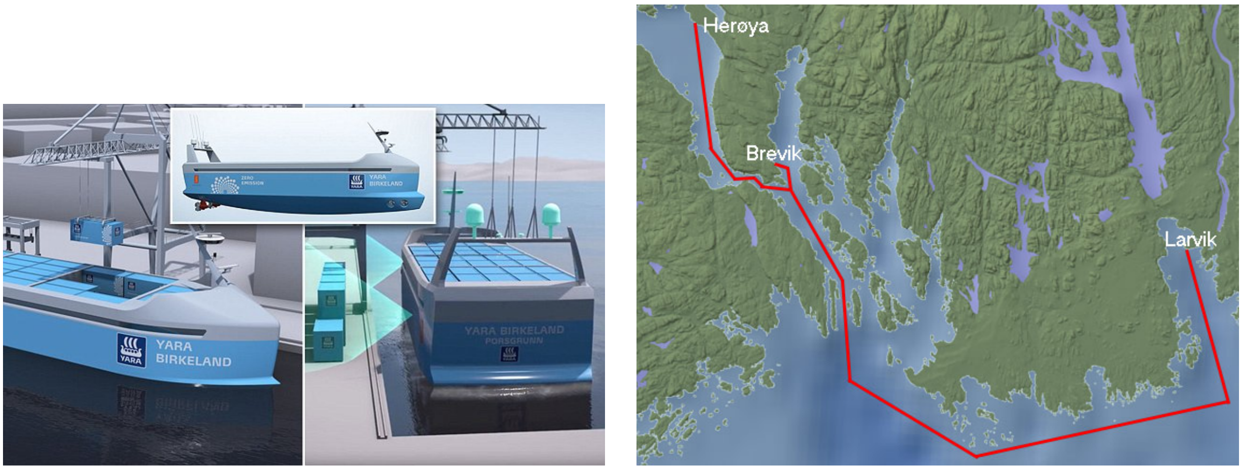
The vessel is installed with sensors such as radar, camera, IR camera and LiDAR to provide decision support for on-board operators as well as fully autonomous operations. Rolls-Royce have also presented a road map for autonomous shipping with the following time frame (Wilson, 2017):

- 2020: Partial autonomy with on-board decision support
- 2025-2030: Remote operation with possibly a reduced passive crew on board
- 2035: Full autonomy

The Electric Blue concept is a fine example of how modularity principles from design methodologies can be applied to achieve a more flexible and efficient design.

4.1.4 Yara Birkeland

The world first fully-electric, autonomous container ship, Yara Birkeland, is currently under construction and will according to Kongsberg, 2017 be launched in 2018 and perform autonomous operations by 2020. All key enabling systems including the sensors and integration required for remote and autonomous ship operations as well as the electric drive, battery and propulsion control systems is developed by Kongsberg AS itself. The ballast free Yara Birkeland is intended to operate between the 3 ports of Herøya, Brevik and Larvik in southern Norway, making it the first fully autonomous maritime logistics concept in the world. Yara Birkeland will also have onshore support from three control centers to ensure safety withing all aspects of operation. (Kongsberg, 2017)



(a) 3D model of Yara Birkeland

(b) Sailing Route for Yara Birkeland

Figure 4.6: Illustration of Yara Birkeland and its Sailing Route (Kongsberg, 2017)

Yara Birkeland will undoubtedly be an important test platform for marine autonomy and the experiences and lessons-learned from this pioneer concept will become valuable for future autonomous developments within all marine sectors. The Yara Birkeland concept is further described and discussed in later sections of this master's thesis.

4.2 Systems Architecture for Autonomous Vessels

This section will go further into the details of the various systems needed to achieve autonomous capabilities on a vessel. As previously mentioned, industries within automotive and aviation have developed proven technologies used for navigation, collision avoidance and situation awareness that can more or less be directly applied to the maritime sector. This indicates that autonomous marine navigation is technically feasible to achieve. However, there are some key differences between the industries that must be addressed in terms of system design. For instance, the operational speed of a vessel is much lower than a vehicle which does not require the same rate for real time situation awareness data processing and navigation manoeuvres. The ocean does not have the same spatial restrictions as roads do which also makes avoiding other vessels less difficult. In addition, the envisioned amount of vessels compared to land-based vehicles will be much lower allowing vessels to be controlled by dedicated shore control centres to ensure reliability and safety (AAWA, 2017).

Figure 4.7 below shows an example of a system architecture for an autonomous vessel proposed by the Advanced Autonomous Waterborne Applications (**AAWA!**) project (AAWA, 2017). It can be seen from Figure 4.7 that it contains many of the same system components as Figure 4.2 from the MUNIN concept.

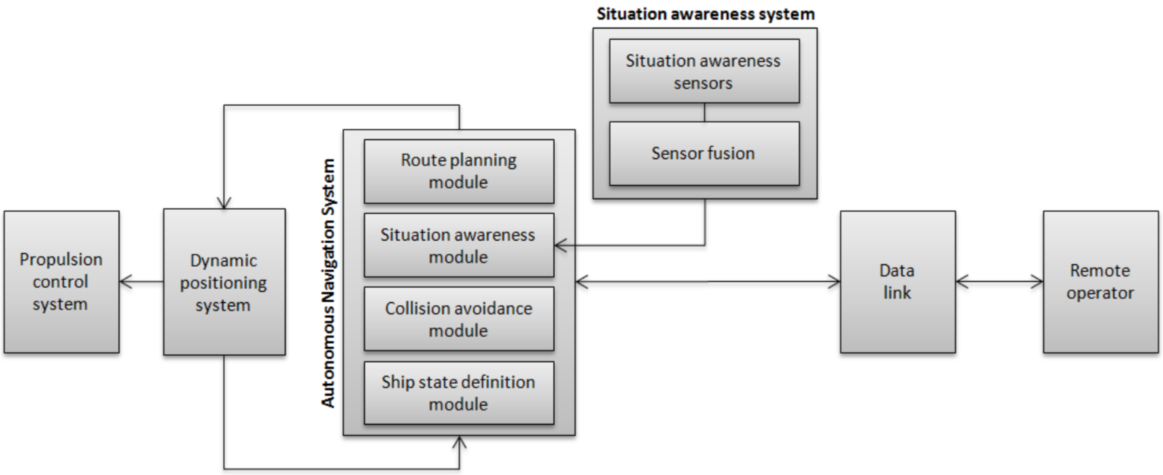


Figure 4.7: Proposed Systems for Autonomous Vessels (AAWA, 2017)

The development towards marine autonomous vessels are in the early stages which means that there are limited sources for marine autonomous system architecture solutions published. However, there are clear similarities and some high-level agreements between the available technological solutions on which systems to include for achieving autonomous operations. The following sections will give a description of the main systems required for autonomous operations and will draw heavily upon the visions from the AWAA project with supplements from comparable literature when possible.

4.2.1 Autonomous Navigation System

The autonomous navigation system (ANS) contains the modules necessary to achieve autonomous capabilities which includes modules for route planning (RP), situation awareness (SA), collision avoidance (CA) and ship state definition. The next paragraphs gives a detailed description of each of the modules which together constitutes AWAA's vision of an autonomous navigation system.

Ship State Definition Module

The main role of the ship state definition module is to determine which of the pre-defined operational mode the vessel should operate in (autonomous, remote-control, failsafe etc.). This decision will be based upon a combination of information from different ANS sub-systems along with other relevant ship systems making the ship state definition module the highest level in the ANS system.

Environmental Mapping

Reliable and accurate mapping of the environment is a requisite for achieving autonomous navigation for vessels and key element for route planning and collision avoidance. Autonomous navigation sets higher requirements to the mapping than traditional use of maps as it needs to be continuously updated as close to real-time as possible and contain more information. While regular manned vessels can solely rely on nautical and terrain charts for sea and harbour area to obtain information regarding shipping lanes, coastal terrain and potential shoals an autonomous vessels would also need to detect and track dynamic obstacles such as other vessels or foreign objects as part of the mapping process. These dynamic obstacles can be included in the map by using the vessels situation awareness system in combination with AIS data (Sanfilippo et al., 2017). AAWA, 2017 states that there has not yet been developed a mapping standard for autonomous navigation and as of now there exists many different methods for modelling and representing a 2D or 3D nautical map and further states that it could also be beneficial to present dynamic obstacles separately.

Hoffmann, 2008 proposes in his thesis a multiple layer mapping for navigation of autonomous land based vehicles. Hoffmann, 2008 divides the mapping into the following three layers:

1. The Map Layer - responsible to provide a precise representation of the road including different lane marking types and roadside objects.
2. The Activity Layer - responsible to track dynamic events as they occur including traffic conditions and hazard warnings.
3. The Analytic Layer - records and utilizes driver behaviour data for every road segment ahead to compute appropriate speed profiles

This reflects the additional information requirements the mapping process needs to fulfill in order for autonomous operations to be feasible by utilizing the environmental information as basis for decision-making processes.

Route Planning Module

Route planning or path-planning is a well-known element within control system design and is responsible for planning the path for the controlled object from start to finish. It is usually done by defining waypoints ahead of the operation by using navigational information from the mapping system as well as headings and speed for the ship. The main requirement for the route planning system is to define a safe route from start to finish that satisfies the mission requirements while avoiding static obstacles by using input from the mapping system. While the route planning is performed ahead of the operation, real time events can happen that conflicts with the predefined waypoints. However this is taken care of by the vessels collision avoidance system (Casalino et al., 2009). One also needs to consider the weather conditions since it has a large effect on the selection of the optimal voyage path. Design challenges that occurs is related to the dynamic properties of the ship, the surrounding environmental forces and being able to get the proper information from the ships situation awareness system which all must be addressed to achieve reliable reactive navigation.

Collision Avoidance Module

To be able to assess and avoid unexpected dynamic and/or static obstacles is of paramount importance in order to achieve a safe autonomous operation for an autonomous vessel. An autonomous collision avoidance controller has according to Miller et al., 2014 two main functionalities:

- Assessment of the collision risk
- Navigate the ship safely in both the harbour and in the open sea

In order to detect and correctly assess a collision risk the collision avoidance system requires information from both the route planning system, situation avoidance system as well as the dynamic positioning system. The route planning system gives a suggested path which the collision avoidance system must evaluate whether it should follow or deviate from. The situation awareness system gives input on any nearby obstacles that needs to be avoided. If an obstacle in the seaway is detected both the kinematic and dynamic constraints of the vessel needs to be considered which mean that the dynamic positioning system capabilities greatly affects the which maneuvers that actually are possible to do and determines which new waypoints that can be realistically assigned (Feng et al., 2012).

COLREGs is the baseline for determining right of way between manned vessels and an autonomous collision avoidance controller must be designed to respect these regulations. However, Burmeister et al., 2015 states that the COLREG regulations is characterized as having fuzzy formulations and relying on good seamanship customs and practices which is not transferable when designing an autonomous controller and points out that current state-of-the-art methods for automated evaluation of COLREG situations and counter measures most often assume perfect information conditions during the determination process and fails to certain parts of the COLREG convention.

An example of a collision avoidance controller respecting COLREG is given by Burmeister et al., 2015 which presents its own collision avoidance module which can deal with input uncertainty from real world conditions. It uses data input based on analyzing AIS-, radar and camera data to identify and distinguish between objects and ships and decide through analysis on which evasive manoeuvre to perform with respect to COLREG restrictions (for ship mainly). The method takes in factors such as safety level and harsh weather conditions but also economic impact of the manoeuvre. However, an issue arises since the controller only uses AIS-data and not visual detection of lights and shapes to determining the ships obligations which strides against the COLREG convention. COLREG requires manually input of such data leaving room for human errors. An generic description of COLREG decisions flow for a collision avoidance system is given in the Figure 4.8 below:

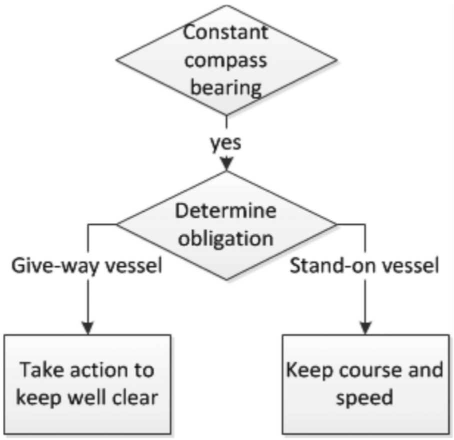


Figure 4.8: Generic Description of COLREG Decisions Flow for a Collision Avoidance System (COLREGs, 1972)

This master's thesis will go further into the legal issues associated with autonomous vessels entering the maritime shipping industry later in this chapter.

Dynamic Positioning System

A dynamic positioning system (DPS) is a system that enables a vessel to maintain a predetermined heading and position, fixed or moving, by use of propulsion units to counteract the effects of displacing forces such as wind, current, and wave action (Asgeir J. Sørensen, 2013). Having a well performing DP system is more or less a requisite to achieve safe and effective maritime operations and is a major contributor to reduce operational expenses, emissions and facilitates for optimum power and propulsion performance. The DP system relies on inputs from a global or Local positioning reference such as Global Navigation Satellite System (GNSS), various sensors and the vessels own Inertial Measurement Units (IMUs)

The main applications for maritime DP has been within the offshore industry where it has been an inevitable element for successful operations for decades. Traditionally, DP systems has been a low-speed application, where the basic DP functionality is either to keep a fixed position and heading or to move slowly from one location to another. However, the maritime industry continues to expand into new operational areas that are characterized by harsher environmental conditions with strong wind and current as well as autonomous applications which have led to more advanced control designs of DP systems striving for increased positional accuracy, flexibility and operability (Dong, 2013).

When considering autonomy, the dynamic positioning system will play an important role in operational modes such as autonomous mooring and docking which requires high precision navigation or at other operations where precise manoeuvring is necessary.

4.2.2 Situation Awareness System

> *"No matter how well you have programmed your processor, bad data will lead it to make incorrect choices. Bad things can happen when you have too few sensors. -* (Yenkanchi, 2016)

Situation Awareness is according to (M. Endsley, 1988) defined as the

> *"[...] perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"*

This definition breaks down to three levels in (M. Endsley, 2004):

- Level 1 - perception of the elements in the environment
- Level 2 - comprehension of the current situation
- Level 3 - projection of future states

The definition shows that situation awareness is not only concerned with a systems capability of being aware of the surroundings, but it also needs to understand how it will affect the current and future state of a system which in this case is a vessel. The perception of the environment is mainly achieved by the use of various sensor technologies and is essential for all remotely operated vehicles.

A high level classification of sensors is to distinct between *proprioceptive*- and *exteroceptive* sensors (Sanfilippo et al., 2017). Proprioceptive sensors is responsible for measuring the internal states of the vessel and are essential for accurate estimates of the vessels position and control systems etc. For a vessel this is normally achieved by a Global Navigation Satellite System (GNSS) and an Inertial Measurement Unit (IMU). When considering situation awareness one is mainly referring to exteroceptive sensors which is presented later in this section.

The selection of sensors used for maritime applications differentiates itself from the automotive and aviation industry mainly because the system must be able to perceive the environment both above and below the water surface to some degree. Typical sensors used on autonomous vehicles above the surface are usually laser-based, vision-based or radar-based. However, many of these sensors like GPS and radar systems for instance, cannot be used below the surface because water greatly attenuates electromagnetic radiation, and thus significantly reduce the range of these types of sensors. GPS signals will attenuate completely in just a couple of meters water depth. That is why sonars and the use of hydroacoustic signals are used for underwater perception (Hovem, 2012). However, these sensors is mainly related to underwater vehicles and when selection sensors intended to achieve situation awareness of surface ships one is less dependent on underwater perception.

Ottesen, 2014 states that processing sensor data is considered the biggest bottle neck for achieving situation awareness due to the massive amount of data that the various sensors produce. The data is also going to be interpreted by human operators which has biological limitations for assessing various types of information simultaneously. Ottesen, 2014 further argues that efforts must be made to simplify the gathered information and only present the data that are necessary in order to facilitate for better comprehension of the current situation, decrease the amount of processing needed as well as enhancing the projection of future states.

An useful method to address the third level of M. Endsley, 2004 for predicting the future state of a system is the Kalman filter. A state in this case is a description of all the parameters that is needed to describe the current system and perform the prediction. Further, a mathematical model is developed to describe the system in the most accurate way. For a Kalman filter, this model will always be a linear function of the state. The model will not be an entirely perfect representation of the system so a normally distributed process noise term is introduced to the state. An important part of the Kalman filter is the continuous measurements being made which is used to slightly change the parameters to refine the current model and the next predictions. One should also be aware that the measurements also contains noise which is compensated for in the filter. It is essential to understand that one does not have to measure the same parameters as the ones that are in the state vector. For instance, a Kalman filter describing the motion of a vessel may want to predict the vessels acceleration and velocity but only measures the position. A Kalman filter is more generally referred to as a state observer in control theory which is a essential part of a dynamic positioning system. There exists other systems that provides estimates of the internal state of a given system but Kalman filters remains as one of the most popular choices for state observers (Asgeir J. Sørensen, 2013).

The following sections will give a description of various exteroceptive sensors that are suitable to be implemented in a situation awareness system for autonomous vessels.

Vision-based Cameras

Vision-based cameras are a fundamental element in achieving situation awareness and can provide excellent spatial resolution with colour information that can be used as an input for object identification and separation of objects by either a remote human operator or through automated analysis algorithms. While the cost of the sensor itself is rather cheap, the massive amounts of data generated by these high-resolution sensors sets challenging requirements in terms of processing power and high-bandwidth data links for analysis and transmission (AAWA, 2017). The highest resolutions are achieved by visual spectrum cameras. However, these cameras performs poorly in dark surroundings or in bad weather which is crucial for situation awareness for a vessel that will operate in these conditions. Cameras based on infrared technology such as Long-Wave IR (LWIR) cameras will generate better visibility in low light conditions but offers lower spatial resolutions and are generally more expensive. However, the level of humidity in the atmosphere is known to attenuate the IR-bands which can lead to varying seeing ranges (Beier et al., 2004). The difference of information captioned by a normal camera and an infrared (IR) camera is illustrated in Figure 4.9 below:

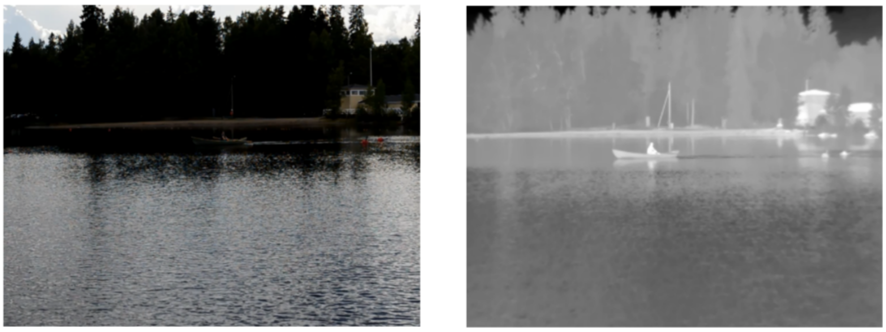


Figure 4.9: Information Captured by a Normal and Infrared Camera (AAWA, 2017)

Radar

Radar has a long history within maritime applications and the concept of detecting the reflection of electromagnetic waves from nearby objects to determine their relative distance, angle and velocity is proven to be robust against weather and light effects. The range capabilities of the radar will naturally depend on the operating frequency band. However, AAWA, 2017 raises the question if the resolution of traditional marine radar systems are sufficient for object detection needed for reactive collision avoidance due to the requirements of being able to detect and track small stationary or moving objects within a variety of ranges. While radars serves as a good sensor for object detection it does have a very limited ability for object identification.

LiDAR

The LIght Detection And Ranging (LIDAR) sensor works on the same principle as a radar but emits a pulsed laser array which is deflected by a rotating mirror rather than electromagnetic waves and calculates the time-of-flight (TOF) to make very accurate distance measurements. A digital 3D representation of the surroundings can be made by using the differences in laser return times and wavelengths. Halterman et al., 2010 states that a possible disadvantage of the use of LIDAR is the fast moving mechanical components used for scanning, which could be prone to malfunctions, especially over longer periods of time in a harsh marine environment. The accuracy and range of the LiDAR will also be affected by weather such as rain, snow and heavy fog, similar to IR cameras due to the pulsed IR laser emitted by the LiDAR.

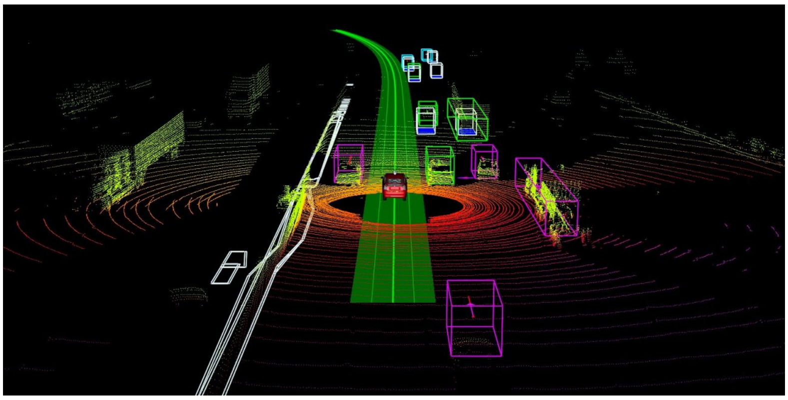


Figure 4.10: Example of LiDAR Output From a Vehicle (Geospacial, 2017)

Sensor Fusion

A common characteristic for sensors is that they usually are specialized for a single purpose with different strengths and weaknesses which means that a combination of different sensors is necessary for a system to achieve a sufficient level of situation awareness. Technology has been developed that are able to combine disparate sensors and handle the different types of data to produce information that has less uncertainty than if the sensors were used individually. Currently, the fusion of multiple sensor types has been successfully applied on automotive vehicles (Mukhtar et al., 2015). This is referred to as sensor fusion and is a key enabling technology to achieve reliable situation awareness. To give an example, affordable and smaller cameras can provide better spatial resolution for object classification while a short- range radar or LIDAR can provide accurate range, velocity and angular measurement of objects for tracking. Near-IR (NIR) cameras, with active illumination, or thermal LWIR cameras can be used also for night-time imaging. On the other hand, the use of a radar allows operation also under difficult weather conditions like heavy rain or snow where the visual-based and IR cameras may fail. The sensor fusion system can be designed to provide a various range of information to the operator as depicted in the four illustrations presented in Figure 4.11 below:

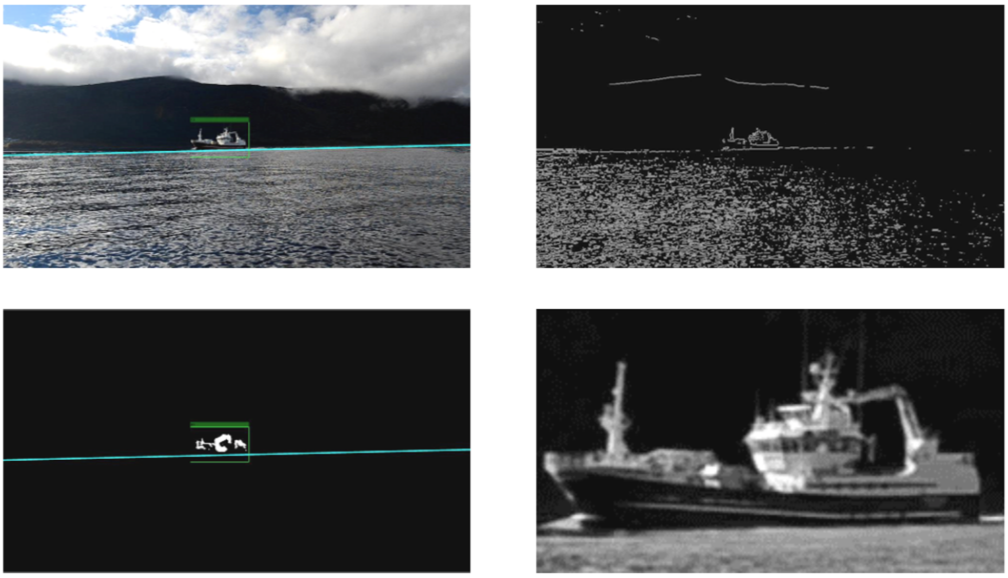


Figure 4.11: Illustration of Various Fusion of Sensor Data (AAWA, 2017)

As the processing power required to assess the various sensor data quickly adds up, especially with high resolution spacial cameras it can be beneficial to reduce the image quality, framerate or even the data actually transmitted from the situation awareness system. The top-left image shows all the sensor data simultaneously while the top-right image has a drastically reduced image quality. It can also be an alternative to remove the high quality imagery of the surroundings and only focus on the object of interest (bottom-left) or just a detailed imagery of the object itself (bottom-right). While the data transferred is minimal it can still be sufficient for human understanding of the situation. For non-critical operations this could be beneficial as communication and bandwidth can be disturbed or limited during voyage. The determination of required sensors and what data to capture, process and transfer will become a key challenge to solve in order to reach the necessary level of reliability in autonomous navigation.

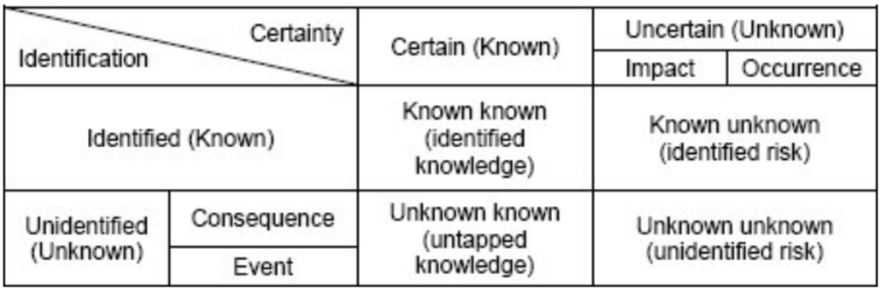
4.3 Safety and Security

> *"A common mistake that people make when trying to design something completely foolproof is to underestimate the ingenuity of complete fools."* - Douglas Adams, The Hitchhiker's Guide to the Galaxy

This section will highlight some of the implications and design challenges related to the safety and security aspects of designing an autonomous vessel for the maritime shipping industry. The former United States Secretary of Defense Donald Rumsfeld gave on February 12, 2002 the following statement regarding the lack of evidence linking the government of Iraq with the supply of weapons of mass destruction to terrorist groups (Rumsfeld, 2002).

> *"... because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know. [...] it is the latter category that tend to be the difficult ones."*

The idea of unknown unknowns was actually based on the Johari Window concept developed by two American psychologists, Joseph Luft and Harrington Ingham as a way to help people understand their relationship with others and themselves (Luft et al., 1955). It is also popularly applied to risk management as a way to classify risks based on the level of knowledge regarding the risk event's occurrence (either known or unknown) and the level of knowledge about its impact (either known or unknown). Figure 4.12 illustrates four types of uncertainties that must be managed based on the knowledge of the type and certainty of an event (Cleden, 2009).



<table>
<tr><th colspan="2" rowspan="2">Certainty
Identification</th><th rowspan="2">Certain (Known)</th><th colspan="2">Uncertain (Unknown)</th></tr>
<tr><th>Impact</th><th>Occurrence</th></tr>
<tr><td colspan="2">Identified (Known)</td><td>Known known
(identified knowledge)</td><td colspan="2">Known unknown
(identified risk)</td></tr>
<tr><td rowspan="2">Unidentified (Unknown)</td><td>Consequence</td><td rowspan="2">Unknown known
(untapped knowledge)</td><td colspan="2" rowspan="2">Unknown unknown
(unidentified risk)</td></tr>
<tr><td>Event</td></tr>
</table>

Figure 4.12: Schematic Structure of Modified Risk Categorization (Cleden, 2009)

Unknown unknowns are risks related to events that are of such a nature that it would never occur to think of but does occur (Biafore, 2011). However, such events does occur and when it does it can be identified and converted to a known unknown. The more unknown unknowns are identified, the less chance a project will have to be affected by a surprise (Kim, 2012).

A similar theory related to unknown unknowns is the Black Swan Theory formulated by Nassim Nichilas Taleb which originates from an ancient saying that presumed black swans did not exist. Taleb writes in Taleb, 2007 that in order for an event to be classified as a black swan it must fulfill the following three criteria:

1. The event is a surprise (to the observer).
2. The event has a major effect.
3. After the first recorded instance of the event, it is rationalized by hindsight, as if it could have been expected; that is, the relevant data were available but unaccounted for in risk mitigation programs.

When considering the safety and security of an autonomous vessel, it will face mostly the same safety threats as conventional ships related to the sea environment, other vessels and its own operation whereas the mitigation strategies are well defined. However, it is also expected that there will arise new hazards and risks when operating the vessel autonomously. While most of the new risks are possible to predict in advance, the disruptive effects from deploying novel technologies can create unexpected events that can be classified within categories such as unknown unknowns and/or black swans.

In terms of safety, both AAWA, 2017 and MUNIN, 2016 states that operations of autonomous vessels must be at least as safe as with traditional ships and that a holistic view is necessary to obtain a more comprehensive knowledge and understanding of the new hazards, risks and mitigation options. This must be addressed already in the early stages of the design and development of autonomous maritime systems and over time systematically build up the knowledge base on autonomy-related risks by conducting simulations, analyses and pilot studies as well as utilizing applicable experience from other applications.

This section will present some of the risks that are most likely arise as a consequence of implementing autonomous capabilities on vessels.

4.3.1 Human Factors

As previously stated, there will be several similarities between conventional and autonomous vessels in terms of the threats they will be facing. However, the main fundamental difference in the way the two different vessels are operated is that there will no longer be any humans present on the vessel during the operation itself which will unquestionably introduce new challenges. Therefore, defining human machine interaction (HMI) for the various on-board systems will become an important element in the risk management design.

For higher levels of autonomous operation it is likely that the supervisory control and monitoring of the vessel will be transferred to a dedicated shore control centres (SCC). Specific operations such as steering in and out of ports or mooring may then require to be carried out remotely by tele-operation. This kind of operations will be sensitive to disturbances, malfunctions, latency or other vulnerabilities in the data communication connections. Hence, it is of paramount importance that the connectivity between the vessel and the shore control centre is continually available with the required capacity. This applies not only to the tele-operated parts of the operation but to all the various stages of an autonomous vessels operation. While the requirements for connectivity and data transfer between the vessel and the shore control centre will vary during different parts of the voyage, it must be ensured that sufficient connectivity throughout the whole operation is achieved before the voyage could commence (Wahlströma et al., 2015).

As previously presented, a combination of various sensors are responsible for providing real-time information of the ships condition. However, (AAWA, 2017) points out that certain maneuvering decisions is based upon the behaviour of the ship such as rocking and the captains familiarity and experience of the vessel. This kind of cognitive interpretation of situations can be proven difficult for sensors to recreate and one must recognize that the sensors will not be able to fully represent the ships conditions. Further, while one can presume that simply increasing the amount of data collected from the vessel will enhance operational safety, it can very well prove to act against its own purpose. Fusing large amounts of different sensor data can lead to the remote operator being exposed to information overload increasing the possibility for the operators to make inaccurate decision or missing important events. Parker, 2013 thesis on *Data Overload in Unmanned Aircraft Systems* brings forth that the information collected is only valuable if it is accessible and appropriately processed. This sets requirements for the sensor fusion system to be able to gather and filtrate data and only present what is necessary as well as making it accessible to its intended user to avoid overloading the operator with data.

It is evident that the on-board systems designed for situation awareness, navigation and collision avoidance must at all times be reliable in order to ensure safe operations of unmanned vessels. However, it is important to not only consider technological risks but also other areas such as the socio-technical impact related to autonomy. Hjetland, 2015 points out that there is a generally a much lower public tolerance of risk with autonomous vehicles. An example being the massive negative reaction and public discussion related to accidents caused by auto piloted vehicles even though the amount and rate of fatal crashes caused by human errors is much higher. However, it is envisioned that one of the main benefits from implementing autonomous systems on-board a vessel is the massive reduction in human related errors which today constitutes one of the major factors to accidents at sea. Increasing ship autonomy will also reduce the degree of exposure to hazards in hostile sea environments for humans involved with the operation of the vessel (Rylander et al., 2016). This will be beneficial in justifying the development of autonomous vessels from a socio-technical point of view.

4.3.2 Maintenance

It is expected that there will occur some new challenges related to the maintenance on the various systems on-board the vessel as well as the systems required to remotely operate the vessel. Today, conventional operation of ships strongly rely on the on-board crew to manually perform various corrective and preventive operations on systems such as machinery during voyage. This has allowed for the ships to use less expensive machinery configuration with sub-optimal reliability capabilities. Removing the on-board crew takes away the possibility of manually maintaining essential equipment and AAWA, 2017 brings forth that there is necessary to design systems that are more resilient to failure and extend the required maintenance intervals. This creates a demand for more efficient diagnostics and prognostic algorithms to assist in controlling the risk of equipment failure during voyage and to reschedule required maintenance to be performed at ports. To save time and resources AAWA, 2017 also suggests that these systems should be designed to be easily maintained or replaced. This implies the need for an increased use of modularity principles in the systems design. By increasing the amount of software based systems also induces risk of systems failure which needs to be considered. Updates, revisions and repairs made on software commonly represents a risk of errors which can have immediate or latent impacts on the performance of the system (Rødseth and Tjora, 2015). While these errors may be insignificant for the user of a conventional computers operating system it may have massive consequences during operation of an autonomous vessel.

4.3.3 Cyber Security

As the vessels gets equipped with an increasing amount of connected on-board information and communications technology (ICT) systems the risk of unauthorized personnel accessing the systems with the intention to illegally manipulate or exploit the system in some undesired manner becomes a real concern. Cyber attacks is expected to be one of the largest known risks with autonomous vessel operation today. The threat of loosing control of the vessel calls for cyber security to be implemented on all ICT systems. The main purpose of cyber security is defined by Schatz et al., 2017 as to protect the systems from the theft and damage to their hardware, software or information, as well as from disruption or misdirection of the services they provide. Disruptive actions for a vessel could be simple manoeuvres meant for annoyance or demonstration, but could also be aimed to create severe damage to the vessel either by grounding or colliding into a nearby vessel. Damage can also be done without hacking the on-board systems by jamming the global positioning system (GPS) or automatic identification system (AIS) data link between the vessel and the shore control centre.

Ensuring cyber security constitutes one of the main challenges to be solved in order to commercialize autonomous operations. Many official instances are currently working on rules and regulations for preventing cyber attacks as well as a number of research studies on the matter is being conducted. An example being the maritime classification society Lloyd's Register (LR) which issued in the beginning of 2017 the *LR Code for Unmanned Marine Systems* as guidelines for the design of ICT systems with the purpose of providing a framework for the assurance of safety and operational requirements for Unmanned Marine Systems (UMS) (Lloyd's Register, 2017).

4.4 Rules and Regulations Concerning Autonomous Vessels

Another relevant future challenge of having operational autonomous vessels is to determine what rules need to be altered or implemented in order for autonomous ships to be legal to operate in national and international waters. Jokioinen et al., 2017 states that the current maritime legal framework contains several shortcomings when considering autonomous vessel and this section is dedicated to present and highlight the most pronounced challenges associated with maritime law and autonomous vessels within three main domains:

- Jurisdictional Rules
- Technical Rules
- Liabilities

Maritime law describes a range of laws, conventions and treaties that govern the legal framework related to ships and their operation. It spans from international law to regional and national rules and down to local rules and covers issues of public concerns, such as safety, security and environmental protection as well as civil law matters, such as contracts of carriage, liability and compensation for damage.

4.4.1 Jurisdictional Rules

The jurisdictional rules is mainly concerned with the rights and obligations various states needs to consider with respect to ships. These rights and obligations are related to the navigation of ships and various states' rights to interfere in the navigation of ships in different sea areas as well as the states obligation to ships flying their flag and are laid down in the 1982 UN Convention on the Law of the Sea (UNCLOS). The fundamental difference when considering autonomous vessels are the absent of crew on-board and the question of whether a ship without crew can be defined as a ship within the meaning of international convention may cause ambiguity as the existing definition of a ship does not include any references to crewing. However, Lee, 2016 and Jokioinen et al., 2017 both assume that it is likely that unmanned vessels will be a subject to the same rules of the law of the sea as conventional ships for both international, flag state as well as port and coastal conventions.

Still, there are some parts of the UNCLOS convention that can prove to be problematic for unmanned vessels. Article 94(4)(b) in UNCLOS, 1982 describes the ships obligation to have a properly qualified master and crew ships. It could be argued that this obligation is met by remotely operating the ship from a shore control centre. However, as it is assumed in the presented visions that a vessel will have different operational modes with varying level of autonomy during the operation it becomes more challenging to define if the obligation is met or not. This becomes a clear example of present laws that needs to be revised to include the new types of operations created by autonomous vessels and a clear definition of ship and master must be made. Further, Article 98(1) in SOLAS, 1974 states that the master and on board crew must provide assistance during distress calls from other vessels. While autonomous vessels are able to assist in terms of communication it will presumably not be able to meet the obligations where physical assistance is required.

4.4.2 Technical Rules

The intention with having technical rules is to provide legal protocols covering areas such as safety, environment, training and watchkeeping standards. These rules are issued by International Maritime Organization (IMO) which has adopted more than 50 international conventions for international shipping (AAWA, 2017). The following sub-sections will present a selection of the most central conventions from IMO where grey areas and conflicts imposed by autonomous vessels entering the shipping industry is highlighted.

The International Convention for the Safety of Life at Sea (SOLAS)

The first version of the SOLAS Convention was created as a response to the Titanic disaster in 1914 to specify minimum standards for construction, equipment and operation of ships and are considered the most important of all international treaties concerning the safety of merchant ships according to (IMO, 2017). While the rules for construction and equipment is believed to not cause any considerable conflicts with the convention it is the rules regarding manning of ships that is expected to be challenging for unmanned vessels (SOLAS, 1974). Regulation V/14 states that *"from the point of view of the safety of life at sea, all ships shall be sufficiently and efficiently manned."* A key question will be on whether having an unmanned vessel qualifies as sufficiently manned if the crews operational functionalities are to be moved to on shore control centres. (AAWA, 2017) brings fourth that the term *manning* not necessarily implies any requirements to *attend* the vessel and that a vessel indeed can be sufficiently and efficiently manned from an on shore control centre. Another point being made is that the idea of unmanned vessel was nonexistent at the time when these rules were developed and one should not rely too much on the existing legal texts, implying that revisions of the SOLAS convention is to be expected.

International Convention for the Prevention of Pollution from Ships (MARPOL)

The International Convention for the Prevention of Pollution from Ships (MARPOL) is according to MARPOL, 1973 *"the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes."* While unmanned vessels undoubtedly will have to comply with these requirements it is assumed both from Simonsen Vogt Wiig, 2017 and AAWA, 2017 that the MARPOL convention is unlikely to induce any new challenges. However, responses to pollution emergencies from unmanned vessels must be addressed in the same was as in the UNCLOS convention.

International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW)

The STCW applies to *"seafarers serving on board seagoing ships flying the flag of a state party"* and the rules relating to manning and crew training are in principle not relevant insofar for unmanned vessels according to Simonsen Vogt Wiig, 2017 which also states that *"current regulation will therefore have to be amended and new regulations will have to be adopted, with respect to, inter alia, training, qualification of personnel at onshore control centres, as well as operation technology and communication"*. In terms of the present governing rules stated in the STCW there is some challenges related to watchkeeping, most evident in Regulation VIII/2(2)(1) of STCW, 1978 which reads:

> *"Officers in charge of the navigational watch are responsible for navigating the ship safely during their periods of duty, when they shall be physically present on the navigating bridge or in a directly associated location such as the chartroom or bridge control room at all times."*

There is probably unfeasible for unmanned vessels to meet the current watchkeeping requirements in the STCW which coincides with the presumptions presented in both Lee, 2016 and AAWA, 2017.

Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)

The COLREGs encompasses rules regarding manoeuvring and navigation for different vessels at various operational scenarios at sea and it is likely that an unmanned ship will have to comply to the COLREGs in the same manner as every other conventional ship (AAWA, 2017). However, a challenge arises due to a central topic within the COLREGs being the requirement of *look-out* given in Rule 5 of the COLREGs, 1972:

> *"Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision"*

For an unmanned vessel it is expected that the situation awareness system earlier presented is the system that is intended to fulfill the requirement of Rule 5. The challenge is whether the system can be regarded as *"proper look-out by sight and hearing"* by replacing the human lookout with various sensors, cameras and audio solutions since the rules clearly refers to human capabilities. However, the vague term *"proper"* provides some flexibility to which the situation awareness system is sufficient to comply with the rules regarding look-out.

The wording in the COLREGs rules regarding the ships manoeuvring and operational decision does not refer to the crew or captain on board but rather to the vessel itself. In remote operational mode the manoeuvring and decision-making can be considered similar to conventional vessels but problems arises when the the vessel is fully autonomous without an human operator and is a topic that must be addressed. From a pure technical point of view it will most likely be possible to create algorithms that can perform the same operational tasks as an human operator. However, the COLREGs, 1972 does not include a complete definition on appropriate conduct for every operational scenario and relies merely on *"good seamanship"* in several cases which will be an industrious task to implement in an automated navigational system. It is clear yet again that the legal framework needs revision in order for commercially autonomous operated vessels to be feasible.

4.4.3 Liability

In shipping, like any other industry, there is essential to allocate the risk and liability in governing contractual and legal regulations for the various parties involved in the shipping operation. If an accident or damage occurs during a part of the operation it is necessary to determine issues such as which party is responsible, on what basis and the amount of financial compensation that is owed to the plaintiff through various contractual arrangements. While the rules have to some extent been standardized due to international conventions, it is still dependent on factors such as location and type of incident as well as the nationality and the ship's flag state of key players (AAWA, 2017). According to Falkanger et al., 2011 the determination of liability for damage is traditionally triggered by negligence in maritime law. This means that the one that causes the damage to other parties due to the fault or neglect is liable for the damage. However, due to the high values of the various assets in play in a shipping operation the economic claims from an accident may become extensive. The placement of liability is then normally directed towards the shipowners or operators of the ship rather than individual crew members. Thus meaning that the person whose fault actually caused the damage will not be liable as long as the fault is associated with the operation of the ship. The shipowner itself is also protected by being exposed to the full financial claim by an unique characteristic of the maritime law which is the limitation of liability and the right is only revoked in rare, exceptional cases (Lee, 2016).

Both AAWA, 2017 and Lee, 2016 states that there is no immediate need to make changes to the maritime liability rules as errors committed by remote operations may be treated the same way as conventional operation. However, bringing autonomous vessels to shipping may have some implications that still must be assessed. For instance, if an accident occurs when the ship is operated fully autonomous due to malfunction of the autonomous systems or loss of communication it is less obvious to who is to carry the liability. Lee, 2016 points out that the claimants may seek compensation from other relevant parties instead such as system developers, component manufacturers, shipyards and classification societies due to their negligence in designing and/or manufacturing the autonomous systems.

A statement given by the Chief Executive Officer (CEO) of Volvo Car Corporation, Håkan Samuelsen gives insight into the automotive industry view on liability related to autonomous systems:

> *"We are the suppliers of this technology and we are liable for everything the car is doing in autonomous mode. If you are not ready to make such a statement, you shouldn't try to develop an autonomous system."* (Cruickshank, 2015)

AAWA, 2017 expects that the implementation of autonomous systems on vessels will create a shift towards product liability in the maritime context. This may become beneficial for claimants since governing product liability directives does not generally include financial limitation of liability. Figure 4.13 illustrates a possible change in the liability framework induced by autonomous vessels entering the shipping industry showing that there is plausible that product and other liability rules may operate in parallel with the traditional maritime liability.

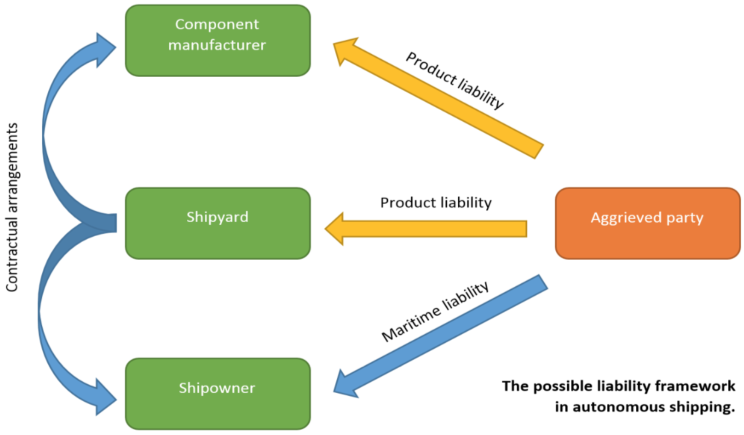


Figure 4.13: The Possible Liability Framework in Autonomous Shipping (AAWA, 2017)

Another example is if the injured party seeks claims from a classification society it is according to De Bruyne, 2015 no limitation of liability for the classification society. Normally, they have been well protected from claimants as the certificates issued by the classification society after inspection do not serve the role of ensuring seaworthiness of the vessel which is the shipowners responsibility (Miscallef, 2016). However, according to European Law, any injured parties are allowed to seek compensation from the classification societies if they are able to prove that the damage is caused by the negligence act of the classification societies (EU, 2009). This highlights the importance that maritime classification societies also needs to extent their area of competences to autonomous systems as they are expected to be more prone to be liable for third parties' damage due to their special role and unlimited liability. The same challenges may also apply to actors such shipyards and component manufacturers. This highlights that the implications of autonomous vessels does not only affect the design of vessels but other actors within the maritime industry as well.

Chapter 5

Case Study: Autonomous Container Vessel

So far, this master's thesis has presented a literature review covering the concept of autonomy, autonomous visions and projects as well as various design challenges that one needs to consider when designing an autonomous vessel for the maritime shipping industry. The following case study will also attempt to uncover additional design challenges related to the operations of an autonomous container vessel. However, due to autonomous vessels still being under development there are a lot of uncertainties and few details regarding the operation of autonomous vessel to be found.

The author of this master's thesis sees more value in the actual application of various design principles rather than to make a complex analysis which would mainly be based upon limited information and most likely inaccurate assumptions. Thus, the main intention with this case study is first and foremost to demonstrate some of the earlier presented design methodologies to investigate if they can provide decision support for autonomous systems design, while less emphasis will be placed on the fidelity of the analysis itself.

5.1 Selecting Design Methodologies

The first part of the case study is aimed to answer the research question regarding which physical system changes would result from including autonomous capabilities in the ship design of a conventional container vessel. The chosen methodologies for this part is to use principles from the system based ship design approach to make a functional breakdown of the various systems on board a regular container vessel. Once all the main systems describing the functional requirements of the vessel is identified, an analysis of the function-to-form mapping based upon the axiomatic design methodology is made. Figure 5.1 gives a conceptual illustration of the effects autonomous capabilities can have on function-to-form mapping:

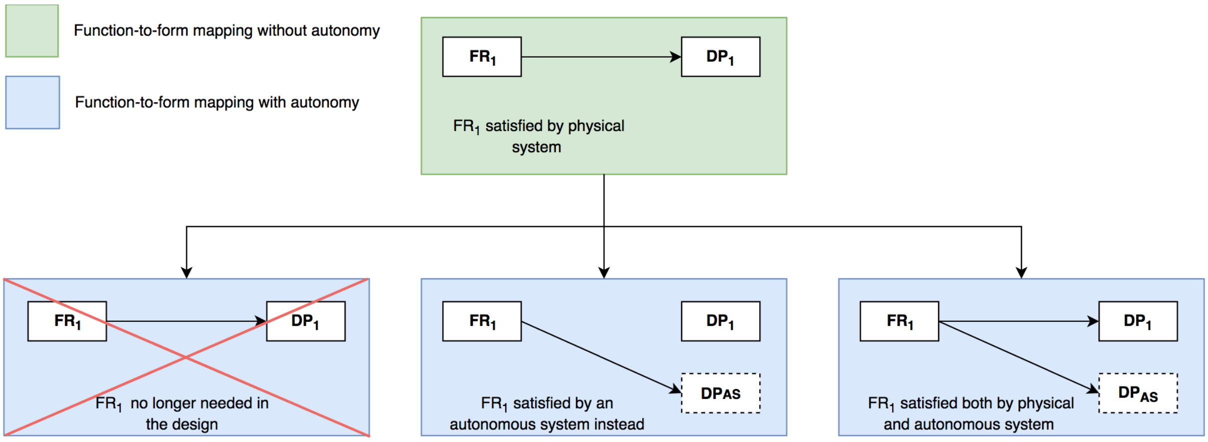


Figure 5.1: Illustration of the Effects Autonomous Capabilities has on Function-to-form Mapping

Implementing autonomy in the design can render certain functional requirements redundant, which means that it is no longer need for the corresponding form to be included in the design. Another effect is that a functional requirement could be satisfied by an autonomous system instead, which would make it possible to discard the physical form entirely. This could either replace an already existing functional requirement or be a new functional requirement created by the autonomous system itself. The third effect that autonomy will have on the function-to-form mapping is where a functional requirement is satisfied by both a physical and autonomous system. For a container vessel this could represent both having an autonomous system and an operator to navigate the vessel, which would not only give redundancy in ensuring that the functional requirement is met, but also flexibility in terms of having several design parameters satisfying the same functional requirement.

For the second part of the case study the operation of an autonomous container ship is analyzed, by using the autonomous job analysis method previously presented, to uncover operational modes, functional requirements, limitations and other design challenges related to autonomous systems.

5.2 Container Ship

The concept of containerized shipping had its advent in the 1950s and makes up close to 10% of the world's merchant fleet (Levander, 2012). Standardized containers allows the ship to accommodate for an immense amount of different cargo types and today about 90 percent of non-bulk cargo worldwide is transported by container (Castonguay, 2016). The cargo capacity of a container ship is measured in terms of Twenty-foot Equivalent Units or TEUs and the benefits related to economies of scale has created a development towards increasing the size of container ships with the largest vessels having a capacity exceeding 21,000 TEU (Merk, 2015). This section will first present the operational profile and a functional breakdown of a regular container ship. Then, a proposal of a systematic breakdown for an autonomous container vessel is given following design principles from the system based ship approach presented earlier in this master's thesis.

5.2.1 Operational Profile

The operational profile of a container ship can be considered as liner services as they operate with a regular schedule with predetermined port calls. One route for a container ship can contain two or more port calls which is often organized with the same port calls on the way back making it a roundtrip. While there is a great span in container ship sizes, the on-board systems and operational profile for container ships are quite similar and mainly defined by the type of payload or cargo on-board. The operations of a container ship can be broken into several parts where the most time is spent during transit between ports which is usually performed at a single design speed. Another part of the operations of a container vessel is entering or leaving the port which often requires piloting or tug boats to get the vessel to the correct berth. There, operations such as docking or undocking as well as mooring and unmooring of the vessel is carried out before the loading and unloading operation of the cargo can commence. Cranes are usually the preferred way of loading and unloading containers and are either located on shore or on the vessel itself to bring the cargo to the next stage of the logistical value chain.

5.2.2 Functional Breakdown for a Container Ship

The operational profile of the container ship defines a number of functional requirements that must be fulfilled by one or a combination of several systems and based on this it is possible to outline a functional breakdown for a container ship. Figure 5.2 below is the result of a functional breakdown of a container vessel which is based upon the one presented in (Levander, 2012). This will serve as the basis of comparison for answering one of the research questions earlier presented in this master's thesis.

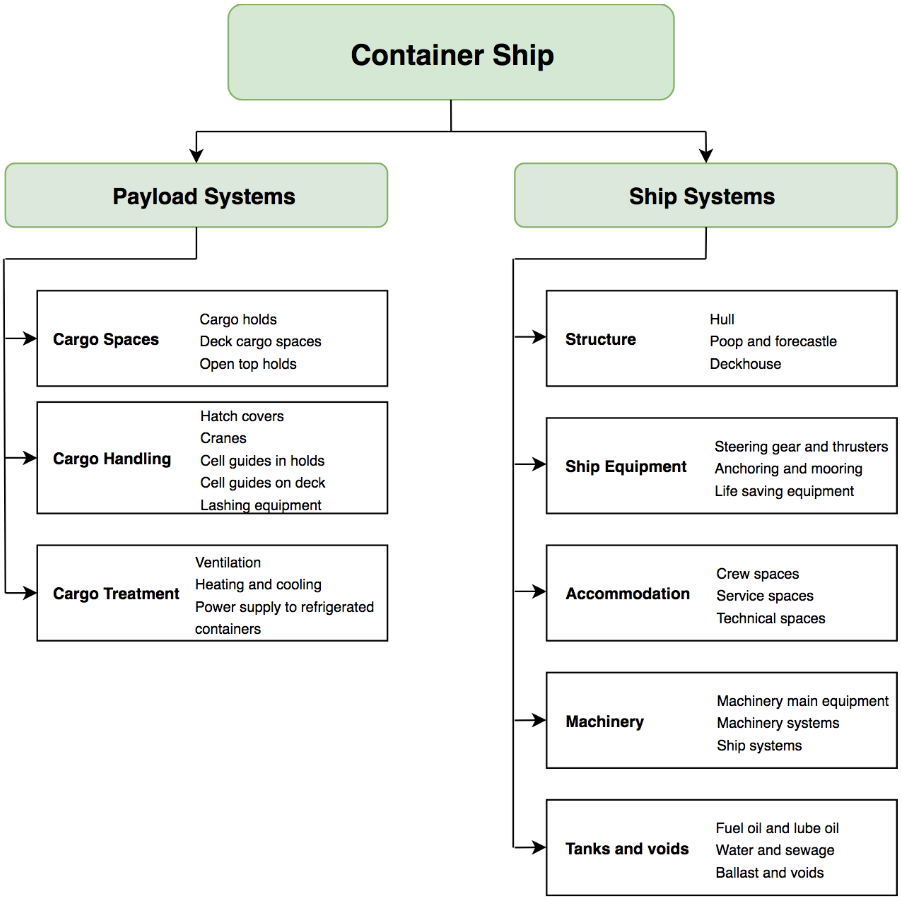


Figure 5.2: Functional Breakdown of a Container Ship (Levander, 2012)

The following paragraphs are dedicated to give a brief description of the various systems on a container ship and which functional requirements they fulfill.

5.2.3 Payload Systems

The payload systems are according to Levander, 2012 the most important in the ship design process as it describes the functions and requirements that generate cash flow for the vessel. These systems are mainly related to various types of cargo the vessel is transporting and the design of the required space, handling equipment and treatment of the cargo greatly depends on which type of cargo that is transported.

Cargo Spaces

The cargo spaces includes spaces for the storage of the containers. The containers can either be stored in a cargo hold below the deck covered by a hatch cover or in a so-called open top container ship which has open holds without the hatch. An open top container solution requires higher freeboard and are more sensitive to higher sea-states. The functional requirement for the cargo spaces is to have sufficient cargo holds for the amount of cargo specified in the mission statement.

Cargo Handling

The systems needed for cargo handling depends on the layout of cargo spaces, but generally includes hatch covers, cranes and lashing equipment. Operations such as lifting containers on and off the ship in a safe and efficient manner is also included in the cargo handling systems. The cargo handling system is required to safely handle the cargo and ensure that the cargo is securely placed into the cargo spaces of the vessel.

Cargo Treatment

The treatment of various types of cargo could require different levels of ventilation, heating and cooling, in addition to power for refrigerated containers. The cargo treatment systems main requirement is to to ensure that the state of the cargo is intact by avoiding damage or contamination during the voyage.

5.2.4 Ship Systems

The main responsibilities for the ship systems on-board a vessel is to be able to carry the payload safely from port to port according to Levander, 2012 and can be regarded as systems that contributes to the seaworthiness of the vessel (Pettersen, 2017). Thus, the ship systems are related to the functions needed to operate the ship, independent from the cargo on board.

Ship Structure

When considering the ships structure one is mainly referring to the ships hull. The main functional requirement of the hull is to provide sufficient buoyancy for the vessel. However, the hulls geometry, size and strength creates functional constraints in terms of the placement and amount of other on-board systems and vice versa. For example, a reduction of the required on-board systems will increase the flexibility in the structure design of a vessel. As the hull design greatly affect the performance of the vessel, having flexibility in the ship structure design can have a huge impact on the economical feasibility of a ship design.

Ship Outfitting

Ship outfitting includes both the equipment used on open decks, like mooring, anchor winches and deck stores. Other systems that goes under ship outfitting is below deck equipment such as steering gear, bow and stern tunnel thrusters, garbage handling and incinerator plant. In addition, ship outfitting includes safety equipment like rescue- and lifeboats, lifesaving appliances and fire fighting monitors.

Accommodation

Accommodation on-board a vessel describes the functions required by the crew such as cabins, common areas and emergency stairways in addition to functions dedicated for the operations of vessels operation. This includes areas like the bridge, offices, provision stores, and the heating, ventilation, and air conditioning (HVAC) systems. Depending on the size of the vessel, the accommodation normally constitutes roughly 3 % of the total gross volume of a container vessel (Levander, 2012). While this may sound slightly insignificant, the hotel functions and the bridge are usually a part of the vessels superstructure, which main purpose is to provide sufficient overview of the vessel and its surroundings. As a consequence of this the superstructure is responsible for inducing a large amount of air drag on the vessel. An unmanned vessel would not require the same type of superstructure or hotel functions which creates possibilities for more drag optimized vessel designs. This can have a major impact of the operational costs of the vessel (MUNIN, 2016).

Machinery

The main function for the machinery of the vessel is to produce sufficient amount of power to meet the speed requirements defined in the operational profile of the vessel. A container vessel usually has machinery control and switchboard rooms with on-board experts to monitor the performance of the machinery as well as workshop spaces to perform minor repairs during transit. An obvious challenge with unmanned vessels is that the monitoring of the machinery must be done remotely and repairs cannot be performed during transit. This creates requirements for being able to get accurate, real-time machinery performance data and sufficient machinery redundancy meeting the requirement of being "always on".

Tanks and Voids

Tanks and voids on board any vessel is responsible for providing storage for fluids needed for the whole operation of the ship. Normally a vessel has tanks for fuel oil and lube oil for the machinery and fresh water and grey water tanks intended to meet the requirements of the crew.

5.3 Autonomous Container Ship

Bringing autonomous capabilities to a container vessel opens up for new possibilities in the design of the vessel. The mission related functional requirements for an autonomous container ship are assumed to be similar to a regular vessel but needs to be fulfilled by different design parameters. The following sub-sections will present a proposal for a functional breakdown and required systems for an autonomous container ship, based upon the available literature and the author's own assumptions.

5.3.1 Proposed Functional Breakdown

After reviewing available literature and visions of autonomous vessels an attempt to create a functional breakdown including the systems needed to achieve autonomy was made following the system based ship design approach. Previously required systems on board a container vessel which no longer is needed has been removed and new systems to achieve autonomy is included in Figure 5.3 below:

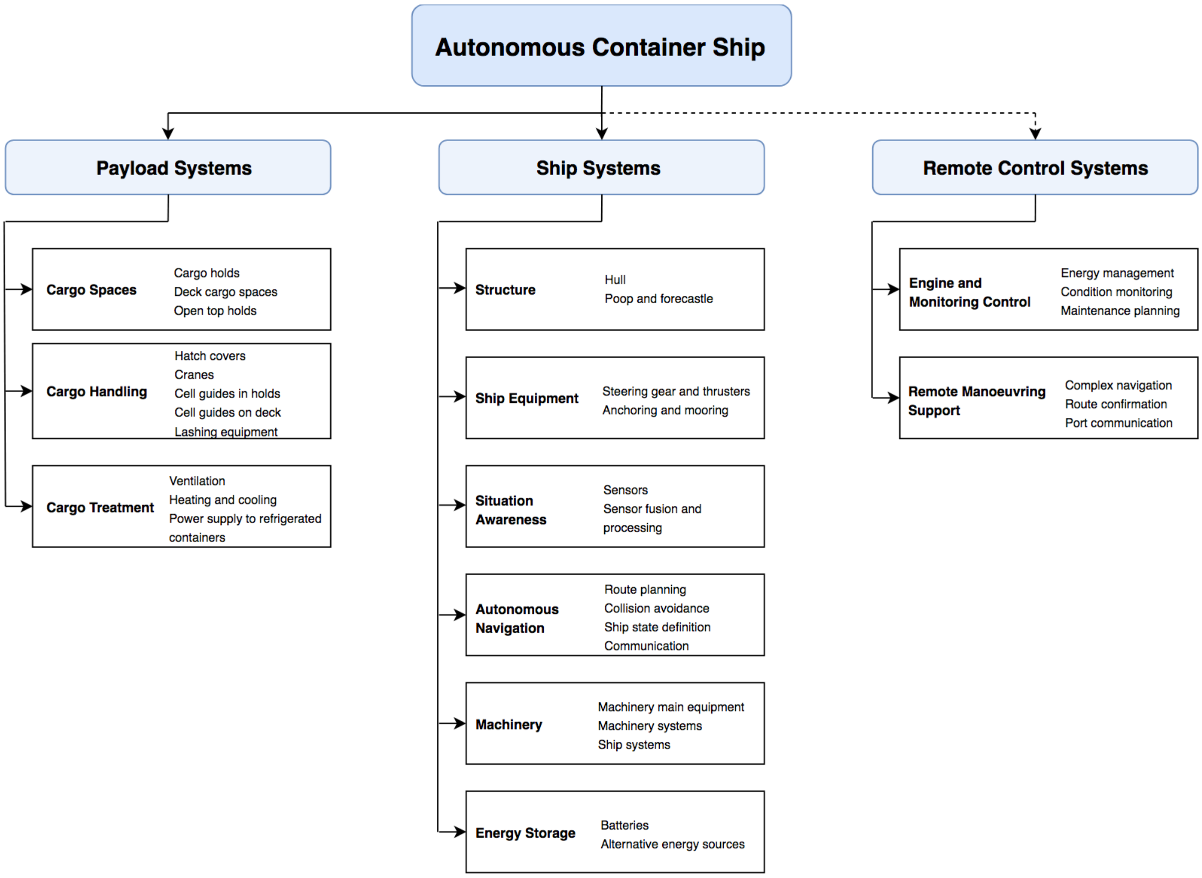


Figure 5.3: Proposed Functional Breakdown of an Autonomous Container Ship

The following paragraphs gives a description of the changes made to the physical systems of a conventional container vessel.

5.3.2 Payload Systems

The payload systems for an autonomous container ship is expected to remain fairly similar as the ones on a regular container ship. However, it will be necessary to make changes to how the functional requirements are satisfied by design parameters. First and foremost it will be possible to increase the cargo spaces on board the vessel due to more available space created by the removal of crew related facilities, which is economically beneficial. Further, it is envisioned in the Yara Birkeland concept that the cargo handling will be done autonomously. This was recently confirmed in (Stensvold, 2018) which states that the straddle carriers and cranes on Herøya is going to load and unload cargo onto Yara Birkeland autonomously which sets requirements for the kind of infrastructure available at the ports. While it is assumed no changes to the cargo treatment system there may be some limitations to which types of cargo are feasible to be transported by autonomous container ships, as cargo treatment systems will introduce additional system complexity and increase energy consumption on board the vessel.

5.3.3 Ship Systems

It is within the ship systems that the largest differences between regular and autonomous container ships are found. Due to the vessel being unmanned, several structural requirements to the vessel becomes more flexible and most systems can be discarded or redesigned. In the functional breakdown, the deckhouse ship system has been removed due to the absence of crew. While the vessel may still require spaces for poop deck and forecastle they may undergo structural design changes as well. As an example, Yara Birkeland is designed to be ballast free which further increases the flexibility in the structural hull design and can give reduced operational costs, due to the vessel no longer having to transport ballast together with the cargo (Kongsberg, 2017). In addition, the design of the hull does no longer have to facilitate for aspects such as on board comfort for the crew and can be optimized even further in terms of reducing hydrodynamic resistance as long as the stability of the vessel is still intact. Spaces for accommodation has also been discarded which together with the deckhouse and bridge removes the necessity of having any kind of superstructure as long as the sensors have sufficient field of view. This opens up the possibility of streamlining the structural design for reducing wind induced drag.

Ship equipment on board a vessel intended for emergency and life saving purposes for the crew have also been omitted from the ship systems. This includes systems needed for rescue- and lifeboats and lifesaving appliances. However, the vessel should be designed to have sufficient ship equipment for preventing and fighting fire. These systems are already required on container vessels but systems such as CO2 flooding system can be designed to release even faster in the event of fire as there is no risk of crew members being inside the engine room or any other space where fire can occur (Paulsen et al., 2012). Other ship equipment designed to facilitate crew members will also be redundant on an autonomous container vessel.

Systems intended to replace human functionalities such as navigation and environmental perception are new additions to the ship systems for the autonomous container ship. The situation awareness system includes the physical sensors needed on board the container ship along with the necessary hardware and software for fusing and processing the sensor data on the vessel which has been presented in detail earlier in this master's thesis. The autonomous navigation system can be considered the active part of the vessels autonomous capabilities. The system performs operations such as voyage planning, making necessary deviations to avoid collision with nearby obstacles and defining which level of operational autonomy is best suited for each part of the voyage. These decisions are based upon input data from the situation awareness system and the autonomous navigation system is also responsible for maintaining communication with the shore based control centre.

It has been mentioned earlier that it is of paramount importance to design the machinery systems to be highly reliable and robust with minimal requirement for maintenance. While there are no requirement for autonomous vessels to be operated with alternative prime movers it can be seen that concepts such as Yara Birkeland are designed to be fully electric. One of the reasons for replacing diesel based machinery with battery-driven engines is due to the the high complexity and low reliability associated with diesel engines. The vessel would still require redundancy for the machinery systems which is different from conventional vessels. Thus, a system for energy storage is included in the ship systems which is monitored by the shore-based control centre. A limitation worth mentioning is that fully electric vessels might not be feasible for longer, deep sea voyages do the existing technological capacity of batteries.

5.3.4 Remote Control Systems

A new branch of the functional breakdown for the autonomous container ship has been defined as *remote control systems*. While these systems are not located physically on board the ship they are still necessary systems for operating the vessel which is why it is indicated by the dotted line in Figure 5.3. These systems represents the functionality of a shore control centre envisioned in Kongsberg, 2017, AAWA, 2017 and MUNIN, 2016 which includes capabilities such as monitoring of the energy consumption and condition of various equipment on board the vessel as well as planning of required maintenance. In addition, the remote control systems are responsible for giving remote manoeuvring support if events occurs that the autonomous ship systems are not capable of solving on its own. This includes taking remote control of the vessel for complex navigation, confirming deviations of the planned route, as well as communicating with port authorities which is unlikely that an autonomous system is capable of performing.

5.4 Autonomous Job Analysis

This section demonstrates how the autonomous job analysis method can be applied to a container ship operation.

5.4.1 Context Description: Short-sea Autonomous Container Ship

The main goal of the operation is to be able to fulfill the mission statement of transporting cargo containers safely between two or more ports with the highest possible level of autonomy at each part of the operation. The following sections gives a context description of four different sub-operations related to short-sea shipping. While the operation could be broken down into even more sub-operations, the intention of this analysis is as previously mentioned to investigate whether the method can provide decision support in autonomous systems design.

Preliminary Stage: Voyage Planning and Initiation

Before carrying out the autonomous operation it is necessary to create a voyage plan for the vessel. Most important is to ensure that there is sufficient communication capacity for every part of the mission, which may vary depending on the operational area. Other aspects such as weather forecasts which may interfere with the communication link should also be assessed ahead of the operation. The voyage plan should include a definition of which operational mode the vessel should have at each leg of the voyage. Further it should define a navigational plan for the mission as well as a fail-to-safe strategy. The flow chart in Figure 5.4 below shows an example of a fail-to-safe strategy for an autonomous vessel:

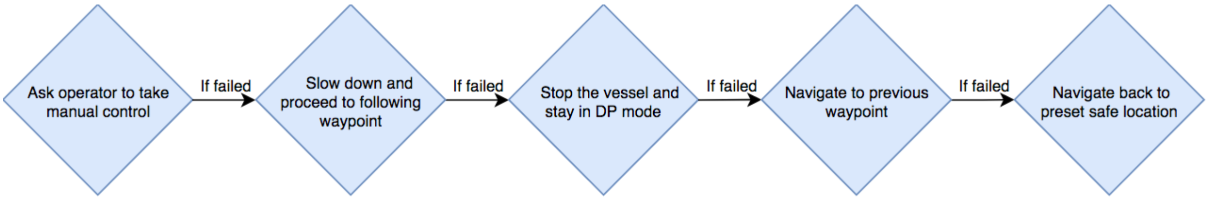


Figure 5.4: Flow Chart of a Fail-to-safe Strategy for an Autonomous Vessel (AAWA, 2017)

The fail-to-safe strategy sequence illustrated above is not necessarily applicable for every part of the voyage. For instance, stopping the vessel and remain in DP mode may not be feasible if the vessel is located in a passage with heavy traffic or in harsh environmental conditions. These fail-to-safe strategies may be changed during the voyage if there are deviations from the pre-defined operational conditions. Once completed, the voyage plan should be transferred to the autonomous vessel and other aspects such as securing cargo should be verified either by a remote operator or an automatic system before the voyage can be initiated.

Stage 1: Unmooring and Manoeuvring Out of Harbour

It is expected to be two different alternatives for mooring systems for an autonomous vessel according to Rødseth and Nordahl, 2017. The first alternative is to let the complete mooring and unmooring operation to be automatically carried out by the vessel itself or remotely controlled by an operator. This alternative would require modifications to the dockside infrastructure which will depend on the suitability and/or the economical feasibility of the dock where the vessel is going to operate. A different option would be a less autonomous solution where the connection to the quay is executed automatically with the use of the vessels dynamic positioning system, but an on-site crew is present to secure the docking by the use of conventional rope-based systems.

Manoeuvring the ship out of the harbour is a critical operation due to the relatively dense traffic, including leisure vessels and other ships. In addition, the water may be shallow which further restricts the maneuverability. During this part of the operation it is evident that high capacity and low latency communication is necessary as the vessel may have to be remotely operated or following predetermined way points. It also sets requirements to the communication systems available at the harbour.

Stage 2: Transit at Open Sea

At this stage there are fewer obstacles and ships nearby the autonomous vessel which makes it possible to increase the level of autonomy, allowing the vessel to potentially operate fully autonomous for large parts of the open sea transit. As the communication bandwidth may not be as good as in the harbour, the vessel should minimize the amount of data transferred to the shore control centre. Further it should only provide relevant status data such as location, speed, heading and estimated time of arrival (ETA) to the next way point, in addition to key information from the situation awareness system. Simple evasive maneuverings and minor changes to the route plan is carried out by the autonomous system itself, where the shore control centre is only informed of the decisions or asked for confirmation with minimal human-machine interaction requirements. However, if a more complex situation occurs which the systems route planning algorithms are not capable of solving, the operational mode should be changed to remote operation.

A fail-to-safe strategy should also be implemented if external and/or communication conditions makes it infeasible to safely controlling the vessel or if the vessel is unable to contact the shore control centre. This implies that the level of autonomy will be dynamically adjusted during the transit at open sea if the autonomous navigation system is incapable of performing the operation autonomously or if the execution of the mission is not proceeding according to the original voyage plan.

Stage 3: Port Approach and Docking

Similar to stage 1, the operator can choose to remotely control the vessel when approaching the port as the environment becomes more complex. The operator will also need to communicate with the port authorities to get assigned to the correct berth and organize piloting or tug boats if required at the port. Piloting will also apply for the manoeuvring out of the harbour and can be organized in different ways. AAWA, 2017 suggests that the pilot may get permission to take control over the autonomous vessel or that the vessel operator holds a pilot license for the intended operation area. When safely docked at the port, operations such as unloading of cargo, transfer of operational data and re-charging of the batteries (or bunkering if fueled by diesel) may commence.

5.4.2 AJA Tables

The resulting AJA tables for each of the operational stages earlier defined can be found in Appendix B.

Chapter 6

Discussion

Two research questions were stated in the introduction of this master's thesis. They raised the questions of which methodologies could be applicable for the design of autonomous systems and what changes to the physical systems on a conventional container ship would result from including autonomous capabilities in the ship design. As the development of autonomous systems in the maritime industry is still in the early stages it limits the possibility for this master's thesis to reach a quantitative conclusion. Hence, all argumentation will be based on the literature presented in this master's thesis, as well as the author's own opinions.

First, a reflection on the various topics specified in the literature review on the concept of autonomy and the various design challenges related to autonomous systems design will be presented before a discussion on whether this master's thesis was able to answer the previous stated research questions is given.

To properly understand the concept of autonomy the importance of defining a suitable taxonomy is evident. While the literature review only presented a few of the available taxonomies created for autonomous systems it can still be stated that it is not possible to determine a taxonomy that is best suited for all types of application. A high fidelity taxonomy with marginal distinctions between levels will not necessarily be better at describing an autonomous system than a taxonomy with fewer levels of autonomy. When choosing or creating a taxonomy for levels of autonomy one must rather prioritize the needs and requirements for the given application and choose a suitable taxonomy accordingly.

Further, several design challenges were highlighted in this master's thesis as a consequences of introducing autonomy into marine systems design. Most prominent is the challenges related to the technical operations of the vessel, which is considered to be the most complex part of shifting from conventional to autonomous ships. Besides the technical difficulties related to actually achieving autonomous capabilities such as situation awareness and autonomous navigation, a key challenges to be solved lies within determining the human machine interaction of various operations. While it is envisioned that the operation of unmanned vessels will dynamically combine different levels of autonomy depending on the state of the vessel and external conditions, it is expected that the first commercial applications of autonomous vessels will be carried out at a low level of autonomy with most operations being performed by on-board crew and remotely controlled operations.

The main reasons for this is considered to be the technological immaturity and lack of experience with autonomous systems intended for maritime shipping, which contains a lot of uncertainty in terms of maritime safety in addition to various shortcomings in the maritime legal framework. However, after following an initiative by the Norwegian Maritime Authority, among others, IMO put autonomous ships on the agenda for the 99th session of IMO's Maritime Safety Committee (MSC), which was recently held at May 15th 2018. This marked the first steps towards adoption of autonomous ships within maritime law (IMO, 2018). Further, as technologies such as control algorithms evolves, the ships will be capable of handling increasingly complex operations on their own and Yara Birkeland will undoubtedly be an important test platform for marine autonomy in the future. The experiences and lessons-learned from this pioneer concept will not only become valuable for technological developments and design of marine systems, but also set standards for how entire value chains around autonomous vessels needs to adapt and develop further to accommodate for autonomous systems.

The proposed functional breakdown of the autonomous container ship illustrated that there will be certain on-board systems that no longer will be necessary to include in the ship design. The literature on designs and envisions of autonomous vessels, previously presented, all concur on facilities meeting crew requirements no longer being required as long as the vessel is unmanned. However, while these systems would have a major impact on the design of the vessel, they are still necessary in the early phases of autonomous shipping. Apart from that, the available literature does not indicate any more physical on-board systems to be rendered redundant.

However, there are several physical systems that can be or must be redefined as a consequence of autonomy. For instance, the absence of crew on-board make it a necessity to add redundancy in the design of critical systems such as machinery to ensure that the vessel is still operable if failure was to occur in one or several of the systems. Autonomy also facilitates for other physical systems to be optimized in terms of volume and/or performance which renders more efficient systems design possible. Autonomous systems does not necessarily have to replace a physical system but can also be implemented as an additional system that fulfills the same functional requirements with the intention to provide flexibility, redundancy and/or decision support in the systems design.

The first part of the case study on the autonomous container vessel also revealed that new physical systems would be necessary to implement. There is a general consensus between the various projects and visions presented in this master's thesis that many functions is to be moved to a dedicated shore control centre, expanding the system boundary from just being concerned with the vessel itself. The main responsibilities for these shore control centres will be to manage, monitor and remotely intervene in the operation of autonomous vessels. Design principles from Industry 4.0 regarding interoperability and information transparency allowing equipment to connect and communicate will become of paramount importance for functions such as condition monitoring, energy management and maintenance planning to be successfully performed at these shore control centre.

The accompanying disruptive effects from autonomy creates an immense amount of new possibilities in the conceptual design of autonomous vessels. Hence, it is not possible for this master's thesis to state which physical systems will be changed as a consequence of bringing autonomy to the systems design. This highlights an important finding in this master's thesis as changes to the vessels physical systems will depend on many different factors and varies from design to design. However, while it was not possible to determine *which* physical systems on-board the vessel is going to change, the function-to-form mappings presented in Figure 5.1 depicts *how* we can expect to see physical systems change as a consequence of autonomy. This realization may be considered abstract and does not provide any concrete answer to the first research question but it underlines the importance of understanding fundamental design methodology principles, especially the mapping between functional and physical design spaces which the author believes to be just as valuable.

As earlier stated one of the research question to answer was to investigate which methodologies existed that could provide decision support for the design of autonomous systems. One of the challenges when dealing with autonomy is that it is an abstract and non-tangible concept which can be difficult to comprehend. In addition, a generic consequence of autonomy is that it increases system complexity. However, it is important to mention that autonomous systems does not necessarily need advanced, custom-made design methods to be developed just due to the fact that there is lack of experience and complexity associated with designing such systems. The approaches presented in this master's thesis all has the element of decomposing systems down to its core functions to gain additional insight and reduce complexities which is believed to be a key factor to designing autonomous systems.

Function-to-form mapping principles from axiomatic design in combination with the systematic breakdown of the system based ship design approach has been proven as an efficient method to analyze how autonomy will affect an existing design. By identifying various ways of mapping from the functional domain to a physical or cyber-physical domain establishes a generic foundation for decision-making. However, the way axiomatic design assesses a system could be non-beneficial when considering the novel and disruptive characteristics of autonomy. A shortcoming with the axiomatic design approach is that to perform a top-down process of breaking down the system one needs to define design parameters for every functional requirement which may force the designer to create new solutions that satisfies the functional requirements. As earlier mentioned this requires extensive knowledge and experience of the system at hand and will most often lead to an optimization of an already created solution, instead of coming up with something innovative.

There are similarities related to the way axiomatic design and catalogue design maps between the functional and physical space. Both approaches are characterized by having a process of going back and forth between the two spaces to achieve a detailed design. However, the difference is that the catalogue design approach performs a bottom-up process to develop concepts as shown in Figure 3.6. This makes for a better way of building up novel, complex systems where different forms that fulfills the same functional requirement could be created from a database or fundamental knowledge of natural science. If this approach was to be applied to autonomous systems it would require that most of the effort was put into identifying and improving the interactions between the various sub-systems as well as focusing on creating solutions based on first principles. In this way the database will grow over time as more solutions is made.

Innovative solutions are difficult to achieve and basing reasoning on analogies could very well become a pitfall for the future designs of autonomous vessels. Conventional ship design has developed for hundreds of years to facilitate for human requirements. While autonomy is a key technology for unmanned vessel designs there might still be difficult to achieve innovative solutions as humans has the tendency to optimize form rather than improve the core function of a design. This makes the process of assessing a design problem by using fundamental or first principles of paramount importance. However, while first principles are trivial in their definition they are difficult to put into practice and requires much more effort.

As an example, Yara Birkeland will become the first commercially operated autonomous vessel, but apart from exchanging crew with autonomy it is very much like a conventional container ship. When considering the disruptive possibilities of autonomy it is unlikely that the design for Yara Birkeland would even be close to the optimal design for an autonomous vessel. This implies the need to be wary of inherited ideas due to the fact that old conventions and previous forms are often accepted without question and, once accepted, can be a limiting factor for creativity.

There are a lot of uncertainties related to how autonomous vessels are going to be operated, especially in the early implementation phases. Designing with regards to modularity will be applicable for several aspect of autonomous systems design as it provides a structured and flexible decision support for most technical aspects of the design. The Electric Blue concept previously presented illustrates how modularity principles from design methodologies can be applied to achieve a more flexible and efficient design by enabling the possibility to easily exchange modules to adapt to changes in operational contexts.

If the first commercial autonomous vessels are required to be manned, it can be beneficial to modularize the bridge, deckhouse and accommodation spaces. In that way, if technology and regulations allows for fully unmanned operations these modules can be removed avoiding to make costly structural modifications to the ship design. Further, the use of a design structure matrix is believed to be a beneficial tool to get useful insights into different sensor fusion concepts to discover the relationships and interactions between various sensors and other entities. Achieving modularity in the sensor design can have a huge impact on the development costs as well as the flexibility in what the autonomous system is capable of performing, opening up the possibilities for *multi-purposed autonomous systems.*

For the last part of the case study the autonomous job analysis was demonstrated to investigate if it could provide decision support in determining additional functional requirements and modes related to the operation of an autonomous container ship. While little emphasis was laid on the fidelity of the analysis, it is evident that the method is tailored to reveal design challenges, needs and limitations regarding autonomous behavior by analyzing and breaking down the operation.

The results presented in the AJA tables was able to catch relevant functional requirements to the autonomous systems. However, many of the findings can be considered trivial and to some extent repetitive. One reason for this is believed to be due to the operation being broken down into just four stages, whereas stage 1 and stage 3 are almost identical which does not capture all the details in the autonomous container ships operational profile. Further, the lack of available information and the authors knowledge of details regarding the operation is definitely a contributing factor. However, the intention with the analysis was not to identify all functional requirements related to the operation of the autonomous container ship, but merely to investigate if the method in fact was able to provide decision-support in autonomous systems design.

The autonomous job analysis is stated as one of the cornerstones in the SEATONOMY methodology. SEATONOMY addressed several high level challenges for the design of industrial autonomous systems whereas one of the challenges was to determine the right degree of autonomy for any given application. Achieving clear answers to what is the optimal level of autonomy for any given application is considered to be difficult and would be heavily dependent on operational context and desired goals. This stands out as one of the key challenges to solve in autonomous shipping operations. An interesting feature of the SEATONOMY methodology is that it addresses the development of autonomous systems from different viewpoints, creating a foundation for multidisciplinary assessment. It is evident that close collaboration and expertise is needed from a multitude of disciplines such as marines system design, information and communications technology (ICT) architecture and cybernetics to cover the various aspects of designing autonomous systems.

The intention with the SEATONOMY methodology is evidently that it should be applicable to autonomous system design. However, SEATONOMY is not a step-by-step guide of how one should design a system, but rather a recommendation on how autonomous system design can be approached. A limitation with the methodology is that its scope is directly related to autonomous functionality, meaning that choices such as hull design and general arrangement is not covered. While SEATONOMY is a promising methodology it is still under development. Hence, it would be interesting to investigate whether other approaches, for example those presented in this master's thesis, could also be implemented in this methodology if proven applicable to autonomous system design to make SEATONOMY a more comprehensive methodology.

Chapter 7

Conclusion and Further Work

7.1 Conclusion

This master's thesis set out to investigate which physical systems changes will result from including autonomous capabilities in ship design of a conventional container vessel and to compare how different methodologies could provide decision support for autonomous systems design. Due to limitations in available information and the early phase of development of autonomous systems design within the maritime shipping industry, reaching a quantitative conclusion to the research questions was not an objective for this exploratory research study.

By reviewing and comparing various sources of literature regarding autonomous visions and projects within maritime shipping this thesis has identified a consensus of opinion regarding the main systems architecture for achieving autonomous capabilities as well as highlighted the main design challenges facing the industry.

To conclude on the first research question, it is safe to say that autonomous systems will have a disruptive impact on physical systems for container ships. Further, it as been shown that while it is not possible to exactly determine *which* physical systems on-board the vessel is going to change, it is valuable from a systems design point of view to understand *how* we can expect to see physical systems change as a consequence of autonomy.

The case study demonstrated how applicable design methodologies can be utilized to identify design challenges and functional requirements related to autonomous operations as well as to understand the relationships and interactions between the various on-board systems of a container vessel. Thus, this thesis has successfully identified and applied design methodologies that provided decision support for autonomous systems design answering the second research question.

The approaches presented in this master's thesis all have the element of decomposing systems down to its core functions to gain additional insight and reduce complexities, which is believed to be a key factor to designing autonomous systems. It has also been pointed out that following each methodology to the letter may be a daunting and inefficient task, but combining certain principles from applicable design methodologies is considered more feasible and an important contributor for performing a successful design process.

Finally, the thesis addresses that a multitude of expertise from disciplines such as marine systems design, information and communications technology (ICT) architecture and cybernetics is required to cover the various aspects of autonomous systems and that the combination of different areas of competencies is a key factor for achieving a more holistic autonomous systems design.

7.2 Further Work

Autonomy is going to be one of the great game-changers in the maritime shipping industry and there is no doubt that further work needs to be carried out in the future. While this master's thesis demonstrated the applicability of various design methodologies, a more comprehensive study on the operation of an autonomous container vessels, ideally based upon quantitative data, should be performed.

This thesis has shown that autonomous systems design requires expertise from various disciplines and it would be interesting to see a collaboration project focusing on the SEATONOMY methodology, addressing not only the performance aspects of an autonomous vessel, but the design of both software and hardware as well. In that way one could gain further insights into how the results from one viewpoint affects the other and uncover additional details regarding the design.

Further, due to the high-level focus of this thesis a thorough investigation of the interaction between vessels, port facilities and operations such as autonomous mooring along with exploring how various levels of autonomous solutions could benefit the interactions was not performed. While most of the literature and projects seen today are related to short-sea shipping it would also be of interest to look into the additional functional requirements and design challenges needed for deep sea voyages.

Finally, in a long-term perspective a natural subject to recommend for further work would be to study the management of a fleet of autonomous vessels from a shore control centre in terms of optimal resource utilization, monitoring and logistics.

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Appendices

Appendix A

List of Acronyms

AI	Artificial Intelligence
AIS	Automatic Identification System
AJA	Autonomous Job Analysis
ALFUS	Autonomy Levels For Unmanned Systems
AMOS	Autonomous Marine Operations and Systems
ANS	Autonomous Navigation System
AUV	Autonomous Underwater Vehicles
AWAA	Advanced Autonomous Waterborne Applications
CA	Collision Avoidance
CAC	Contextual Autonomous Capability
CEO	Chief Executive Officer
COLREGs	Convention on the International Regulations for Preventing Collisions
DNV GL	Det Norske Veritas Germanischer Lloyd
DP	Design Parameter
DPS	Dynamic Positioning System
DSM	Design Structure Matrix
ETA	Estimated Time of Arrival
EU	European Union
FR	Functional Requirement
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAZOP	Hazard Operability Analysis

HMI	Human Machine Interaction
HTA	Hierarchy Task Analysis
HVAC	Heating, Ventilation, and Air Conditioning
ICT	Information and Communications Technology
IMO	International Maritime Organization
IMR	Inspection, Maintenance and Repairs
IMUs	Internal Measurement Units
IoSS	Internet of Services at Sea
IoT	Internet of Things
IR	Infrared
JSA	Job Safety Analysis
LCC	Life Cycle Costing
LIDAR	LIght Detection And Ranging
LR	Lloyd's Register
LWIR	Long-Wave Infrared
MARPOL	Marine Pollution
MIT	Massachusetts Institute of Technology
MSC	Maritime Safety Committee
MTM	Multi Domain Matrix
MUNIN	Maritime Unmanned Navigation through Intelligence in Networks
NIR	Near-Infrared
NTNU	Norwegian University of Science and Technology
ROI	Return On Investment
RP	Route Planning
SA	Situation Awareness
SBSD	System Based Ship Design
SCC	Shore Control Centre
SOLAS	Safety of Life at Sea
STCW	Standards for Training, Certification, and Watchkeeping
TEU	Twenty-foot Equivalent Unit

TOF Time-of-flight

UMS Unmanned Marine Systems

UNCLOS UN Convention on the Law of the Sea

Appendix B

Autonomous Job Analysis Tables

B.1 Voyage Planning and Initiation

Table B.1: AJA Table for Voyage Planning and Initiation

Categories	**Answers**
Communication	Must establish communication between vessel and shore control centre Provide information regarding real time weather conditions
Perception	No requirement for perception at this stage
Success Criteria	Hardware and software are working fine Voyage plan as been transmitted and received correctly
What can go wrong?	Incorrect transfer of voyage plan Communication error
Operational Safe-state	In case of any failure, it should be solved and system should be reconfigured and re-initialized
Human Machine Interaction	Operator should confirm that all systems is working properly and initiate the next sequences

B.2 Unmooring and Manoeuvring Out of Harbour

Table B.2: AJA Table for Unmooring and Manoeuvring Out of Harbour

Categories	**Answers**
Communication	Must have reliable high bandwidth and low latency communication between vessel and shore control centre The operator must receive all relevant information from situation awareness system and autonomous mooring system Contact port authorities to arrange piloting.
Perception	All sensors in the situation awareness systems must be active to identify all surrounding objects
Success Criteria	Cargo should be correctly loaded and secured within the vessel Vessel is correctly unmoored from the berth Vessel must be able to follow way points according to voyage plan if operated autonomous Avoid obstacles and other vessels while following nautical conventions
What can go wrong?	Loss of communication Hardware/software failure
Operational Safe-state	Move out of the heavy traffic lanes and remain in position to wait for assistance.
Human Machine Interaction	High human involvement, either remotely operated or closely monitored. Will depend on the complexity of the surrounding environment

B.3 Transit at Open Sea

Table B.3: AJA Table for Transit at Open Sea

Categories	**Answers**
Communication	Potentially low bandwidth and some delay in communication due to lack of nearby infrastructure.
Perception	Reduced need for all situation awareness capabilities due to less complex environment Will still require sensors for object detection and internal measurement units
Success Criteria	Follow intended voyage plan and remain in autonomous mode Successful make changes to voyage plan by the autonomous system if small deviations occurs
What can go wrong?	Loss of communication between vessel and shore control centre Hardware/software failure Change in weather conditions
Operational Safe-state	Follow fail-to-safe strategy which will depend on the type of error and surronding conditions
Human Machine Interaction	High level of autonomy where operator intervention only if complex situation occurs. Decide best fail-to-safe strategy based upon current conditions

B.4 Port Approach and Docking

Table B.4: AJA Table for Port Approach and Docking

Categories	**Answers**
Communication	Must have reliable high bandwidth and low latency communication between vessel and shore control centre The operator must receive all relevant information from situation awareness system and autonomous mooring system Contact port authorities to arrange piloting.
Perception	All sensors in the situation awareness systems must be active to identify all surrounding objects.
Success Criteria	Vessel must be able to follow way points according to voyage plan if operated autonomous Avoid obstacles and other vessels while following nautical conventions Vessel is correctly moored from the berth Cargo should be correctly unloaded
What can go wrong?	Loss of communication Hardware/software failure
Operational Safe-state	Move out of the heavy traffic lanes and remain in position to wait for assistance.
Human Machine Interaction	High human involvement, either remotely operated or closely monitored. Will depend on the complexity of the surrounding environment