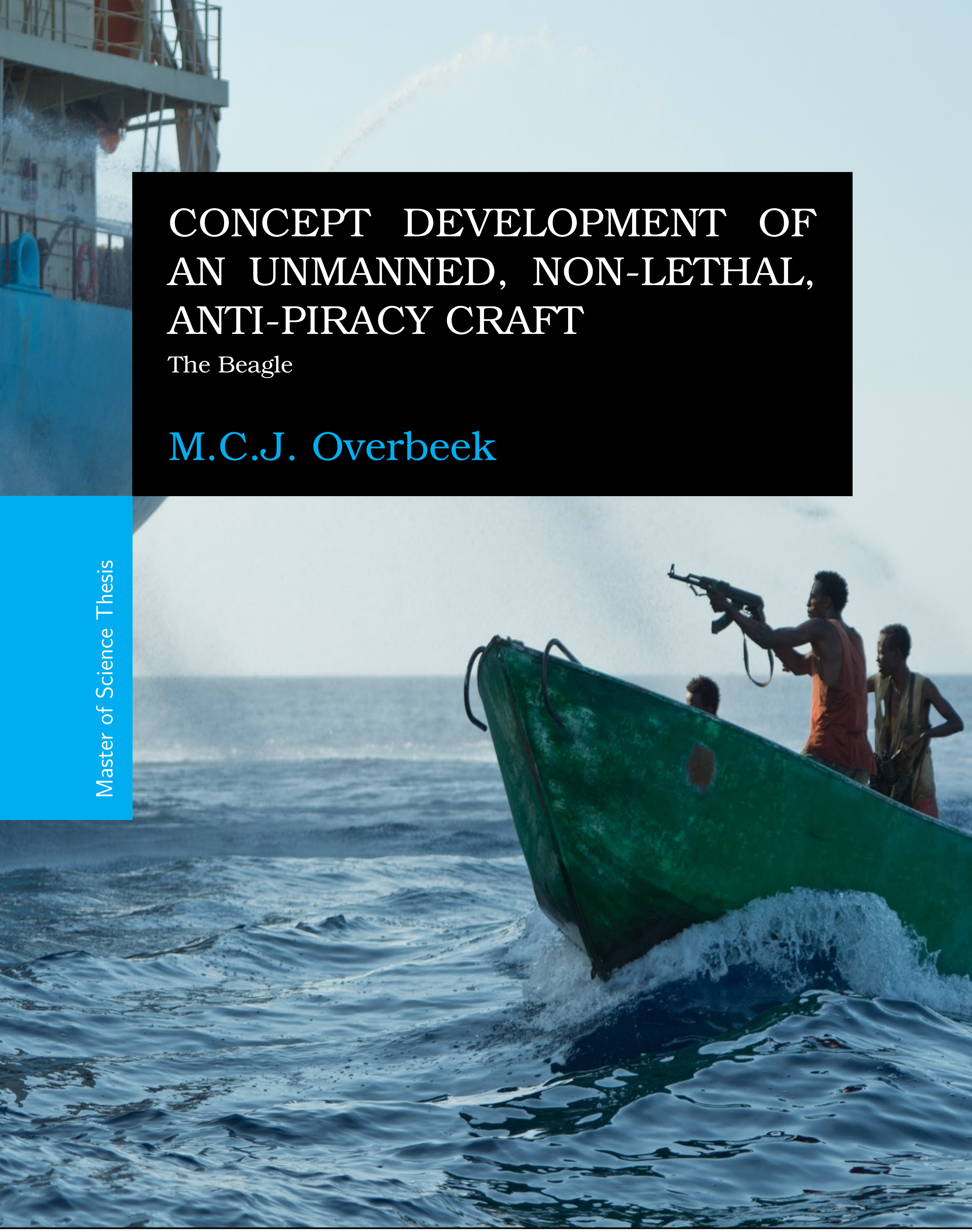

CONCEPT DEVELOPMENT OF AN UNMANNED, NON-LETHAL, ANTI-PIRACY CRAFT

The Beagle

M.C.J. Overbeek

Master of Science Thesis

Delft University of Technology

Maritime Technology

Report number: SDPO.18.041.m

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For the degree of Master of Science in Maritime Technology at Delft University of Technology

to be defended publicly on Tuesday November 13, 2018

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Abstract

Maritime piracy has been a problem for the last decades and peaked in 2010. This resulted in large investments in anti-piracy measures, but as piracy waned over the following years, so did the investments in anti-piracy measures. This could be an indication that the stage for maritime piracy has been reset. This report suggests a more efficient and cheaper approach to counteract maritime piracy on merchant vessels indefinitely.

SeaState5, the company at which this research is done, came up with the idea to combat pirate attacks on merchant vessels using a Fast Rescue Craft (FRC). Merchant vessels are obligated by law to carry an FRC; used for instance for man over board missions. SeaState5 focuses on developing an add-on plug and play system compatible with existing FRC. It turns these sole-purpose rescue craft into a multi-purpose craft, in this research referred to as the Beagle. This Beagle will serve both rescue and anti-piracy purposes. In this report the concept development of this add-on system is established.

This is done by developing a simulation in MATLAB and Simulink that mimics a pirate attack on a merchant vessel. During the pirate attack the Beagle uses a defense strategy to repel the pirates. A Beagle defense strategy is a combination of a non-lethal weapon and a set of parameters that define the trajectory of the Beagle. Different Beagle defense strategies are subjected to different pirate attack scenarios to find the most effective one.

The simulations resulted in a list of requirements for the Beagle. A check has been done to prove the feasibility of equipping an existing FRC with the add-on system meeting these requirements.

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Preface

This graduation project, titled "Concept development of an unmanned, non-lethal, anti-piracy craft" was proposed by SeaState5. I would like to thank the company for providing such an awesome, actual and exciting thesis topic. Furthermore, I would like to thank SeaState5 for providing the facilities and expertise I needed to work on this topic.

I would like to take this moment thank Robert Hekkenberg. Knowing that my thesis would be about autonomous vessels, I wanted you as my supervisor, after one visit at your office you directly said yes. I would like to thank you for your critical and creative thinking which brought this project to a higher level.

Also, I would like to thank my friend Laurens Žnidaršič. Thank you for inspiring and helping me to make a better post process plot of the simulations. This helped me process the results better and show remarkable videos for the presentation.

And last but certainly not least, I would like to take this moment to put Edward Belderbos in the spotlight. Your expertise in both the maritime and robotics field, kind guidance and funny jokes make you a great supervisor. You created a great working atmosphere at SeaState5, which makes every day unique and amusing. Keep that going! I am going to miss all the ambitious and funny colleagues I met during my thesis internship.

À la prochaine!

Delft, University of Technology — Mike Cornelis Johannes Overbeek
to be defended publicly on Tuesday November 13, 2018

Chapter 1

Introduction

1-1 Problem statement

At any given time, over 100,000 seafarers are either sailing or preparing a trip through so-called High Risk Areas. Including their families, at any given moment there are about 500,000 people gripped by the fear of maritime piracy, [4].
The International Maritime Bureau (IMB) of the International Chamber of Commerce (ICC) reported that worldwide in 2016, 150 vessels were boarded, twelve vessels were fired upon, seven were hijacked, and 151 seafarers were taken hostage, [5]. From the moment of hijacking, the life and well-being of the seafarers is in the hands of the pirates. Negotiation with pirates is a slow process; on average a hijacking can last for eight months, usually the pirates get paid. If the negotiations become too protracted, the pirates often resort to torturing their prisoners. Despite the fact that seafarers are often released in the end, they speak of losing hope and faith, and of psychological damage, because of the exposure to torture and abuse, [4].
The other major consequence of maritime piracy can be found in the economic costs. In 2011 the following estimation has been made of the costs of maritime piracy (in dollars), [6].

- 2,710 million in fuel costs of increased speeds of vessels transiting through High Risk Areas
- 1,270 million for military operations
- 1,100 million for security equipment and armed guards
- 635 million is attributed to insurance
- 580 million is spent on re-routing vessels along the western coast of India
- 195 million is estimated for increased labor costs and danger pay for seafarers
- 160 million is paid in ransoms
- 16 million is spent on the prosecution and imprisonment of Somali pirates

Maritime piracy was at its peak in 2010, with over 700 hostages and 32 vessels being held by Somali pirates, [7]. This resulted in large investments in anti-piracy measures by the international community's commitments to combat piracy in the High Risk Areas. As piracy waned over the following years the international community's commitment to combat piracy diminished, resulting in a declining number of vessels using private security and other anti-piracy measures. Furthermore, the deployment of naval vessels dedicated to counter-piracy operations decreased as well. In 2015 there was an increasing series of pirate attacks, this could be an indication that the stage for piracy has been reset due to the lack of investment in anti-piracy measures and missions, [8]. Finally, the Anti-Piracy Operation, "Atlanta Mission", which is one of the biggest of its kind, will be ended in the end of 2018, [7].

The most effective way to counteract pirate attacks on merchant vessels available right now, is contracting armed Private Maritime Security Contractors (PMSC), [9]. These are private mercenaries that are hired when sailing in High Risk Areas and paid to secure the ship from pirates. The disadvantages are:

- Usually four PMSC are taken on board, this is quite expensive, costing the ship operator on average around 46,000 dollars per trip, [10].
- PMSC are exposed to danger when pirates shoot back.
- In the past PMSC have shot innocent civilians that tried to fish behind the merchant vessel, [11].
- PMSC are not allowed when sailing under certain flag states, this forced lots of ships to change their flag state, [11].

In conclusion, maritime piracy has been a problem for decades, and several anti-piracy missions have been undertaken, but they are always temporary and expensive. The current anti-piracy measures that shipping companies can consider are not efficient or effective. The aims of this report is to find out whether an unmanned, non-lethal, anti-piracy craft, carried on board of a merchant vessel, is a good solution for counteracting pirate attacks on merchant vessels.

1-2 Thesis subject and deliverable

SeaState5 is a business that develops high-tech maritime products that push the boundaries of current technologies. Their focus is on maritime robotics and control systems. They are located in Delft within a stone's throw from Delft University of Technology. One of the projects SeaState5 is working on is developing an unmanned, non-lethal, anti-piracy craft that is capable of counteracting pirate attacks on merchant vessels in a cheaper, more effective and more efficient way than the current anti-piracy measures. In this report this anti-piracy craft will be referred to as the Beagle. The Beagle will be a multi-purpose craft and will also serve as a Fast Rescue Craft (FRC); merchant vessels are obligated to carry an FRC by law. A picture of an FRC is shown in Figure 1-1, [1]. The goal of SeaState5 is to develop an add-on plug and play system, compatible with existing FRC, to replace this sole-purpose FRC for the multi-purpose Beagle. In this report the concept development of this add-on system will be established.

Figure 1-1: Fast Rescue Craft (FRC), [1]

The mission of the Beagle is to successfully counteract pirate attacks on merchant vessels. Pirates attack merchant vessels with so called skiffs, which are small fast boats, powered by an outboard motor. To verify whether the Beagle repels this pirate attack successfully, a computer simulation has been made that mimics a pirate attack on a merchant vessel. In this simulation the pirates try, for instance, to board the merchant vessel, while the Beagle tries to neutralize the threat. The Beagle uses a defense strategy to carry out its mission. The Beagle defense strategy controls a non-lethal weapon and determines the Beagle's trajectory. Different Beagle defense strategies will be subjected to different pirate attack scenarios. Fundamental to the Beagle defense strategies and the pirate attack scenarios is a literature study about pirate operations and anti-piracy measures. The goal of this research is to find the best and most robust Beagle defense strategy. This Beagle defense strategy will be translated into the deliverable for this report: requirements for the Beagle. Finally, a check will be done to verify whether it is possible to equip an existing FRC with the add-on system.

1-3 Scope of the study and research questions

To achieve the research goal set in Section 1-2 the following research question is formulated:

> **Research question:** What is the most suitable Beagle defense strategy to successfully counteract pirate attacks on merchant vessels?

A suitable Beagle defense strategy is a strategy that repels the pirate attack in an effective way without being too costly. Furthermore, it needs to be compatible with current FRC. Below, four sub-questions are introduced.

"*If you know the enemy and know yourself, you need not fear the result of a hundred battles. If you know yourself but not the enemy, for every victory gained you will also suffer a defeat. If you know neither the enemy nor yourself, you will succumb in every battle*" - Sun Tzu, The art of war, [12].
For this reason, the first sub-question will be on how pirates operate. After answering this question, it will become clear how the pirates can be simulated realistically. What does a pirate attack looks like, how do the pirates behave in certain scenarios, and when is an attack successful?

1. *How do pirates operate and how can this be modeled?*

An important aspect of the Beagle defense strategy is the weapon used to repel the pirate attack. The next sub-question will treat this aspect. Furthermore, it will give an insight on when the Beagle's mission is carried out successfully.

2. *Which non-lethal weapons are available to successfully repel pirate attacks on merchant vessels with the Beagle?*

The weapon systems used to repel the pirate attacks and how pirates operate, is fundamental information to the simulation setup. The next step is to formulate the defense strategies.

3. *Which defense strategies can be used to successfully carry out the Beagle's mission?*

Multiple computer simulations will be used for validation of the most effective Beagle defense strategy. Different Beagle defense strategies will be tested in different pirate attack scenarios. The Beagle defense strategy that repels most pirate attacks is the most effective:

4. *How do different Beagle defense strategies perform in different attack scenarios?*

1-4 Thesis outline

Chapter 2 addresses the research method used to answer the research question. It describes the computer simulation that mimics a pirate attack on a merchant vessel. Before this computer simulation could be built, literature about pirate operations and anti-piracy measures needed to be studied. This is elaborated upon Chapter 3. Based on this literature, the Beagle defense strategies are defined in Chapter 4. This literature is also used to describe the pirate attack scenarios, see Chapter 5. The Beagle defense strategies and pirate attack scenarios are fundamental to the computer model. Chapter 6 describes the computer model. Both the Beagle defense strategy and the pirate attack scenarios have a large number of parameters, this results in a large number of possible computer simulations. To limit the number of simulations while keeping the ability to draw clear conclusions, systematic parameter variations have been done. This is explained in Chapter 7. The results of the simulations described in Chapter 7 are discussed in Chapter 8. Finally, Chapter 9 the implementation of the results in the real world are discussed: is the optimal Beagle defense strategy compatible with current FRC? In Chapter 10, the important conclusions and recommendations of this research are discussed.

Chapter 2

Research method

This chapter will discuss the used research method in three parts: the literature study, computer simulation and feasibility study are explained in Sections 2-1, 2-2 and 2-3 respectively.

2-1 Literature study

The literature study is divided into two groups. First, it will contain information on how pirates operate, what does a pirate attack look like? This is needed to simulate the pirates as realistically as possible.
Secondly, it will elaborate on non-lethal weapons that are suitable to repel the pirate attacks. Inspiration for this will be gained by looking at current anti-piracy missions and riot control methods. Combining this literature will give enough information to answer sub-question one and two, see below. Furthermore, this information is fundamental to the simulation setup. The literature part of this research is discussed in Chapter 3: *Pirate operations and anti-piracy measures*.

1. How do pirates operate and how can this be modeled?
2. Which non-lethal weapons are available to successfully repel pirate attacks on merchant vessels with the Beagle?

2-2 Computer simulation

A Beagle defense strategy consists of a combination of four parameters as listed and elaborated on the next page. Each parameter has three to five variations, this is also indicated in this list. A total of $4 \cdot 3 \cdot 5 \cdot 3 = 180$ unique Beagle defense strategies are possible.

Beagle defense strategy parameters

1. Non-lethal weapon (4)
2. Skiff priority coefficient (3)
3. Defense zone radius (5)
4. Control strategy (3)

Four different non-lethal weapons will be simulated and are explained in Chapter 3: *Pirate operations and anti-piracy measures*. The other Beagle defense strategy parameters determine the trajectory of the Beagle, they will be elaborated in Chapter 4: *Beagle defense strategy*. The skiff priority coefficient determines which skiff has the priority at any given moment, if the pirates attack with two skiffs. The Beagle makes a consideration whether to sail to the skiff closest to itself, or to sail to the skiff closest to the merchant vessel. The radius of the defense zone determines the area in which the Beagle can operate. Finally, the control strategy determines how the Beagle will follow its target.

The goal of the Beagle is to successfully repel pirate attacks on merchant vessels. The aim of this research is to find the most efficient and effective Beagle defense strategy to achieve this goal. This leads to requirements for the Beagle. A computer simulation that can simulate pirate attacks has been made to verify the most efficient and effective Beagle defense strategy. This simulation has been made in MATLAB and Simulink and is explained in Chapter 6: *Computer model*.

This computer simulation subjects different Beagle defense strategies to different pirate attack scenarios. A pirate attack scenario is a combination of the parameters shown in the list below, they are elaborated in Chapter 5: *Pirate attack scenarios*. Each parameter has two to four variations, in total there are $4 \cdot 2 \cdot 4 \cdot 3 \cdot 3 = 288$ possible pirate attack scenarios possible. SeaState5 focuses on delivering an add-on plug and play system. This system must be compatible with existing Fast Rescue Craft (FRC). The Beagle is the combination of an FRC with this add-on system. The pirate attack scenarios are considered external parameters, SeaState5 cannot influence them. Therefore, the design speed of the Beagle is considered a pirate attack scenario parameter.

Pirate attack scenario parameters

1. Beagle design speed (4)
2. Number of skiffs attacking (2)
3. Pirate attack strategy (4)
4. Time for the skiffs to reach the merchant vessel (t_{reach}) (3)
5. Direction in which the pirates are spotted (3)

Combining all the unique Beagle defense strategies (180) and pirate attack scenarios (288), 51,840 unique simulations are possible. To limit the number of simulations while keeping the ability to draw clear conclusions, the parameters will be systematically varied to find the best Beagle defense strategy, this is explained in Chapter 7: *Systematic simulation variations*. The results of these simulations will be explained in chapter 8: *Simulation results*. The simulations can be divided into two rounds.

Simulation round 1 In the first simulation round, the Beagle defense strategy parameters will be changed systematic, while the pirate attack scenario parameters are kept constant. This pirate attack scenario will be a challenging one. By systematically varying the Beagle defense strategy parameters, different Beagle defense strategies will be defined. The goal of simulation round 1 is to find the combination of defense strategy parameters that repels this pirate attack the most effective, per weapon. Four non-lethal weapons will be tested, so four initial Beagle defense strategies will be defined and tested in simulation round 2.

Simulation round 2 In the second round of simulations those four Beagle defense strategies will be subjected to different pirate attack scenarios. In these simulations the outcome is binary. Either the Beagle or the pirate can successfully carry out its mission, the Beagle can succeed or fail. By comparing the results of the four Beagle defense strategies conclusion can be drawn about the best Beagle defense strategy or combination of strategies. This defense strategy will be translated into a set of requirements for the Beagle.

2-3 Feasibility study

The last step is to check the feasibility of the Beagle, i.e. is it possible to equip an existing FRC with the suggested add-on plug and play system? This will be done in Chapter 9: *Feasibility study Beagle*. This chapter checks the aspects of the first iteration of the design spiral as shown in Figure 2-1.

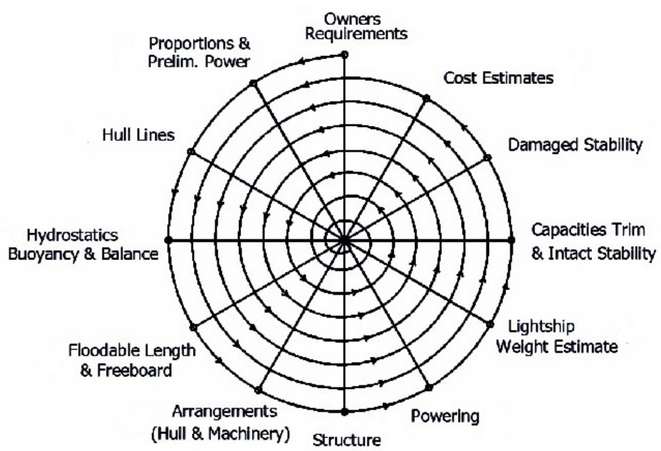


Figure 2-1: Naval architect design spiral, [2]

Chapter 3

Pirate operations and anti-piracy measures

This chapter discusses the literature part of the research as explained in Section 2-1. First, in Section 3-1 the non-lethal weapons that are available to repel the pirate attacks will be discussed. After, in Section 3-2 the pirate operations are discussed to learn more about pirate behavior, this is important to simulate the pirates correctly. Finally, in Section 3-3 the conclusion of this chapter will be elaborated. In this section the information from the first two sections will be translated into ways to simulate the non-lethal weapons and the pirate behavior.

3-1 Non-lethal weapons

In this section, all the promising weapons to repulse the pirate attacks will be discussed. It is important to keep in mind that only non-lethal weapons are considered. The reason non-lethal weapons are chosen is because in that way, the Beagle would be a better alternative than the lethal Private Maritime Security Contractors (PMSC), which have shot innocent fisherman, [13]. Furthermore, in the researcher's opinion it would be unethical to have an autonomous killing machine. Lethal weapons, weapons that can easily be counteracted by the pirates or weapons that are too heavy to install on the Beagle are not discussed. A few examples of non-effective, non-lethal weapons are for instance rubber bullets and bean bags since the pirates can easily defend themselves against it. Furthermore, smoke and tear gas are considered non-effective since the scene is at sea and moving all the time. The weapons that will be discussed are a water cannon, Mobility Denial System (MDS), the Long-Range Acoustic Device (LRAD) and a battering ram.

Water cannon Water cannons are used at protests and riots to maintain order. The goal of the water cannon is to scare people away in a non-lethal way, although water cannons caused fatal incidents, [14]. The pressure in these water cannons can rise to 15 bars and the average water cannon used in riots uses 20 liters per second, [15]. A water cannon can fire up to 60 meters, although the effect is larger in close combat, [16]. A water cannon operating at full power can bring down people aggressively, [17]. When applying a water cannon on pirates it is important to adjust the pressure to the distance of the pirates, to harm them but not to kill them. The disadvantage is that water cannot be taken on board so adjustments on the Beagle needs to be made to suck water from the ocean. It will be a design challenge to suck the water from the ocean while sailing at high speeds. To install a water cannon, one needs a gearbox, a pump and a controllable nozzle. For a water cannon that operates at 20 liters/second at 15 bar this will be around 600 kilograms. For a water cannon that operates at 20 liters/second at 10 bar this will be around 400 kilograms, [18]. Finally, when the skiff has been inside the water cannon range for 180 seconds the assumption is that the skiff is full of water, it cannot sail properly anymore and will stop the attack. In that case the Beagle wins.

Mobility Denial System The MDS is also used in protest and riots. It uses a slimy, slippery goo that, when sprayed across any surface, makes that surface impassable. It has as much friction as wet ice and therefore cannot be walked on or driven on. The idea of using the MDS is to make the pirates too slippery to board the merchant vessel. The effective range is about 15 meters, the system can quickly spray large areas, [19], [20]. The current MDS system is designed to be operated by a human. Modifications need to be made to make it operate autonomously or remote control. To install an MDS on the Beagle one needs a storage tank, a small pump and a controllable nozzle. An estimation of the weight of this system is 80 kilograms, [20]. The MDS does not need as much time as the water cannon to eliminate a skiff. The assumption is that the MDS only needs 20 seconds within range to eliminate a skiff, [19], [20].

Long-Range Acoustic Device The LRAD is not necessarily a weapon, it is a large speaker. It is used to bring messages to large groups of people over a long range. The LRAD can be used in an offensive way by using the alarm tone capability. The offensive range of the alarm tone capability per LRAD is unknown, it is estimated to be in the order of a few dozen meters, [21]. Victims describe the exposure of the alarm tone as a kind of psychological torture and were unable to move or think. LRADs come in different sizes, furthermore, some are controlled manually and some remotely. LRADs come in different prices ranging from 6,000 to 115,000 U.S. dollars. The performance of those LRADs are measured in the capability to carry a message over a large area, [22]. A large LRAD only consumes around 1200 watts, therefore it does not need much battery power, it is a lightweight option. The smaller manual LRADs weighs around 40 kilograms, while the larger remote control LRAD systems weigh around 150 kilograms. The LRAD cannot eliminate a skiff, like the other weapons. It can only keep the pirates at distance. The LRAD wins the simulation if it prevents the pirate from executing their mission for an hour. The simulation stops if either the Beagle or the pirates win the simulation. The LRAD wins if the simulation time is 3600 seconds.

Battering ram The fourth weapon is a reinforced battering ram installed at the bow of the Beagle to knock off the skiff's engines. The battering ram is successful if the bow of the Beagle is within half meter of the stern of the skiff. At the same time the relative velocity must be greater than 3 m/s. The battering ram is the only weapon that is not based on riot control. It is an out-of-the-box solution.

3-2 Pirate operations

According to the Best Management Practices for Protection against Somalia Based Piracy (BMP4), [9], a common pirate attack consists of two small, high speed (up to 25 knots) open boats or so-called skiffs, see Figure 3-1. The skiffs often approach from either quarter or stern. Skiffs are frequently fitted with two outboard engines or a larger single 60hp engine. An attack is usually planned from motherships. A mothership is generally a bigger ship, varying from fishing boat to merchant vessel, often stolen or hijacked. The motherships usually have their own crew on board as hostages. It carries skiffs, food, fuel and pirates. This allows the pirates to operate over a much larger area and be less effected by the weather.

Figure 3-1: Captured Somalian pirates with their skiff, [3]

Up to date, no attacks have been reported where the pirates boarded a merchant vessel that has been sailing more than 18 knots, but pirates use small fire arms like the Kalashnikov and a Rocket Propelled Grenade (RPG) to intimidate captains of merchant vessels to reduce speed. Pirates often shoot or threaten to shoot around the bridge or accommodation area. Once the speed of the vessel is reduced sufficiently, the pirates place their skiffs alongside the hull of the merchant vessel. Pirates use long lightweight ladders or long-hooked poles with a knotted climbing rope to climb on board. Once boarded, pirates generally will make their way to the bridge to take control of the ship. From this moment on there is a hostage situation. Usually pirate attacks take place during the day, however, attacks have occurred at night, particularly during clear moonlit nights. Skiffs are hard to operate in higher sea states. Pirates plan their attacks in sea state 1 or 2, [9]. Even with watch keepers, one of the most important anti-piracy measures, it is hard to spot the small skiffs from afar in the open ocean. A normal distance to spot the pirates is around 2 kilometers, [23].

3-3 Conclusion

The information in Section 3-1 needs to be translated to useful information for the computer simulation. The weapons will be simulated as a bubble with a certain range (R_{bubble}) around the Beagle. If the skiffs enter this bubble the weapon will be deployed. If the pirates are in the bubble, they will experience this as horrendous and will react on this by trying to escape the bubble. The water cannon and the MDS can eliminate a skiff with their bubble, this will be done if the skiff is within bubble range (R_{bubble}) for a certain time (t_{bubble}). The LRAD cannot eliminate the skiff with their bubble, it can only push the skiffs away from the merchant vessel. If it does this for an hour, the LRAD wins. Finally, the battering ram can only win if it hits the engines of the skiffs with a relative speed of 3 m/s. Table 3-1 gives an overview of the bubble range (R_{bubble}) and bubble time (t_{bubble}) per weapon.

Table 3-1: Overview of weapon specifications

	R_{bubble} [m]	t_{bubble} [s]
Water cannon	60	180
MDS	15	20
LRAD	40	-
Battering ram	-	-

Table 3-2 gives an overview of the Beagle weapons and their corresponding wins.

Table 3-2: Beagle weapons and corresponding wins

Beagle weapon	**Beagle wins if**
Water cannon	Skiff inside R_{bubble} for a total of t_{bubble}.
Mobility Denial System	Skiff inside R_{bubble} for a total of t_{bubble}.
Long-Range Acoustic Device	Simulation time must be over 3600 seconds.
Battering ram	Bow of the Beagle must be within 0.5 meter of of the stern of the skiff and the relative speeds must be higher than 3 m/s.

Chapter 4 will continue to elaborate on the other Beagle defense strategy parameters (2, 3 and 4):

Beagle defense strategy parameters

1. Non-lethal weapon
2. Skiff priority coefficient
3. Defense zone radius
4. Control strategy

The information given in Section 3-2 results in five parameters to describe the pirate attack scenario. Chapter 5 will elaborate on the pirate attack scenarios. The skiff's speed is not considered a pirate attack scenario parameter, because the Beagle design speed already is considered a pirate attack scenario parameter. To draw clear conclusions, the ratio of the speeds between the two is considered important, the skiffs' speed is fixed at 25 knots.

Pirate attack scenario parameters

1. Beagle design speed
2. Number of skiffs attacking
3. Pirate attack strategy
4. Time for the skiffs to reach the merchant vessel (t_{reach})
5. Direction in which the pirates are spotted

Chapter 4

Beagle defense strategy

This chapter will elaborate on the other Beagle defense strategy parameters. Below, an overview is given of the Beagle defense strategy parameters.

Beagle defense strategy parameters

1. Non-lethal weapon
2. Skiff priority coefficient
3. Defense zone radius
4. Control strategy

First, in Section 4-1 the skiff priority coefficient will be discussed. In Section 4-2 the different defense zone radii simulated will be explained. In Section 4-3 the control strategies used are elaborated upon. Finally, in Section 4-4 a conclusion of the Beagle defense strategy parameters is given, it gives a prediction of the best Beagle defense strategy per weapon.

4-1 Skiff priority coefficient

As described in Section 3-2, pirates often attack with two skiffs. An algorithm has been made to determine which skiff has priority and will be elaborated in this section. One of the assumptions is that the Beagle has perfect knowledge about the whereabouts and heading of each vessel ($C_O^M, C_O^B, C_O^{S_1}$ and $C_O^{S_2}$). This is the most key assumption in this research. Within SeaState5, a research project is going on to study the use of sensors for situational awareness. Adding sensor uncertainty to the model will be part of a future research. C_O^B means the Cartesian coordinates of the Beagle (B) expressed in the fixed global coordinate system (O). This can be rewritten to polar coordinates (P_O^B):

$$P_O^B = \begin{bmatrix} \theta_O^B \\ \rho_O^B \\ \psi_O^B \end{bmatrix} C_O^B = \begin{bmatrix} x_O^B \\ y_O^B \\ \psi_O^B \end{bmatrix} \tag{4-1}$$

Figure 4-1 visualizes this:

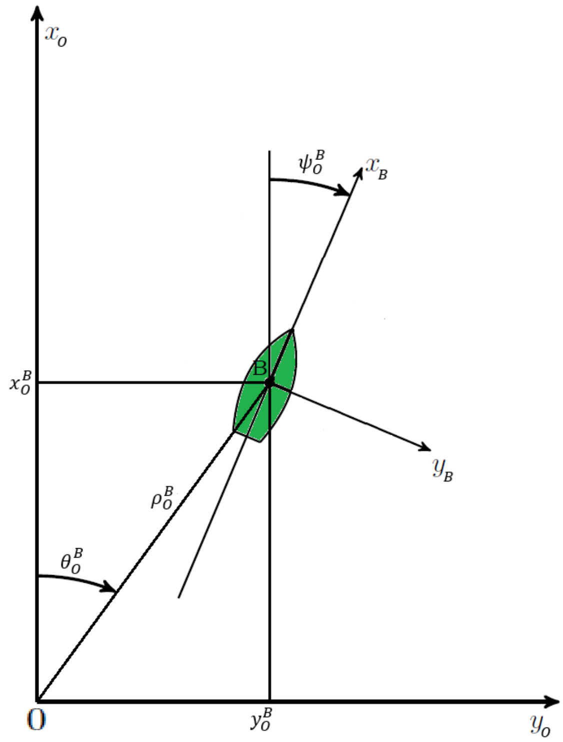


Figure 4-1: Sign convention

In the simulation there will be five different coordinate systems:

- The fixed global coordinate system with origin O
- The local coordinate system of the Beagle, with origin B
- The local coordinate system of the merchant vessel, with origin M
- The local coordinate system of skiff 1, with origin S_1
- The local coordinate system of skiff 2, with origin S_2

To determine the prioritized skiff, the distances between skiff x and merchant vessel ($\rho_M^{S_x}$) and the distances between the Beagle and skiff x ($\rho_B^{S_x}$) has been considered. These distances are translated to the time it takes skiff x to sail to the merchant vessel ($t_M^{S_x}$) and the Beagle to sail to skiff x ($t_B^{S_x}$), respectively. Because all vessels are moving, it is not straightforward to calculate this time. It will be explained in the next paragraph.

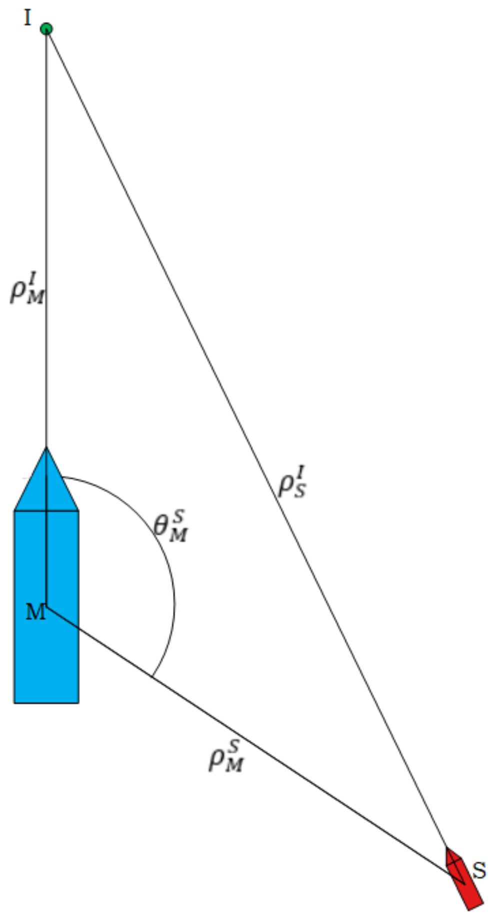


Figure 4-2: Situation sketch of merchant vessel and a skiff

In Figure 4-2 a situational sketch is drawn. From this graph one can conclude that for the skiff (S) to sail to the moving merchant vessel (M), it needs to sail to point I. The time it takes for the merchant vessel (M) to get to point I will be the same as the skiff (S) to get to point I. To calculate these times the following formula is used:

$$t_M^I = t_S^I \rightarrow \frac{\rho_M^I}{u_M} = \frac{\rho_S^I}{u_S} \rightarrow \rho_S^I = \frac{u_S \; \rho_M^I}{u_M}. \tag{4-2}$$

In this equation ρ_M^I and ρ_S^I are the distances between points M and I and S and I respectively. u_M and u_S are the speeds of the merchant vessel and the skiff respectively. This equation has two unknowns, the distance between the merchant vessel (M) and point I (ρ_M^I) and the distance between the skiff (S) and point I (ρ_S^I). Using goniometry, another relation for ρ_S^I can be derived:

$$\rho_S^I = \sqrt{(\rho_M^S)^2 + (\rho_M^I)^2 - 2\rho_M^S \rho_M^I cos(\theta_M^S)}. \tag{4-3}$$

In this equation ρ_M^S is the distance between the points M and S. θ_M^S is the angle of point S with respect to the merchant vessel's local coordinate system M as shown in Figure 4-2. Two unknowns and two equations will lead to an answer for ρ_S^I, ρ_M^I and thus t_S^M. Theoretically it is harder to estimate how much time the Beagle needs to sail to the skiff (t_B^S). The reason for this is that the path the skiff is going to sail, is not as predictable as the path the merchant vessel is going to sail. For the calculation of this time (t_B^S) the same equations are used. The only difference is that instead of the merchant vessel's velocity (u_M), the skiffs maximum velocity (u_S) is used. The merchant vessel is simulated to sail north with respect to the fixed global coordinate system at a velocity of 9 m/s (around 18 knots). The assumption is that the skiffs sail north as well, at their maximum speed (12 m/s). This is a safe assumption, since the merchant vessel is moving north with a velocity of 9 m/s. The extra speed is used as a safety factor to compensate for the unpredictability of the skiffs.

After obtaining the time it takes the skiff to sail to the merchant vessel (t_S^M) and the time it takes the Beagle to sail to the skiff (t_B^S) the question, which one of the two parameters is more important, arises. The skiff priority coefficient (c_p), with a value between 0 and 1, is introduced to compare the two. c_p determines whether it is important to attack the skiff closest to the Beagle (low c_p) or the skiff closest to the merchant vessel (high c_p). The following equations are introduced to determine the priority of the skiffs:

$$\text{Summation of times skiff 1} = c_p\, t_{S_1}^M + (1 - c_p) t_B^{S_1} \tag{4-4}$$

and

$$\text{Summation of times skiff 2} = c_p\, t_{S_2}^M + (1 - c_p) t_B^{S_2}. \tag{4-5}$$

It is both tempting to sail to the skiff closest to the merchant vessel (low t_S^M) and to sail to the skiff closest to the Beagle itself (low t_B^S). Thus, the priority skiff is the minimum of the two:

$$\text{Priority skiff} = \min(\text{Summation of times skiff 1,Summation of times skiff 2}) \tag{4-6}$$

The three values for the skiff priority coefficient that will be tested are:

Table 4-1: Variance in values for c_p

	c_p
Skiff priority coefficient 1	0.25
Skiff priority coefficient 2	0.50
Skiff priority coefficient 3	0.75

To explain what those values for the skiff priority coefficient mean a fictional situational sketch is shown in Figure 4-3. If the skiff priority coefficient (c_p) is 0, the values for $t_{S_1}^M$ and $t_{S_2}^M$ are not considered in the calculation. In Figure 4-3 those are lines C and B respectively. This means that the Beagle will calculate the minimum of lines A and D, which is A, and sail to skiff 1.

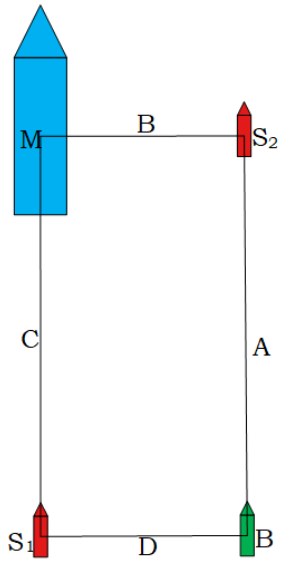


Figure 4-3: Situation sketch to explain priority coefficient

If the skiff priority coefficient (c_p) is 1, the values for $t_B^{S_1}$ and $t_B^{S_2}$ are not considered in the calculation. In Figure 4-3 those are lines D and A respectively. This means that the Beagle will calculate the minimum of lines B and C, which is B, and sail to skiff 2.

4-2 Defense zone radius

The defense zone radius determines the size of the circle around the merchant vessel in which the Beagle can operate, see Figure 4-4.

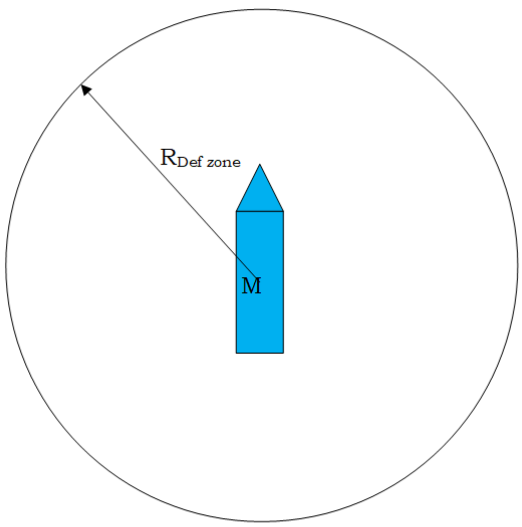


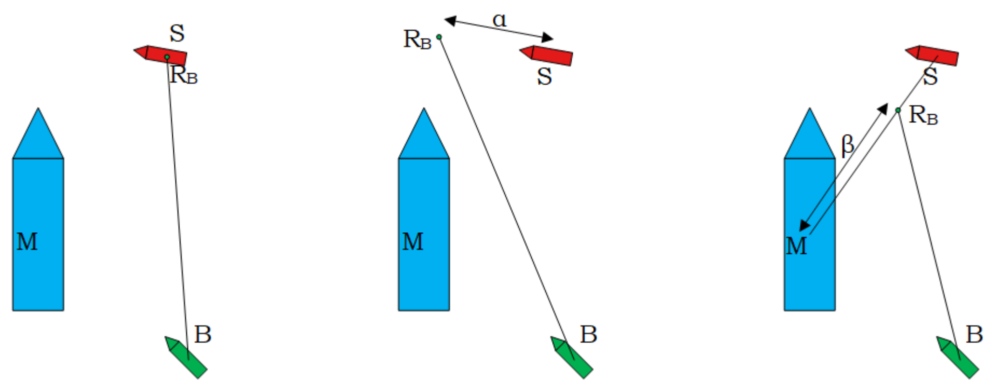
Figure 4-4: Visualization of defense zone radius ($R_{def\ zone}$)

The radii that will be tested are:

- $R_{def\ zone} = 100$ m
- $R_{def\ zone} = 200$ m
- $R_{def\ zone} = 400$ m
- $R_{def\ zone} = 800$ m
- $R_{def\ zone} = 1600$ m

4-3 Control strategy

Three different control strategies will be tested, these are the Pure Pursuit (PP), Constant Bearing (CB) and Line-Of-Sight (LOS) control, [24]. These are the control guidance systems most commonly used in target tracking, [25]. Figure 4-5 shows a sketch of the three controls.



(a) Pure Pursuit control **(b)** Constant Bearing control **(c)** Line-Of-Sight control

Figure 4-5: Pure pursuit, constant bearing and Line-Of-Sight control

The PP control is the simplest of the three. It places the reference point of the Beagle (R_B) on the skiff. The reference point is the point in the horizontal plane to which the Beagle wants to sail as fast as possible, see Figure 4-5 as example. The CB control takes the heading and the speed of skiff into account. It places the Beagle reference point (R_B) in front of the skiff at a distance (α). α is a distance in meters it is a function of the time it takes for the Beagle to sail to the skiff (t_B^S) multiplied by the maximum speed of the skiff (u_S):

$$\alpha = t_B^S u_S. \tag{4-7}$$

Finally, the LOS control considers that the skiff has a certain target, in this case the merchant vessel. The Beagle reference point (R_B) is therefore placed on the line between the merchant vessel and the skiff, at a distance β from the merchant vessel. β is a function of the time it takes the Beagle to sail to the skiff (t_B^S), the time it takes the skiff to sail to the merchant vessel (t_S^M) and the distance between the skiff and the merchant vessel (ρ_S^M):

$$\beta = \frac{t_B^S}{t_B^S + t_S^M} \rho_S^M. \tag{4-8}$$

4-4 Conclusion

This chapter discussed the part of the Beagle defense strategy that is responsible for the trajectory of the Beagle, the non-lethal weapons were already discussed in Section 3-1. For each Beagle defense strategy parameters, three to five different variations are available, which leads to a total of 180 possible Beagle defense strategies. Table 4-2 gives an overview of the Beagle defense strategy parameter variations.

Table 4-2: Overview of Beagle defense strategies parameter variations

Weapon	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Water cannon	0.25	100	PP control
Mobility Denial System	0.50	200	CB control
Long-Rang Acoustic Device	0.75	400	LOS control
Battering ram		800	
		1600	

Here a prediction will follow for the best Beagle defense strategy parameters per weapon. To do so, first the weapons will be divided into two groups:

Group 1. Attack and neutralize threat

1. Mobility Denial System (MDS)
2. Battering ram

Group 2. Defend and guard merchant vessel

1. Water cannon
2. Long-Range Acoustic Device (LRAD)

The MDS and the battering ram have an 'attack and neutralize threat' strategy. Their strength is to eliminate the skiffs as soon as possible. The water cannon and the LRAD cannot neutralize the threat quickly. Therefore, they have a more 'defend and guard merchant vessel' strategy.

The prediction is that lower values for the skiff priority coefficient (c_p) will be better for a quick dismantling of a skiff; the 'attack and neutralize threat' strategy. The reason for this is that for lower values for c_p, the Beagle will stick longer to the skiff that is closest to itself and eliminate it instead of switching halfway through the elimination. The other way around, for higher values of c_p, the 'defend and guard merchant vessel' strategy is presumed to be more suitable. The reason for this is that if the Beagle stays too long with the skiff closest to itself, the other skiff will achieve its objective.

The prediction is the larger the defense zone radius ($R_{def\ zone}$), the better. For the MDS and battering ram the reason for this is that these weapons can intercept and eliminate the skiffs at a larger distance from the merchant vessel. The effect of the water cannon and LRAD is similar. The Beagle is faster and for a larger $R_{defzone}$ has a larger area to counteract the skiffs, i.e. it is harder for the skiffs to reach the merchant vessel.

Finally, for the ‘defend and guard merchant vessel’ strategy the LOS control is predicted to be the best solution. This control makes sure the Beagle positions itself between the merchant vessel and the skiff. That way it can push away the skiff from the merchant vessel. For the ‘attack and neutralize threat’ strategy the PP control is predicted to be the best solution. The reason for this is that the Beagle needs to get close to the skiff to eliminate it. The PP control makes sure the Beagle gets close to the skiff.

Table 4-3: Overview of best Beagle defense strategies per weapon based on prediction

Strategy	Beagle weapon	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control strategy
Defend and guard merchant vessel	Water cannon LRAD	0.75	1600	Line-Of-Sight (LOS)
Attack and neutralize threat	MDS Battering ram	0.25	1600	Pure Pursuit (PP)

Chapter 5 will discuss the pirate attack scenario parameters to which the Beagle defense strategies will be exposed in the computer simulation.

Chapter 5

Pirate attack scenarios

This chapter will elaborate on the pirate attack scenario parameters. Below, an overview is given of the pirate attack scenario parameters.

Pirate attack scenario parameters

1. Beagle design speed
2. Number of skiffs attacking
3. Pirate attack strategy
4. Time for the skiffs to reach the merchant vessel (t_{reach})
5. Direction in which the pirates are spotted

First, in Section 5-1 the design speed of the Beagle will be discussed. In Section 5-2, it is explained why it is important to differentiate between one and two incoming skiffs. In Section 5-3 four different pirate attack strategies will be elaborated upon. In Sections 5-4 and 5-5 the time to reach the merchant vessel and direction at which the pirates are spotted are discussed respectively. Combining this leads to the starting position of the skiffs in the simulations. Finally, Section 5-6 gives a summary of the pirate attack scenario parameters.

5-1 Beagle design speed

As explained before, the Beagle's design speed is considered a pirate attack scenario. There are different Fast Rescue Craft (FRC) on the market with different design speeds, [26]. Therefore, the influence of the top speed of the FRC will be investigated, ranging from 25 to 40 knots:

- Beagle design speed is 25 knots
- Beagle design speed is 30 knots
- Beagle design speed is 35 knots
- Beagle design speed is 40 knots

5-2 Number of skiffs attacking

Pirates are known to attack with either one or two skiffs, see Section 3-2, this influence will be investigated to reduce the amount of simulations. The assumption is that if the Beagle cannot repel a pirate attack with one skiff, it cannot repel a pirate attack with two skiffs. This helps to reduce the amount of simulations during the systematic changing of the variables, as explained in Chapter 7.

5-3 Pirate attack strategy

The reaction of pirates on the presence of the Beagle could vary; four different pirate tactics are taken into consideration for the simulation. In the next paragraphs these tactics will be elaborated upon. Furthermore, an explanation on when each pirate tactic is successful is added.

Board merchant vessel The first pirate tactic is to board the merchant vessel. It is assumed that the pirate needs to be alongside the merchant vessel for 60 seconds consecutively to successfully board. This assumption is based on reports of pirate attacks, [23].

Threaten with Rocket Propelled Grenade (RPG) The second pirate tactic is threatening the merchant vessel with an RPG, pirates are known to do this, see Section 3-2. It is desirable to avoid this situation. To threaten the merchant vessel the pirates must be within RPG range (100 meter) and have a stationary position with respect to the merchant vessel for 60 seconds consecutively, also an assumption.

Wreck Beagle Pirates are known for their aggressive behavior and usually armed with Kalashnikov rifles, as explained in Section 3-2. Therefore, the third tactic the pirates could apply, is wrecking the Beagle by shooting at it with their riffles. The shooting range (R_{AK}) of the pirates is 50 meters. If the Beagle is in this zone for a total time of 60 seconds it is wrecked, another assumption.

Board Beagle Finally, it is not unimaginable that the pirates will try to board the Beagle, it is obvious that as soon as a pirate boarded the Beagle, the pirate can cause damage and disable it. A pirate can board the Beagle if the skiff is within 2 meters of the Beagle for two seconds consecutively, again an assumption.

In Table 5-1 the information from the previous paragraphs is summarized. If any of these four tactics are executed successfully the simulation will stop and the pirates win.

Table 5-1: Pirate strategies and corresponding wins

Pirate tactic	Pirate wins if
Boarding merchant vessel	Alongside merchant vessel for 60 seconds consecutively.
Threaten with RPG	Within RPG shooting range and maximum relative speed of 3 m/s for 60 seconds consecutively.
Wreck Beagle	In the Kalashnikov shooting range for 60 seconds total.
Board Beagle	Be within 2 meters of the skiff for 2 seconds consecutively.

5-4 Time for the skiffs to reach the merchant vessel

In this research, t_{reach} is defined as the time it takes the skiffs to reach the merchant vessel from the moment they are spotted. Section 3-2 showed the importance of spotting the skiffs in an early stage. The reason for this is that the pirates reach the merchant vessel at a later time (t_{reach}), that way precautions can be made. The Beagle also benefits from a larger t_{reach}. In the simulation, the Beagle has a deployment time of 120 seconds. Three different values for t_{reach} will be investigated, one shorter than the deployment time of the Beagle, one slightly larger than the deployment time and one where the Beagle has enough preparation time:

- $t_{reach} = 100$ s
- $t_{reach} = 120$ s
- $t_{reach} = 300$ s

5-5 Direction in which the pirates are spotted

When discussing the location in which the skiffs are spotted, one should keep in mind that the merchant vessel is sailing north with respect to the fixed global coordinate system (O). Three different locations will be investigated:

- Skiffs spotted south
- Skiffs spotted north
- One skiff spotted west and one spotted east

The last scenario is the least probable since skiffs attack from the same mothership and stay together. Yet it is a challenging one and will be investigated. The combination of the time to reach the merchant vessel (t_{reach}) and the direction the skiffs are spotted leads to the initial positions of the skiffs during the simulation. It is visualized in Figure 5-1. The three circles indicate where the pirates can be spotted to reach the merchant vessel in 100, 150 and 300 seconds, the blue, orange and yellow line respectively. For $t_{reach} = 300$ s the start locations of the skiffs are shown for all three directions. The green, purple and red skiffs represents the skiffs spotted in the south, north and one east and one west respectively. To challenge the Beagle more, when spotted from the south, one skiff is spotted south-west and one is spotted south-east.

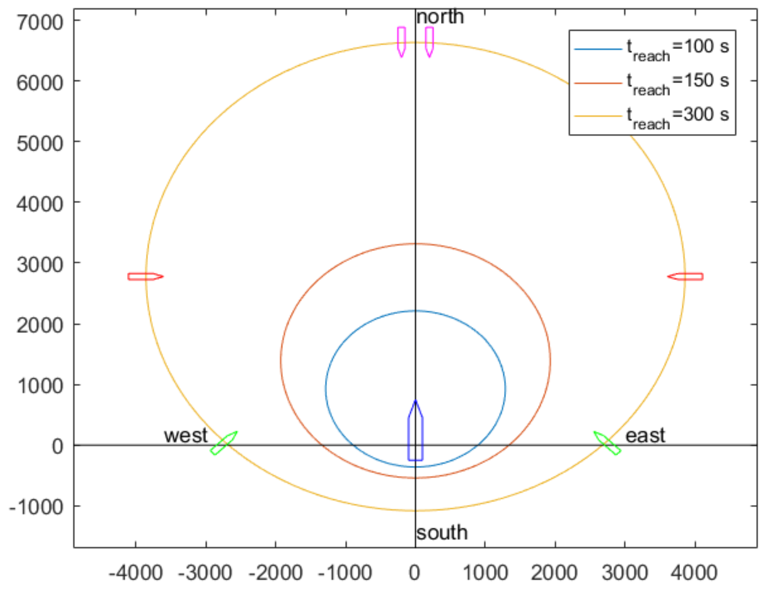


Figure 5-1: All start positions of the skiffs for $t_{reach} = 300$
*vessels are not on scale

5-6 Summary

In this chapter the pirate attack scenario parameters are discussed. The pirate attack scenario consists of six parameters. For each Beagle defense strategy parameter, two to four different variations are available, which leads to a total of 288 possible attack scenarios. Table 5-2 gives an overview of the pirate attack scenario parameter variations.

Table 5-2: Overview of pirate attack scenario parameter variations

Beagle speed [kn]	Number of skiffs	Skiff tactic	Time to reach merchant vessel [s]	Location skiffs spotted
25	1	Board merchant vessel	100	south
30	2	Threaten with RPG	150	north
35		Wreck Beagle	300	east and west
40		Board Beagle		

As discussed in Chapter 4, there are 180 possible Beagle defense strategies. In combination with 288 possible pirate attack scenarios, this leads to a total of 51,840 unique simulations. To save computational time and limit the number of simulations while keeping the ability to draw clear conclusions, a systematically varying of the parameter variations will be done to find the best Beagle defense strategy. How this is done will be explained in Chapter 7. Chapter 6 will discuss the way the computer model is built up.

Chapter 6

Computer model

This chapter will discuss the reasoning behind the computer model Section 6-1 will discuss the high level computer model description. Sections 6-2, 6-3 and 6-4 will discuss more in depth part of the model. These are the decision models, power and maneuvering model and the control of the Beagle respectively. Section 6-5 the power and maneuvering model will be validated. Finally, Section 6-6 gives a summary of this chapter.

6-1 High-level description

In Figure 6-1 the high-level computer model description is shown. Each block represents a vessel. Each vessel has its input and outputs. All vessels have an initial position and velocity input. Pirates often attack smaller cargo vessels due to the smaller free board height. The merchant vessel will therefore be simulated as a small cargo vessel. The vessel's length is fixed on 100 meters and its beam on 20 meters. It will only sail in a straight line, heading north, with a speed of 9 m/s (around 18 knots), regardless of the skiffs or Beagle's positions. 18 knots is chosen because this is the speed skiffs can still board the merchant vessel and a commonly sailed speed in High Risk Areas. As explained in Section 4-1, it is assumed that the Beagle knows the global position and headings of all vessels ($C_O^M, C_O^B, C_O^{S_1}$ and $C_O^{S_2}$). The skiffs know the global positions and headings of the Beagle and the merchant vessel.

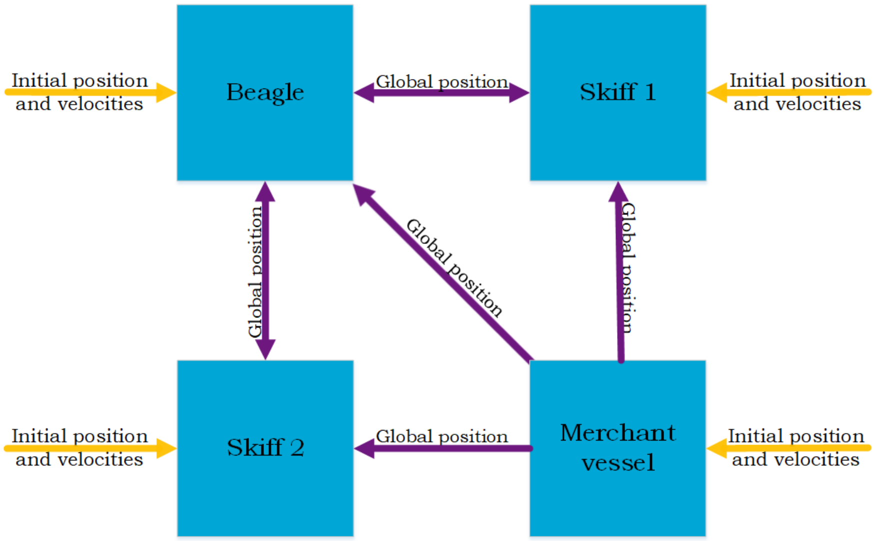


Figure 6-1: High-level computer model description

Figure 6-2 gives an overview of what happens in the Beagle block. This is similar for the skiff blocks. The decision model determines the Beagle's global reference point as a function of all global positions. A reference point is like a target at which the Beagle wants to sail. For the Beagle to sail to the imposed reference point, a controller is used to regulate the power and maneuvering model input. These are the waterjet steering angle (α) and the throttle (X_{set}).

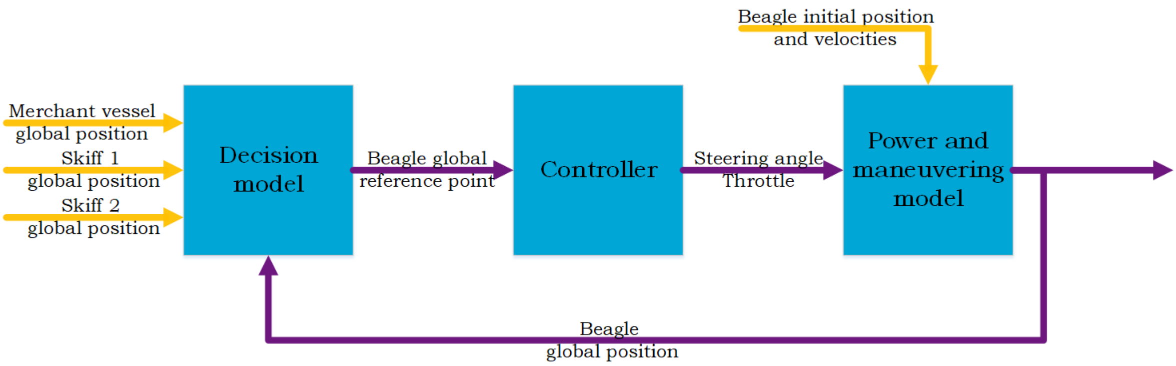


Figure 6-2: Beagle level description

The following sections, Sections 6-2, 6-3 and 6-4, will each elaborate on one of the blocks shown in Figure 6-2. Section 6-2 will discuss the decision model. Section 6-3 will discuss the power and maneuvering model. The controller links the decision model to the power and maneuvering model, in Section 6-4 the controller is explained.

6-2 Decision model

The decision model determines the reference point in the global coordinate system for the Beagle or for a skiff. The input of the decision model is the global position of all the vessels. Each beagle weapon and pirate tactic has its own decision model. The Beagle's decision model consists of two steps. The first step is already explained in Section 4-1. It determines what the priority skiff is, that is the skiff the Beagle will focus on. Step two is to apply a state diagram to this priority skiff.

6-2-1 State diagram

One state diagram is explained, see Figure 6-3, whereas additional state diagrams can be found in appendix A. For each time step in the simulation, the state diagram will always check which state is true. At any moment there is only one state true. Each state is linked to a reference point, which is a coordinate somewhere in the fixed global coordinate system. This way, the Beagle always has a reference point.

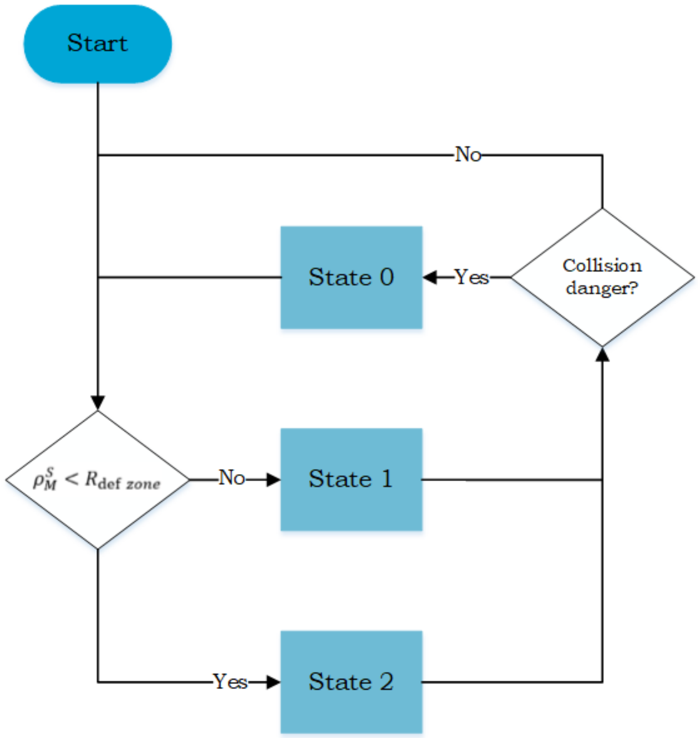


Figure 6-3: State diagram Beagle weapons 1, 2 and 3

In the state diagram as shown in Figure 6-3, the Beagle first checks whether the skiff is in the defense zone radius ($R_{defzone}$). The defense zone is already explained in Section 4-2. If the skiff is outside this circle, state 1 is true, else state 2 is true. Even though either state 1 or state 2 is true, there is an anti-collision system that can overrule these states. If there is any danger the Beagle will collide with the merchant vessel, state 0 is true and overrules state 1 and 2.

In Figure 6-4 a situational sketch of state 1 is shown. It shows the proposed reference point of the Beagle (R_B). R_B is the intersection of the defense zone circle, as explained in Section 4-2, and the line between the merchant vessel and the skiff.

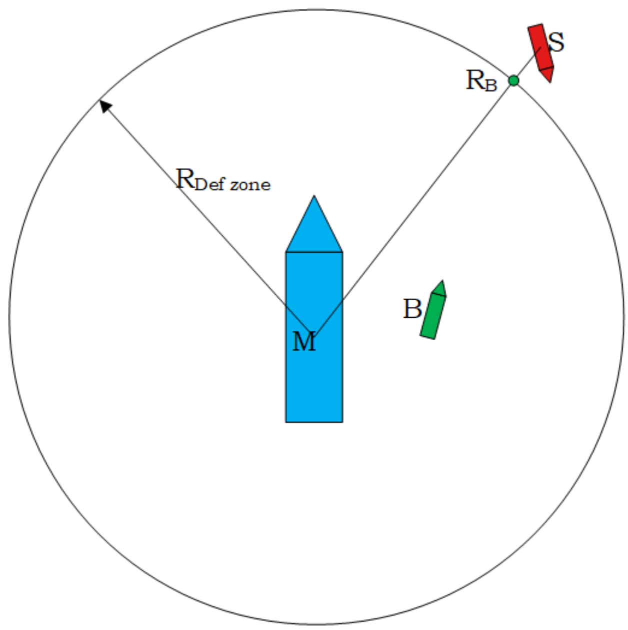
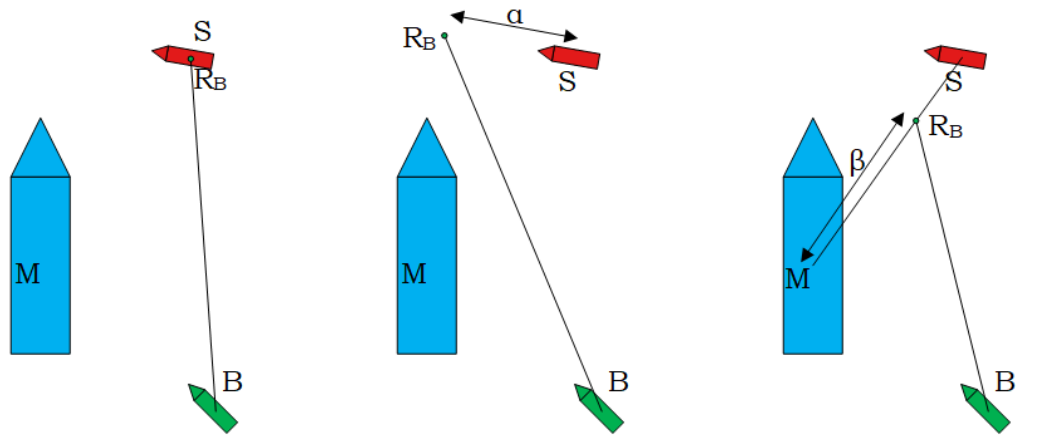


Figure 6-4: State 1

In Figure 6-5 a situational sketch of state 2 is shown. Which one of the situations is true is depending on the control strategy that is chosen in the Beagle defense strategy, as explained in Section 4-3.



(a) Pure Pursuit control **(b)** Constant Bearing control **(c)** Line-Of-Sight control

Figure 6-5: Pure pursuit, constant bearing and Line-Of-Sight control

As explained, for each time step, the state diagram checks whether there is any danger for collision (state 0). As shown in Figure 6-6, there is an imaginary box around the merchant vessel. If there is any intersection with the imaginary box and with the line between the Beagle and its reference point (R_B), state 0 is true. In practice, state 0 is true when the Beagle is on one side of the merchant vessel and the priority skiff is on the other side. If state 0 is true the Beagle wants to go to the other side of the merchant vessel as fast as possible.

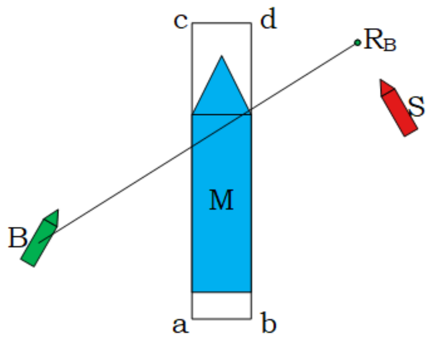


Figure 6-6: State 0

If state 0 is true, an anti-collision system takes over. The Beagle checks this by executing a few steps. If a step has no intersection with the safety box it will be executed, otherwise the next step will checked. The steps are listed below, Figure 6-7 shows a sketch. Steps 1 though 3 are shown.

Anti-collision system steps

1. Find the closest corner to the Beagle reference point (R_B).
2. Find the two corners adjacent to step 1, find the one the Beagle can reach the fastest.
3. Find corner closest to the Beagle.

This always works because step 3 can never give an intersection. Once arrived at corner c, step 1 is still not executable, but step 2 is, the Beagle will sail to corner d. Once arrived at corner d, there is no intersection anymore. State 0 is not true anymore, state 2 (see Figure 6-3) is true again.

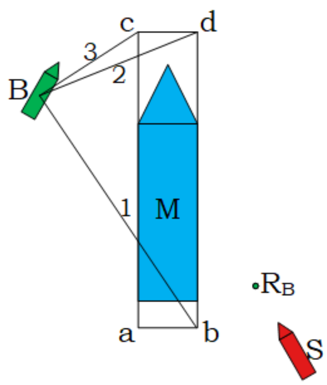


Figure 6-7: Working principle of anti-collision system

6-3 Power and maneuvering model

The Beagle will be simulated as an existing, large, state of the art Fast Rescue Craft (FRC). The Palfinger FRSQ850 model with single diesel engine and single waterjet has been chosen, it is 8.5 meters long, [1]. Most state of the art FRC these days are equipped with waterjets, [1]. Waterjets accelerate faster, have better maneuverability, are safer when it comes to saving people out of the water and have a higher propulsion efficiency at planing speeds when compared to conventional propellers. The one waterjet model is chosen because two waterjets are advantageous especially in port maneuvering situations which is not of particular interest for the current study. Another reason this craft has been chosen is because it is the largest possible FRC according the regulations, [27]. The reasoning behind this is that bigger means heavier and heavier means more robust against aggressive pirates. Furthermore, the Beagle will be equipped with non-lethal weapons, this means that there will be less space for people, so it is better to start with a large FRC. Large FRC can take more people on board than is required for the SOLAS. The FRSQ850 has a capacity of 21 people while the SOLAS requires: "The rescue boat shall be capable of carrying at least five seated persons and a person lying on a stretcher",[27]. Finally, the FRSQ850 model is chosen because Palfinger offered to share the results of the maneuverability test done with this model, which is presented in Section 6-5.

6-3-1 Assumptions

There are some assumptions fundamental to this power and maneuvering model. Below they are summed up and after they are explained.

1. There are no current and wind forces.
2. The diesel engine has a constant efficiency.
3. The waterjet pump has a constant efficiency.
4. No thrust reduction when the waterjet steering angle (α) is not equal to zero.

The first assumption is that there are no current and wind forces exposed to the Beagle, it sails in calm water with no wind. Modeling this would not add anything for the results since the pirates would be exposed to the same environmental forces, with roughly the same effect. It would be a handicap for both. Furthermore, pirates only attack at low sea states as explained in Section 3-2. The second assumption is that the diesel engine has a constant efficiency. The third assumption is that the waterjet pump efficiency is constant. In reality the latter two efficiencies are not constant but a function of the operating point of the engine and pump. The Beagle and pirates mainly operate in the design points and modeling the diesel engine and the waterjet is just a tool not the goal of the research, therefore, these are assumed constant. Furthermore, it would have negligible influence on the speed and maneuvering characteristics of the Beagle and the skiffs. The final assumption is that there is no thrust reduction when the waterjet steering angle (α) is not equal to zero. In reality there is some thrust reduction when the nozzle of a waterjet is put under an angle because the jet stream encounters extra resistance from the nozzle.

6-3-2 Overview of power and maneuvering model components

In Figure 6-8 an overview of the Beagle physics components are shown. In the diesel engine block, a combination of throttle (X_{set}) and engine Revolutions Per Second (RPS) (n_e) results in a brake torque (M_B). In the shaft rotational dynamics block, this brake torque (M_B) in combination with the waterjet impeller torque (M_p) results in an engine RPS (n_e) and a waterjet RPS (n_p). The waterjet block uses the impeller RPS (n_p) and the ship speed (u) to calculate the thrust (T) and the impeller torque (M_p). In the thrust direction block this thrust (T) together with the waterjet steering angle (α) results into a thrust and moment (Local thrust) vector on the vessel. The ships equations of motion block translate these forces into motions (u, v and r) and the global Beagle position (C_O^B). u, v and r are the local velocities of a vessel in surge (x), sway (y) and yaw (r) respectively.

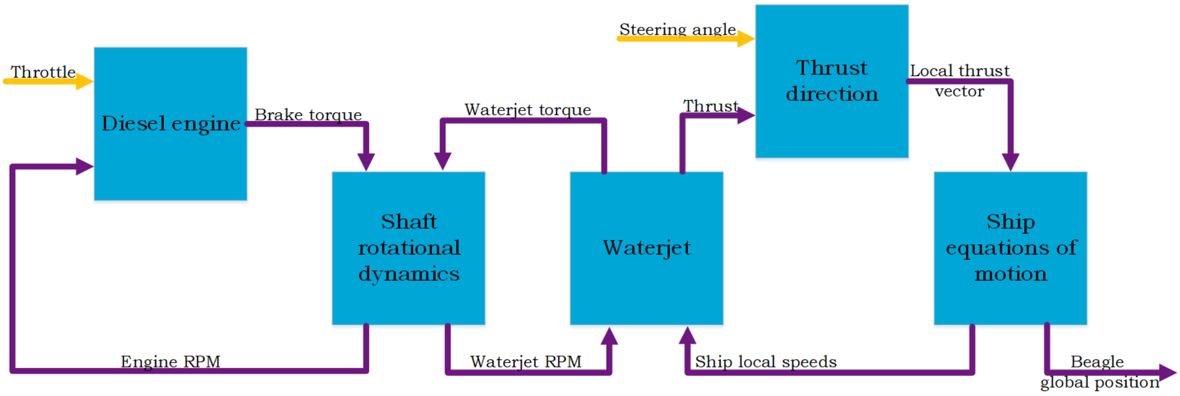


Figure 6-8: Overview of Beagle physics components

There is a reason why this level of complexity is chosen to simulate the Beagle physics and not just simulate a black box with maneuvering characteristics. On an FRC the pilot can handle the throttle (X_{set}) and the waterjet steering angle (α) to operate the vessel. To make this vessel autonomous, these are the system inputs to the plant that need to be controlled. Even though it is outside the scope off this research, to build an autonomous vessel such as the Beagle a controller needs to be made. Tuning such a controller in real life can be a difficult and time-consuming process. A model, as presented, can give an estimation for these tuning parameters and speed up the process.

Diesel engine The diesel engine is modeled using “Design of Propulsion and Electric Power Generation Systems” by H. Klein Woud and D Stapersma, [28]. To keep the following paragraphs readable, only the important parameters will be explained. All parameters are explained in the list of symbols. The diesel engine block has throttle (X_{set}) and engine RPS (n_e) as input. It has the brake torque as output (M_B). The diesel engine is not modeled in detail since it is not necessary to model this process. The relationship between brake torque (M_B) and throttle (X_{set}) is:

$$M_B = \frac{P_B}{2\pi n_e} = \frac{M_f LHV \eta_e i n_e}{2\pi n_e k} = \frac{M_{fnom} X_{set}\ LHV \eta_e i}{2\pi k}. \tag{6-1}$$

The brake torque (M_B) is not a function of the engine RPS (n_e) since it can be found in both the numerator and denominator, still it is send into the engine block to monitor the engine brake power (P_B). The assumed engine efficiency (η_e) is 0.38, [28].

Shaft Rotational dynamics The shaft rotational dynamics block has the brake torque (M_B) and the impeller torque (M_P) as inputs. The engine RPS (n_e) and impeller RPS (n_p) are the outputs. It links the engine and the waterjet:

$$\sum M = I_{trm}\dot{n}_p \rightarrow n_p = \int \frac{M_B - M_p}{I_{trm}} \tag{6-2}$$

and

$$n_e = i_{gb} n_p. \tag{6-3}$$

Waterjet The waterjet is modeled according to “A parametric propulsion prediction method for waterjet driven craft” and “Numerical analysis of a waterjet propulsion system” by T. Terwisga and N. Bulten respectively, [29], [30]. The Waterjet block has impeller RPS (n_p) and ship speed (u) as inputs. It has the impeller torque (M_p) and thrust generated by the waterjet (T) as output. In contrast to propellers, the dimensionless torque coefficient (K_M) is almost constant as a function of the dimensionless advanced velocity (J), for simplicity it is assumed constant. For the impeller torque (M_p) this means the following relation with the impeller RPS (n_p):

$$M_p = K_M n_p^2. \tag{6-4}$$

In this equation K_M can be obtained from the waterjet power versus impeller speed curve which can be obtained at a waterjet manufacturer. To obtain the thrust (T) delivered by the waterjet the following equation is used:

$$T = \rho_{sw} Q (v_{out} - v_{in}), \tag{6-5}$$

where v_{out} and v_{in} can be described as:

$$v_{out} = \frac{Q}{A_{nozzle}} \text{ and } v_{in} = u(1 - w). \tag{6-6}$$

To obtain the volume flow rate (Q) of the impeller the equation for the impeller power (P_p) can be used:

$$\eta_{pump} P_p = \rho_{sw} g H Q. \tag{6-7}$$

The pump efficiency is assumed to be constant. The value of this constant is calculated with an empirical equation for the pump efficiency according to, [31]:

$$\eta_{pump} = 0.95 - \frac{0.05}{\sqrt[3]{\frac{Q}{Q_{ref}}}} - 0.125(\log_{10}(n_\omega))^2, \tag{6-8}$$

with the non-dimensional specific pump speed (n_ω) defined as:

$$n_\omega = \frac{2\pi n_p \sqrt{Q}}{(gH)^{\frac{3}{4}}}. \tag{6-9}$$

In Figure 6-9 the pump efficiency (η_{pump}) is shown as a function of the suction specific speed (n_ω). In design point the efficiency of the pump is 0.85. The Beagle mainly operates in the design point, therefore this efficiency is assumed to be constant at all revolutions.

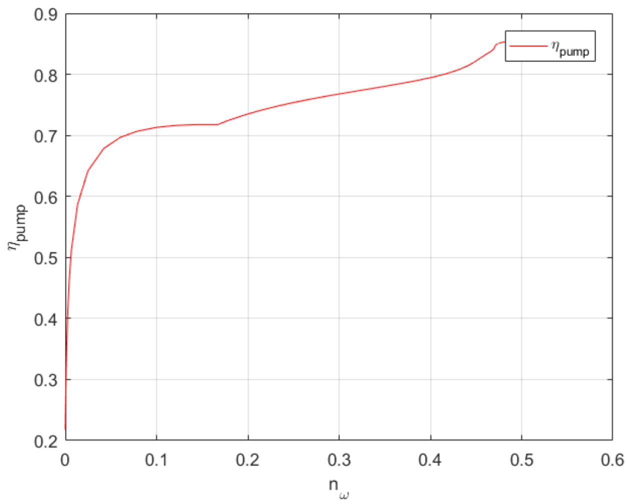


Figure 6-9: Pump efficiency as function of suction specific speed

Another way to define the delivered power of the impeller is:

$$P_p = 2\pi M_p n_p. \tag{6-10}$$

The last unknown is the pump head (H). The acceleration of the fluid in the nozzle requires a certain pressure difference, i.e. the pump head (H). The pump head (H) is also required to overcome hydraulic losses in the inlet and nozzle. Finally, the waterjet nozzle may be positioned above the waterline, which will lead to more required pump head (H). Combining all those factors the equation for the pump head (H) is:

$$H = \frac{v_{out}^2}{2g}(1+\phi) - \frac{v_{in}^2}{2g}(1-\epsilon) + h_j. \tag{6-11}$$

ϕ is the nozzle loss coefficient, ϵ the inlet loss coefficient and h_j the nozzle elevation above the waterline. In general, the elevation (h_j) can be neglected relative to the other contributions in equation.

Thrust direction The thrust direction is a function of the thrust (T) and the waterjet steering angle (α):

$$\text{Local thrust} = \begin{bmatrix} X_{prop} \\ Y_{prop} \\ N_{prop} \end{bmatrix} = \begin{bmatrix} T\cos(\alpha) \\ T\sin(\alpha) \\ T\sin(\alpha)LCG \end{bmatrix}. \tag{6-12}$$

Ship equations of motion The ship equations of motion block has the thrust direction as input and has the ships speed (u, v and r) and global position (C_O^B) as outputs. To describe the ship equations of motion the Abkowitz model is used, [32]. The final implicit equations of motion are:

$$\begin{bmatrix} X_{hull} \\ Y_{hull} \\ N_{hull} \end{bmatrix} = \begin{bmatrix} X_{uu}u^2 + X_{vv}v^2 + X_{rr}r^2 + X_{uv}u|v| + X_{ur}u|r| + X_{vr}vr + X_{\dot{u}}\dot{u} \\ Y_{vv}v|v| + Y_{rr}r|r| + Y_{uv}uv + Y_{ur}ur + Y_{vr}v|r| + Y_{rv}r|v| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} \\ N_{rr}r|r| + N_{vv}v|v| + N_{uv}uv + N_{ur}ur + N_{vr}v|r| + N_{rv}r|v| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + Y_{hull}r_a \end{bmatrix}. \tag{6-13}$$

In appendix B these equations of motion are derived. In the Abkowitz model, the hydrodynamic coefficients are the principal terms in the mathematical model used in the simulation and prediction of ship maneuvering. The coefficients are usually evaluated based on constrained tests of a model in the towing tank, however, such data is not available. Nevertheless, there is another way to obtain the coefficients only knowing design parameters of the ship, [33].

This book, Principles of Naval Architecture Volume: III, discusses empirical equations to determine the Abkowitz coefficients as a function of L_{wl}, B_{max}, T and trim. In appendix C those coefficients are derived. Finally, because the vessel is planing the parameters to obtain the Abkowitz coefficients are not constant but a function of the ship speed (u). Savitsky's method is used to find the relationship of L_{wl}, T and trim as a function of ship speed (u). Furthermore, the ship resistance is determined with Savitksy, [34]. In appendix D the results are shown.

The equations above are solved for u, v and r as explained in appendix B. To obtain the Beagle global displacement (C_O^B) from the local speeds (u, v and r) the following transformation has been applied:

$$C_O^B = \begin{bmatrix} x_O^B \\ y_O^B \\ \psi_O^B \end{bmatrix} = \begin{bmatrix} \int(u\ \cos(\int r\ dt) - v\ \sin(\int r\ dt))\ dt \\ \int(u\ \sin(\int r\ dt) + v\ \cos(\int r\ dt))\ dt \\ \int r\ dt \end{bmatrix}. \tag{6-14}$$

6-4 Controller

The next step is to control the vessel, to make it sail as fast as possible to its imposed reference point. The goal of the simulation is not to create the best controller. The goal of the controller is to create realistic maneuvering behavior for the Beagle and the skiffs. In Figure 6-10 the control loop used is shown.

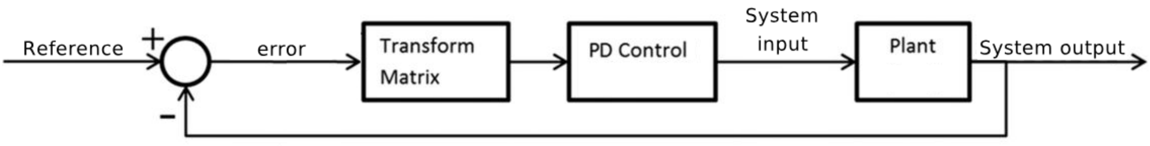


Figure 6-10: Negative feedback control loop

The reference, in this case explained for the Beagle (R_B), is the Cartesian coordinate with respect to the fixed global coordinate system to which the Beagle needs to sail to ($C_O^{R_B}$). As explained in Figure 6-8, the output of the power and maneuvering model, in Figure 6-10 referred to as plant, is the position of the vessel in the global coordinate system (C_O^B). The error ($C_B^{R_B}$) is the reference ($C_O^{R_B}$) minus the system output (C_O^B). For a vessel with inputs throttle (X_{set}) and waterjet steering angle (α), the control works better in polar coordinates, hence the transform matrix. The controller works better because the distance between the Beagle and the Beagle reference point ($\rho_B^{R_B}$) is a direct input for the throttle (X_{set}) controller:

$$e_{X_{set}} = \rho_B^{R_B}. \tag{6-15}$$

Furthermore, the error input for the waterjet steering angle (α) consists of two parameters. The first one is the angle between the Beagle's reference point (R_B) and the Beagle (B), expressed in the Beagle local coordinate system ($\theta_B^{R_B}$). The second one is the heading of the skiff with respect to the Beagle, expressed in the Beagle local coordinate system ($\psi_B^{R_B}$). The input for the controller for the waterjet steering angle (α) is a proportion of these $\theta_B^{R_B}$ and $\psi_B^{R_B}$:

$$e_\alpha = c_\theta \ \theta_B^{R_B} + (1 - c_\theta)\psi_B^{R_B}. \tag{6-16}$$

A PD controller is used to control the throttle (X_{set}) and the waterjet steering angle (α). The advantage is that these controllers are easy to apply. The downside of this controller is that it is tuned for a certain scenario. It does not necessary guarantee that it works for all scenarios. Simulations have shown that these controllers give satisfying maneuvering results of the skiffs and Beagle in other scenarios. For the throttle (X_{set}) controller, the integrator gain (I) is left out because the input to control the throttle is $\rho_B^{R_B}$. ρ is positive by definition, it does not make sense to use an integrator gain, since integrating this positive error will lead to an increasing gain over time. The throttle (X_{set}) is controlled as follows:

$$X_{set} = P_{X_{set}} \cdot e_{X_{set}} + D_{X_{set}} \cdot e_{X_{set}} \frac{d}{dt}. \tag{6-17}$$

The waterjet steering angle (α) is controlled as follows:

$$\alpha = P_\alpha \cdot e_\alpha + D_\alpha \cdot e_\alpha \frac{d}{dt}. \tag{6-18}$$

First, the throttle (X_{set}) controller has been tuned. This has been done by letting the Beagle sail only in one direction towards a moving reference point. The Beagle started at (0,0) and the reference point started at (50,0) and had a constant velocity of 12 m/s. This speed has been chosen, because this is assumed to be the average speed of the Beagle during the simulation, which is the maximum speed of the skiffs. In Figure 6-11 the results of this tuning are shown. The steady state error in this situation is one meter, since there is no integrator gain the steady-state error cannot be tuned to zero. For this study a steady-state error of one meter is acceptable.

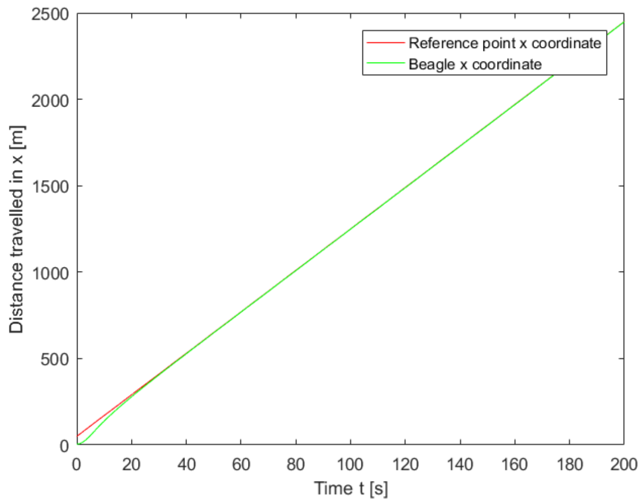
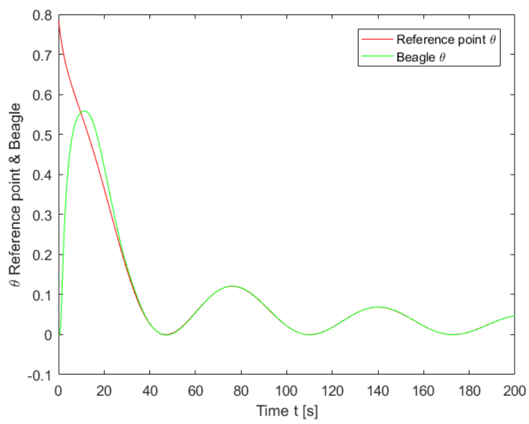
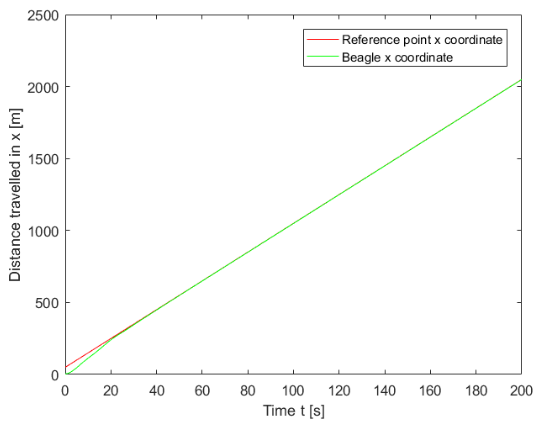


Figure 6-11: Tuning of the PD controller for the throttle

Next the controller for the waterjet steering angle (α) has been tuned. This has been done with a zigzag test. Again, the Beagle started at (0,0), the reference point started at (50,50) and traveled, with a speed of 10 m/s, zigzagging in x direction with a period of 65 seconds and an amplitude of 50 meters. The results of the tuning are shown in Figure 6-12.



(a) θ reference point and Beagle over time



(b) ρ reference point and Beagle over time

Figure 6-12: Tuning of the PD controller for α

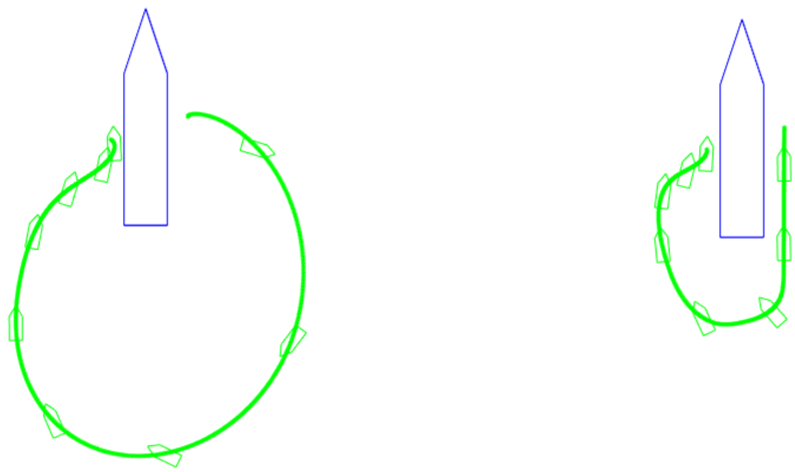
The final controller values are shown in Table 6-1.

Table 6-1: Controller values

$P_{X_{set}}$	$D_{X_{set}}$	P_{α}	D_{α}	c_{θ}
0.45	4	40	40	0.85

6-4-1 Adapted control

A MATLAB plot file has been written to render the four ships over time. This plot file has been used to analyze the simulations. The control proved not to be effective in all situations; especially when the Beagle needs to sail from one side of the merchant vessel to the other side. For the weapons that do not neutralize the threat (water cannon and Long-Range Acoustic Device (LRAD)) this happens a lot since both skiffs focus on another side of the merchant vessel.
The Beagle is modeled to only sail forwards, because it is not desirably that the Beagle sails backwards in this dynamic situation. If the proposed reference point of the Beagle is located behind the Beagle it will make a turn to sail to the reference point. If the Beagle wants to sail from starboard to port side, through the stern of the merchant vessel, it will do that as shown in Figure 6-13a. This figure shows the movement of the Beagle with respect the merchant vessel. To make this plot, different snapshots were made. The merchant vessel, although moving, is kept in the middle of the snapshots. After analyzing this behavior, a new adapted control, has been suggested to make this transition from one side to the other side of the merchant vessel faster. The result of this adapted control is shown in 6-13b.



(a) Original control system **(b)** Adapted control

Figure 6-13: Difference between original control and adapted control

The original control does not consider that the whole scene is moving. The merchant vessel is simulated to sail north with respect to the fixed global axis system, with a speed of 9 m/s (roughly 18 knots). The adapted control does consider that the whole scene is moving north. It does this by "waiting" for the reference point to overtake the Beagle if it is located south of the Beagle. Once the reference point overtakes the Beagle, the Beagle will sail towards it. The result of this adapted control is shown in Figure 6-13b. Furthermore, the adapted control slows down the Beagle when it needs to take a turn. This reduces the turning circle of Beagle. To enforce this kind of behavior, the throttle (X_{set}) is adjusted to new throttle $X_{set\ new}$:

$$X_{set\ new} = X_{set}(\frac{1}{4} + \frac{3}{4}\cos(\psi_O^B + \theta_B^{R_B})). \tag{6-19}$$

In Figure 6-14 a situational sketch is shown.

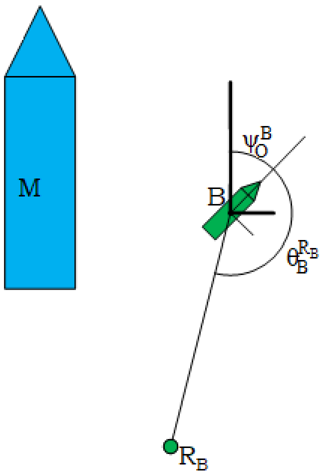


Figure 6-14: Situation sketch reference point south of Beagle

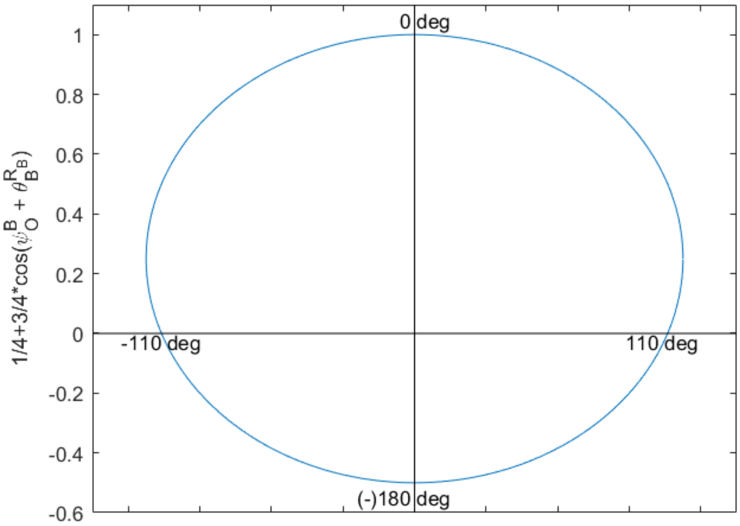


Figure 6-15: Visualization of Equation (6-19)

The formula shown in Equation (6-19) is visualized in Figure 6-15. The y-axis represents $\frac{1}{4}+\frac{3}{4}\cos(\psi_O^B+\theta_B^{R_B})$ the circle represents $\psi_O^B+\theta_B^{R_B}$. Figure 6-15 shows that when the Beagle's reference point is located south of the Beagle, with respect to the fixed global coordinate system ($110 < |\psi_O^B + \theta_B^{R_B}| < 180$), the throttle will be multiplied with a negative number, X_{setnew} will be 0 because it is saturated between 0 and 1. When ($0 < |\psi_O^B+\theta_B^{R_B}| < 110$), the throttle will be multiplied with a number between 0 and 1. This also, helps the Beagle make turns faster by slowing down and reducing the turn circle.

In the original control, Figure 6-13a, it takes the Beagle 55 seconds to get from one side to the other side. For the adapted control, 6-13b, it takes the Beagle 50 seconds. This difference maybe does not seem like a lot, but in a dynamic situation like this, every second counts.

6-5 Validation of the model

This section validates the power and maneuvering model, the validation of the model will be done by checking Palfingers predicted resistance with the resistance calculated by Savitsky's method, see appendix D. Furthermore, Palfinger did a real life turning test at two speeds, 30 and 40 knots. Finally, an acceleration test is done to check the acceleration of the Beagle. In Figure 6-16 the resistance calculated by Palfinger is shown with the red stars. The resistance calculated by Savitsky is shown with the blue line.

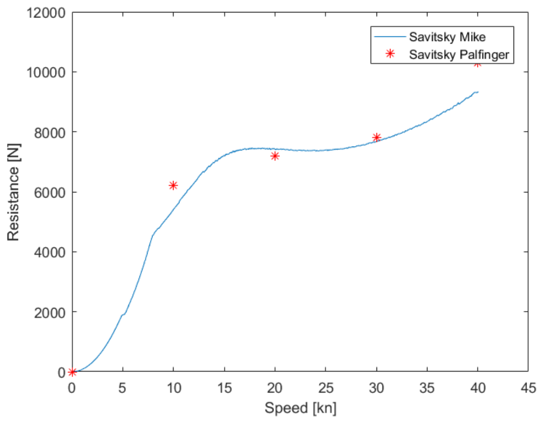
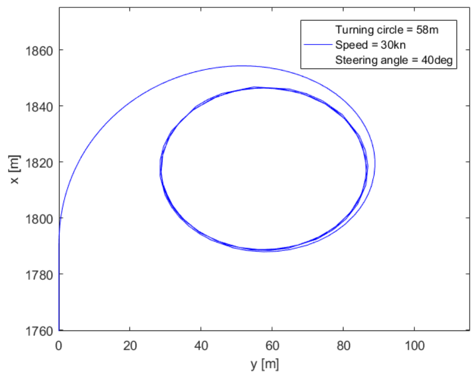
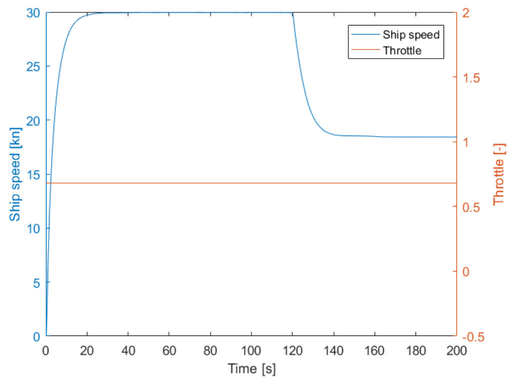


Figure 6-16: Resistance Palfinger and Resistance Savitsky

Figures 6-17 and 6-18 show the results of the turning tests at 30 and 40 knots respectively. In Figures 6-17a and 6-18a the tracks are shown corresponding these turning test. Figures 6-17b and 6-18b show the corresponding speed and throttle during the test. The turn is, in both cases, initiated at 120 seconds. Because of the extra resistance in x-direction due to the sway (v) and yaw (r) velocities (X_{vr}, X_{vv} and X_{rr}), the ships speed (u) drops when the turn is initialized. This results in a decreasing turning circle over time as shown in Figures 6-17a and 6-18a.

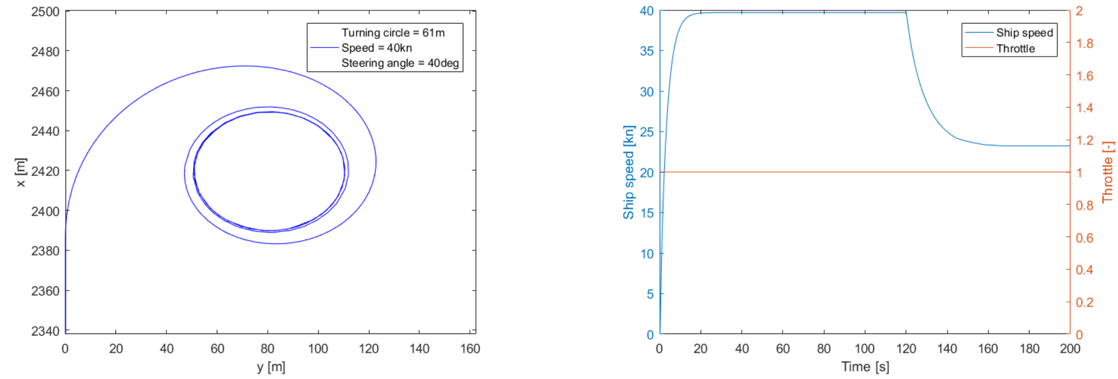


(a) Ship track



(b) Speed drop due to turning test

Figure 6-17: Turning test at 30 knots



(a) Turning test started at 40 knots

(b) Speed drop due to turning test

Figure 6-18: Turning test at 40 knots

Table 6-2 shows that the real life turning test done by Palfinger and the Beagle simulation are similar. The results are close, however, Palfinger indicated one difference, the ships speed drop was in the real life test a bit bigger and steeper. A reason for the difference between the model and the reality might be that roll (ϕ) of the vessel is not considered during the simulation. Due to roll there is an extra resistance in x-direction ($X_{\phi\phi}$). This could lead to a quicker and a steeper drop of the ships speed (u) when a turn is initiated.

Table 6-2: Overview of Palfinger and Beagle turning test results

	Start speed [kn]	End speed [kn]	Turning circle [m]
30 knots Palfinger test	30	17	57
30 knots Beagle test	30	18	58
40 knots Palfinger test	40	20	57
40 knots Beagle test	40	23	61

Figure 6-19 shows the acceleration test of the simulation. Within 20 seconds the Beagle has reached its top speed. Within 10 seconds the Beagle is already within 95 percent of its top speed. Palfinger validated that this is exactly the kind of behavior they experienced.

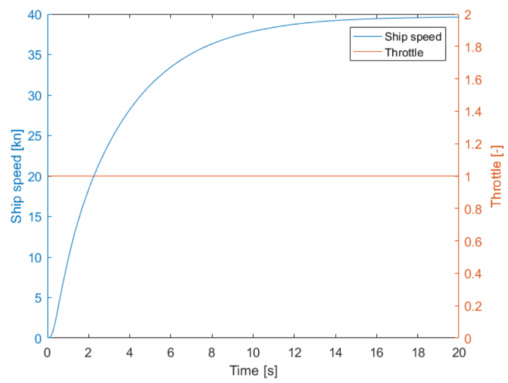


Figure 6-19: Acceleration test

6-6 Summary

A computer model has been made that describes the interaction of three to four vessels during a pirate attack, the Beagle, a merchant vessel and one or two skiffs. A MATLAB and Simulink model has been made and solved by an ODE45 solver. ODE45 solvers performs well for non-stiff problems and should generally be the first choice of solver, [35]. To simulate the maneuvering of the Beagle and the skiffs realistically, a power and maneuvering model has been made. This power and maneuvering model is based on an existing Fast Rescue Craft (FRC), the FRSQ850. The computer model is validated with the maneuvering test of this FRSQ850. The next chapter, Chapter 7, will elaborate on how this computer model is used to do simulations. Chapter 8 will discuss the results of these simulations.

Chapter 7

Systematic simulation variations

In this chapter the systematic simulation variations will be justified. These are done to save computational time, while keeping the ability to draw clear conclusions. The systematic simulation variation was done in two groups. The first simulation group determines the initial values for the best Beagle defense strategy **per weapon**, so four initial Beagle defense strategies will be defined. This simulation setup is discussed in Section 7-1, the results of these simulations are elaborated in Section 8-1.
In Section 7-2 simulation setup of group 2 is explained, in Section 8-2 the results of these simulations are discussed. In this simulation group, the four initial Beagle defense strategies from simulation group 1, will be subjected to different pirate attack scenarios. In this case the Beagle defense strategy parameters are kept constant and the pirate attack scenario parameters change. The Beagle defense strategy that is most robust against the different pirate attack scenarios will be the most effective. Finally, Section 7-3 gives a summary of this chapter.

7-1 Simulation setup group 1: Initial Beagle defense strategies

During these simulations there is only one pirate attack scenario while the Beagle defense strategy parameters are changed systematically. The pirate attack parameters will be a challenging one and is shown in Table 7-1. First of all, a Beagle design speed of 35 knots is chosen because it is a common speed for Fast Rescue Craft (FRC). Two skiffs will be attacking, otherwise the influence of the skiff priority coefficient cannot be studied. Furthermore, the board merchant vessel tactic is chosen because that is the most likely scenario. A large t_{reach} is chosen, otherwise the effect of the defense zone radius ($R_{def\ zone}$) cannot be studied. Finally, one skiff is attacking from the east and one from the west. The reasoning behind this is that the skiffs are further apart, so the influence of the control strategy can be studied better than when the skiffs attack together.

Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
35	2	Board merchant vessel	300	east and west

Table 7-1: Common pirate attack scenario parameters

Simulation group 1 leads to the initial values for the Beagle defense strategy. Section 4-4 already suggested the best Beagle defense parameters per strategy group. This is shown in Table 7-2.

Table 7-2: Overview of suggested initial Beagle defense strategies per weapon

Strategy	Beagle weapon	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control strategy
Defend and guard merchant vessel	Water cannon LRAD	0.75	1600	LOS
Attack and neutralize threat	MDS Battering ram	0.25	1600	PP

Simulation group 1 is going to check whether these suggestions were right. The values of the Beagle defense strategy parameters as shown in Table 7-2 will be the starting point. Each Beagle defense strategy parameter will be changed systematically, three values for the skiff priority coefficient (c_p), five values for the defense zone radius ($R_{defzone}$) and three control strategies will be tested. In Tables 7-3, 7-4 and 7-5 those variations are shown.

Table 7-3: Simulation setup group 1: Variations for skiff priority coefficient (c_p)

Strategy	Variation	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Defend and guard	1	**0.25**	1600	LOS
	2	**0.50**	1600	LOS
	3	**0.75**	1600	LOS
Attack and neutralize	1	**0.25**	1600	PP
	2	**0.50**	1600	PP
	3	**0.75**	1600	PP

Table 7-4: Simulation setup group 1: Variation for defense zone radius ($R_{defzone}$)

Strategy	Variation	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Defend and guard	1	0.75	**125**	LOS
	2	0.75	**200**	LOS
	3	0.75	**400**	LOS
	4	0.75	**800**	LOS
	5	0.75	**1600**	LOS
Attack and neutralize	1	0.25	**125**	PP
	2	0.25	**200**	PP
	3	0.25	**400**	PP
	4	0.25	**800**	PP
	5	0.25	**1600**	PP

Table 7-5: Simulation setup group 1: Variation for control algorithm

Strategy	Variation	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Defend and guard	1	0.75	1600	**PP**
	2	0.75	1600	**CB**
	3	0.75	1600	**LOS**
Attack and neutralize	1	0.25	1600	**PP**
	2	0.25	1600	**CB**
	3	0.25	1600	**LOS**

For each simulation the performance will be monitored. This means that the simulation will not only monitor whether the Beagle or the pirates win the simulation. It will also monitor at what real time in the simulation the Beagle won. Furthermore, it will monitor the average distance between the skiff(s) and the merchant vessel during the entire simulation. These are two Key Performance Indicators (KPIs) that will be used to compare the results if in both cases the Beagle "wins". The faster the Beagle repels the pirate attack the better. This is an important KPI for the Mobility Denial System (MDS) and the battering ram since those two strategies have an 'attack and neutralize threat' strategy. The other KPI, the average distance between the skiffs and the merchant vessel during the simulations, is an important KPI for the other two weapons (water cannon and Long-Range Acoustic Device (LRAD)). This is because the water cannon and the LRAD have another strategy, a 'defend and guard merchant vessel' strategy.

KPI 1: Time to repel the pirate attack

1. Mobility Denial System (MDS)
2. Battering ram

KPI 2: Average distance between skiffs and merchant vessel

1. Water cannon
2. Long-Range Acoustic Device (LRAD)

The result of these simulations gives the initial Beagle defense strategy for each weapon. Each weapon will have its own, skiff priority coefficient (c_p), defense zone radius ($R_{def\ zone}$) and control strategy. The results of simulation group 1 are explained in Section 8-1.

7-2 Simulation setup group 2: Most effective Beagle defense strategy

The latter Section 7-1 simulations variations are described to find the initial Beagle defense strategy parameters per weapon. This section will describe the simulation that will be done to find the best overall Beagle defense strategy. This will be done by finding the Beagle defense strategy or combination of Beagle defense strategies that is most effective against different pirate attack scenarios. A distinction will be made between the first two pirate tactics (board merchant vessel and fire RPG at merchant vessel) and the last two pirate tactics (wreck the Beagle and board the Beagle). Those will be referred to as simulation group 2A and simulation group 2B respectively. The reason for this distinction is that the latter two pirate tactics are different from the first two. First of all, the latter two are not influenced by t_{reach} and location the pirates are spotted. The reason for this is that these simulations will always converge into a cat and mouse game between the Beagle and the skiff(s). Moreover, except for the defense zone radius ($R_{def\ zone}$), the merchant vessel plays no part in the latter two simulations since the skiffs and the Beagle focus on each other. In Subsections 7-2-1 and 7-2-2 the simulations done for respectively group 2A and 2B are explained.

7-2-1 Simulation setup group 2A: Board merchant vessel and fire RPG

Each Beagle defense strategy will win for simulation group 2A if there is only one skiff attacking. The reason for this is that if there is only one skiff, the Beagle can fully focus on this skiff and prevent it from boarding or firing the Rocket Propelled Grenade (RPG) at the merchant vessel. Furthermore, it is fast and maneuverable enough to follow one skiff at all times, i.e. one skiff is not interesting for optimization of the Beagle in this simulation group. For simulation group 2A, there will always be two skiffs that attack.

First, the influence of the Beagle's top speed will be examined. Tables 7-6 and 7-7 give an overview of these simulations for the board merchant vessel and fire RPG tactics respectively.

Table 7-6: Simulation setup group 2A: Influence of Beagle design speed for board merchant vessel tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	40	2	Board merchant vessel	300	south
Variation 2	35	2	Board merchant vessel	300	south
Variation 3	30	2	Board merchant vessel	300	south
Variation 4	25	2	Board merchant vessel	300	south

Table 7-7: Simulation setup group 2A: Influence of Beagle design speed for fire RPG tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	40	2	Fire RPG	300	south
Variation 2	35	2	Fire RPG	300	south
Variation 3	30	2	Fire RPG	300	south
Variation 4	25	2	Fire RPG	300	south

Secondly, the effect of the skiffs attacking from the north at different values for t_{reach} will be examined. Table 7-8 and 7-9 shows an overview of these variations for the board merchant vessel and fire RPG tactics respectively.

Table 7-8: Simulation setup group 2A: Influence of t_{reach} for skiffs spotted north and board merchant vessel tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Board merchant vessel	300	north
Variation 2	35	2	Board merchant vessel	150	north
Variation 3	35	2	Board merchant vessel	100	north

Table 7-9: Simulation setup group 2A: Influence of t_{reach} for skiffs spotted north and fire RPG tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Fire RPG	300	north
Variation 2	35	2	Fire RPG	150	north
Variation 3	35	2	Fire RPG	100	north

The third and last influence that will be examined for the board merchant vessel and fire RPG tactics, is the effect of one skiff attacking from the west and the other one from the east at different values for t_{reach}. Table 7-10 and 7-11 shows an overview of these variations for the board merchant vessel and fire RPG tactics respectively.

Table 7-10: Simulation setup group 2A: Influence of t_{reach} for skiffs spotted east and west and board merchant vessel tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Board merchant vessel	300	East and west
Variation 2	35	2	Board merchant vessel	150	East and west
Variation 3	35	2	Board merchant vessel	100	East and west

Table 7-11: Simulation setup group 2A: Influence of t_{reach} for skiffs spotted east and west and fire RPG tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Fire RPG	300	East and west
Variation 2	35	2	Fire RPG	150	East and west
Variation 3	35	2	Fire RPG	100	East and west

7-2-2 Simulation setup group 2B: Wreck Beagle and board Beagle

Some Beagle defense strategies actually lose if there is only one skiff attacking while using the wreck Beagle or board Beagle tactic. A clear example is if one skiff is trying to wreck the Beagle, while the Beagle tries to keep it at distance with the LRAD. The reason for this is that the bubble (R_{bubble}) for the LRAD is smaller than the shooting range of the Kalashnikov (R_{AK}). For each Beagle defense strategy the two variations explained in Table 7-12 are done. As explained before, the wreck Beagle and board Beagle tactics are independent of the initial position of the skiffs. The influence of those pirate attack scenario parameters will not be investigated.

Table 7-12: Simulation setup group 2B: Wreck Beagle and board Beagle tactics with one skiff

	Beagle speed [kn]	Number of skiffs	Pirate tactic
Variation 1	35	1	Wreck Beagle
Variation 2	35	1	Board Beagle

Table 7-12 explains two variations for the four Beagle defense strategies. This results in a total of eight simulations. The combinations of pirate tactic and Beagle defense strategy in which the Beagle wins during these simulations will be investigated further. The simulations in which the Beagle loses from a single skiff will not be investigated since the Beagle will definitely not win if two skiffs attack. During these subsequent simulations, two skiffs will attack and the Beagle design speed varies as shown in Table 7-13.

Table 7-13: Simulation group 2B: Influence of Beagle speed for two incoming skiffs

	Beagle defense strategy	Beagle speed [kn]	Number of skiffs	Pirate tactic
Variation 1	XXX	40	2	XXX
Variation 2	XXX	35	2	XXX
Variation 3	XXX	30	2	XXX
Variation 4	XXX	25	2	XXX

7-3 Summary

The simulations were split up in two groups to save computational time and limit the total number of simulations while still preserving the ability to draw clear conclusions. In the first simulation group, different Beagle defense strategies will be tested against the most common pirate attack. The goal of this simulation group is to find the initial Beagle defense strategy per weapon. There are four non-lethal weapons, so there will be four initial Beagle defense strategies tested in simulation group 2. Simulation group 2 will be done in two groups. Group 2A examines how the Beagle reacts on different type of simulations for the board merchant vessel and fire RPG pirate tactics. Group 2B will examine how the Beagle reacts on different type of simulations for the wreck Beagle and board Beagle pirate tactics. The results of the simulations will be discussed in Chapter 8.

Chapter 8

Simulation results

In this chapter the simulation results are discussed. In Section 8-1 the simulations done in simulation group 1: *Initial Beagle defense strategy per weapon*, are discussed. This section determines for each weapon what the initial Beagle defense strategy parameters is, using one pirate attack scenario. In Section 8-2 the simulation results of group 2: *Most effective Beagle defense strategy* are discussed. Finally, in Section 8-3 the conclusion is written down. Here the final, most effective, Beagle defense strategy will be elaborated. Furthermore, the set of requirements for the Beagle will be discussed.

8-1 Simulation results group 1: Initial Beagle defense strategy per weapon

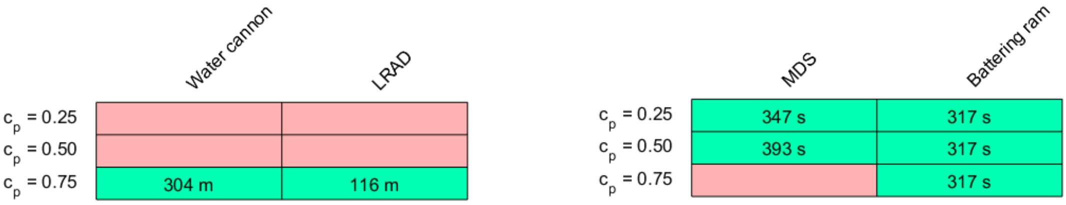
This section elaborates on the results of simulation group 1 as explained in Section 7-1. In the next subsections, 8-1-1, 8-1-2 and 8-1-3 the influence of the different defense strategy parameters, skiff priority coefficient (c_p), defense zone radius ($R_{def\ zone}$) and control algorithm will be discussed respectively by means of the simulation results.

8-1-1 Skiff priority coefficient

Table 8-1 shows the variations done to find the influence of the skiff priority coefficient (c_p). Figure 8-1 shows the results of these variations. A green box means a win for the Beagle, a red box means a loss for the Beagle i.e. a win for the pirates.

Table 8-1: Simulation setup group 1: Variations for skiff priority coefficient (c_p)

Strategy	Variation	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Defend and guard	1	**0.25**	1600	LOS
	2	**0.50**	1600	LOS
	3	**0.75**	1600	LOS
Attack and neutralize	1	**0.25**	1600	PP
	2	**0.50**	1600	PP
	3	**0.75**	1600	PP



(a) Average distance between skiffs and merchant vessel

(b) Time to repel the pirate attack

Figure 8-1: Simulation results for skiff priority coefficient (c_p) variation

Conclusions In section 4-4 an estimation has been done on the influence of the skiff priority coefficient (c_p) for the different tactics. It suggested that lower values for c_p are more efficient for the 'attack and neutralize threat' strategy and higher values for c_p are more efficient for the 'defend and guard merchant vessel' strategy.

Group 1. Attack and neutralize threat

1. Mobility Denial System (MDS)
2. Battering ram

Group 2. Defend and guard merchant vessel

1. Water cannon
2. Long-Range Acoustic Device (LRAD)

From Figures 8-1a it can be concluded that indeed low values for the skiff priority coefficient ($c_p = 0.25$ & $c_p = 0.50$) are not effective for the water cannon and the LRAD. The reason for this is that the Beagle will stick longer to the skiff that is closest to itself. It will push this skiff far away from the merchant vessel before switching to prior on skiff 2. In this scenario it stayed too long near skiff 1, skiff 2 already achieved its objective before the Beagle could reach this skiff. $c_p = 0.75$ is the optimal value for the 'defend and guard merchant vessel' strategies.

From Figure 8-1b it can be concluded that lower values for c_p work better for the MDS. The difference looks small but one should keep in mind that the skiffs have a reaching time (t_{reach}) of 300 seconds to reach the merchant vessel and for the first 120 seconds the Beagle is not deployed. For c_p $= 0.75$ the MDS fails. The reason for this is that during the 20 seconds it takes the Beagle to eliminate skiff 1, the Beagle will switch its priority to skiff 2 because its gets "to close" to the merchant vessel compared to skiff 1. This creates a ping ponging

effect where the Beagle takes turns focusing on skiff 1 and 2 instead of the desired, attack and neutralize effect. For $c_p = 0.25$ this attack and neutralize effect is present.
The maneuvering behavior of the battering ram is independent of the choice of c_p for these simulations. The reason for this is because the skiffs do not react on the presence of the Beagle, there is no bubble. The Beagle sails to skiff 1, eliminates it and than sails to skiff 2. The battering ram has the same, 'attack and neutralize threat' strategy like the MDS, therefore, the same value for c_p has been chosen. The last conclusion that can be drawn is that both the MDS and the battering ram are quite effective. The time to reach the merchant vessel (t_{reach}) is 300 seconds and the MDS and battering ram eliminate both skiffs in 347 and 317 seconds respectively (see Figure 8-1b).

The expectation of the influence of the skiff priority coefficient (c_p), stated in Section 8-1-1 was correct:

- Water cannon: $c_p = 0.75$
- LRAD: $c_p = 0.75$

- MDS: $c_p = 0.25$
- Battering ram: $c_p = 0.25$

8-1-2 Defense zone radius

Table 8-2 shows the variations done to find the influence of the defense radius ($R_{defzone}$). Figure 8-2 shows the results of these variations.

Table 8-2: Simulation setup group 1: Variation for defense zone radius ($R_{defzone}$)

Strategy	Variation	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Defend and guard	1	0.75	**100**	LOS
	2	0.75	**200**	LOS
	3	0.75	**400**	LOS
	4	0.75	**800**	LOS
	5	0.75	**1600**	LOS
Attack and neutralize	1	0.25	**100**	PP
	2	0.25	**200**	PP
	3	0.25	**400**	PP
	4	0.25	**800**	PP
	5	0.25	**1600**	PP

	Water cannon	LRAD
$R_{def\ zone}$ = 100 m	280 m	113 m
$R_{def\ zone}$ = 200 m	281 m	114 m
$R_{def\ zone}$ = 400 m	298 m	114 m
$R_{def\ zone}$ = 800 m	308 m	117 m
$R_{def\ zone}$ = 1600 m	304 m	116 m

(a) Average distance between skiffs and merchant vessel

	MDS	Battering ram
$R_{def\ zone}$ = 100 m	362 s	
$R_{def\ zone}$ = 200 m	410 s	
$R_{def\ zone}$ = 400 m	350 s	353 s
$R_{def\ zone}$ = 800 m	348 s	319 s
$R_{def\ zone}$ = 1600 m	347 s	317 s

(b) Time to repel the pirate attack

Figure 8-2: Simulation results for defense zone radius ($R_{defzone}$) variation

Conclusions Section 4-4 predicted that, especially for the 'attack and neutralize threat' strategy, a larger defense zone radius ($R_{def\ zone}$) would be better. From Figures 8-2a and 8-2b the conclusion is quite frank and the same for all Beagle defense strategies. The larger the defense zone the better. For the MDS and battering ram the reason for this is that these weapons can intercept and eliminate the skiffs at a larger distance from the merchant vessel. The effect of the water cannon and LRAD is similar. Since the Beagle is faster and for a larger defense zone radius ($R_{defzone}$) has a larger area to counteract the skiffs, it is harder for the skiffs to reach the merchant vessel. Once the skiffs reach the merchant vessel the influence of the defense zone radius is over. For all weapons the conclusion can be drawn that, the larger the defense zone radius the better the performance. For each Beagle defense strategy a defense zone radius of 1600 meter is chosen.

- Water cannon: $R_{defzone} = 1600$ m
- LRAD: $R_{defzone} = 1600$ m

- MDS: $R_{defzone} = 1600$ m
- Battering ram: $R_{defzone} = 1600$ m

8-1-3 Control algorithm

Table 8-3 shows the variations done to find the influence of the control algorithm. Figure 8-3 shows the results of these variations.

Table 8-3: Simulation setup group 1: Variation for control algorithm

Strategy	Variation	c_p $[-]$	$R_{def\ zone}$ $[m]$	Control algorithm
Defend and guard	1	0.75	1600	**PP**
	2	0.75	1600	**CB**
	3	0.75	1600	**LOS**
Attack and neutralize	1	0.25	1600	**PP**
	2	0.25	1600	**CB**
	3	0.25	1600	**LOS**

	Water cannon	LRAD
Pure Pursuit control		
Constant Bearing control		
Line-Of-Sight control	304 m	116 m

(a) Average distance between skiffs and merchant vessel

	MDS	Battering ram
Pure Pursuit control	347 s	317 s
Constant Bearing control	367 s	339 s
Line-Of-Sight control	390 s	323 s

(b) Time to repel the pirate attack

Figure 8-3: Simulation results for control strategy variation

Conclusions From Figure 8-3a it can be concluded that for both the water cannon and the LRAD, the Line-Of-Sight (LOS) control is the best option. The reason for this is that the Beagle knows where the skiff is headed and takes that into account when maneuvering. It intercepts the skiff at exactly the right moment. For the water cannon and the LRAD, the other controls fail. The reason for this is because these controls gets the Beagle close to the skiff, which keeps the priority at this skiff. In the mean time, skiff 2, achieved its objective. From Figure 8-2b it can be concluded that for the MDS and battering ram, the Pure Pursuit (PP) control is the best option. The reason for this is because for these, 'attack and neutralize threat' strategies, the Beagle needs to get close to the skiffs. The PP control makes sure the Beagle gets close to the skiff. The Constant Bearing (CB) does not work well for these strategies. The reason for this is, if the skiffs are close and the skiff steers away, the Beagle reacts fierce to this. That way, the skiffs can escape the Beagle more easy.

- Water cannon: Control = LOS
- LRAD: Control = LOS

- MDS: Control = PP
- Battering ram: Control = PP

Table 8-4 gives an overview of the four initial Beagle defense strategies that will be tested by group 2 in the next section. Section 4-4 already predicted these values.

Table 8-4: Overview of initial Beagle defense strategies

Strategy	Beagle weapon	c_p [−]	$R_{def\ zone}$ [m]	Control strategy
Defend and guard merchant vessel	Water cannon LRAD	0.75	1600	Line-Of-Sight (LOS)
Attack and neutralize threat	MDS Battering ram	0.25	1600	Pure Pursuit (PP)

8-2 Simulation results group 2: Most effective Beagle defense strategy

This section elaborates on the results of simulation group 2 as explained in Section 7-2. Subsection 8-2-1 will discuss the results group 2A: *Board merchant vessel and fire RPG tactics*. Subsection 8-2-2 will discuss the results of group 2B: *Wreck Beagle and board Beagle tactics*.

8-2-1 Simulation results group 2A: Board merchant vessel and fire RPG

In Figures 8-4 and 8-5 the results to find the influence of the Beagle design speed for the board merchant vessel and fire Rocket Propelled Grenade (RPG) tactics are shown, followed by a conclusion.

Table 8-5: Influence of Beagle design speed for board merchant vessel tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	40	2	Board merchant vessel	300	south
Variation 2	35	2	Board merchant vessel	300	south
Variation 3	30	2	Board merchant vessel	300	south
Variation 4	25	2	Board merchant vessel	300	south

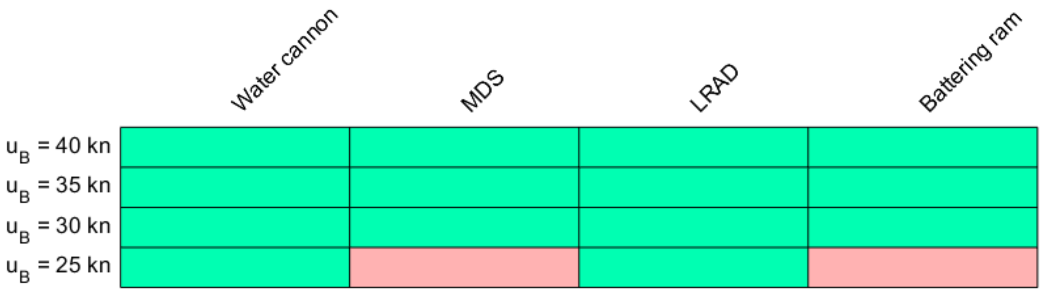


Figure 8-4: Influence of Beagle design speed for board merchant vessel tactic

Table 8-6: Influence of Beagle design speed for fire RPG tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	40	2	Fire RPG	300	south
Variation 2	35	2	Fire RPG	300	south
Variation 3	30	2	Fire RPG	300	south
Variation 4	25	2	Fire RPG	300	south

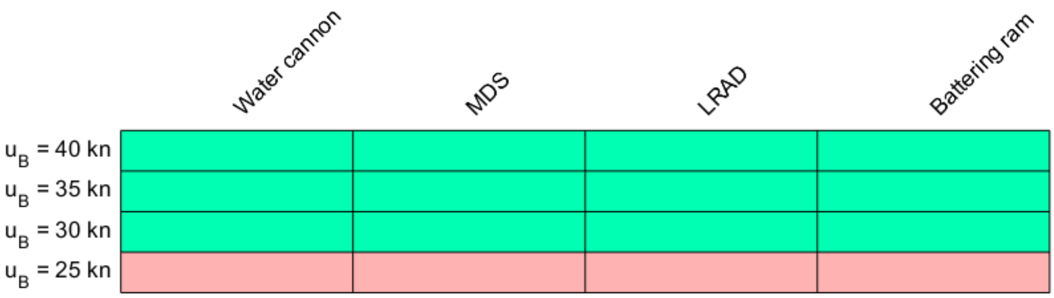


Figure 8-5: Influence of Beagle design speed for fire RPG tactic

Conclusion Beagle design speed From Figures 8-4 and 8-5 conclusions can be drawn about the required design speed for the Beagle. The first conclusion that can be drawn is that the fire RPG tactic is more difficult for the Beagle to repel than the board merchant vessel. This make sense since it is basically the same tactic, but instead of taking a stationary position alongside the merchant vessel the skiffs take a stationary position at 100 meters of the merchant vessel. Since this is further apart, this is harder for the Beagle to repel. For the MDS and the battering ram it is hard to repel the pirate attack if the Beagle design speed is the same as the skiffs speed. If the design speed is the same, MDS cannot keep up with the skiffs since it needs to react upon the skiffs, its always to late. Furthermore, the battering ram needs to accelerate to a velocity faster than the skiff to hit the engine.
For the water cannon and the LRAD a design speed of 25 knots is enough to sail from port side to starboard to keep the pirates from boarding. This is due to the adapted control as explained in subsection 6-4-1. If the skiffs use the fire RPG tactic, the distance is too large, and the Beagle is not in time to keep the skiffs at distance. For all Beagle defense strategies a top speed of 30 knots should be sufficient.

In Figures 8-6, 8-7, 8-8 and 8-9 the results to find the influence of the locations spotted of the skiffs are shown, followed by a conclusion.

Table 8-7: Influence of skiffs spotted north and t_{reach} for board merchant vessel tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Board merchant vessel	300	north
Variation 2	35	2	Board merchant vessel	150	north
Variation 3	35	2	Board merchant vessel	100	north

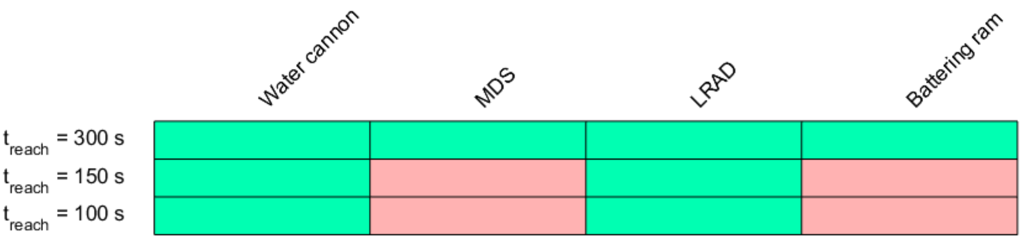


Figure 8-6: Influence of skiffs spotted north and t_{reach} for board merchant vessel tactic

Table 8-8: Influence of skiffs spotted north and t_{reach} for fire RPG tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Fire RPG	300	north
Variation 2	35	2	Fire RPG	150	north
Variation 3	35	2	Fire RPG	100	north

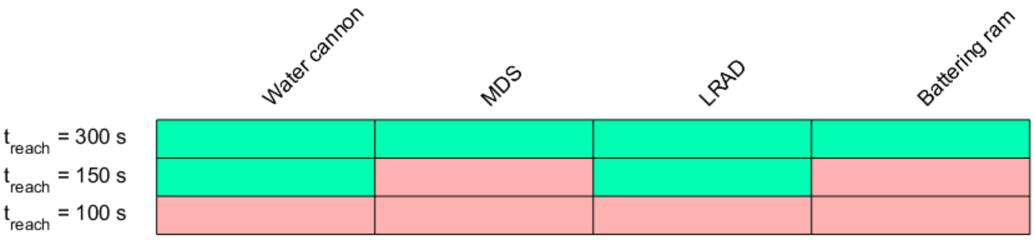


Figure 8-7: Influence of skiffs spotted north and t_{reach} for fire RPG tactic

Table 8-9: Influence of skiffs spotted west and east and t_{reach} for board merchant vessel tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Board merchant vessel	300	west and east
Variation 2	35	2	Board merchant vessel	150	west and east
Variation 3	35	2	Board merchant vessel	100	west and east

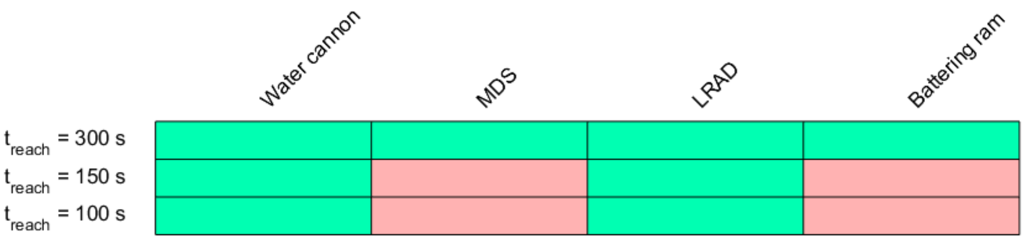


Figure 8-8: Influence of skiffs spotted west and east and t_{reach} for board merchant vessel tactic

Table 8-10: Influence of skiffs spotted east and west and t_{reach} for fire RPG tactic

	Beagle speed [kn]	Number of skiffs	Pirate tactic	t_{reach} $[s]$	Location skiffs spotted
Variation 1	35	2	Fire RPG	300	west and east
Variation 2	35	2	Fire RPG	150	west and east
Variation 3	35	2	Fire RPG	100	west and east

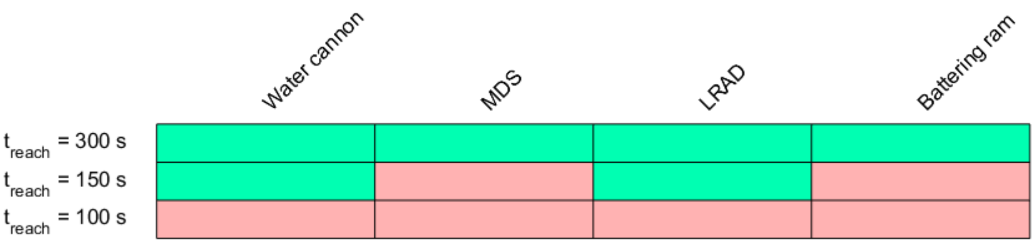


Figure 8-9: Influence of skiffs spotted east and west and t_{reach} for fire RPG tactic

Conclusion skiff spotted locations From Figures 8-6, 8-7, 8-8 and 8-9 it can be concluded that the MDS and the battering ram are not a good solution when the skiffs are spotted close to the merchant vessel ($t_{reach} = 100$ s & $t_{reach} = 150$ s). The reason for this is that it does not have enough time to neutralize skiff 1 and sail to skiff 2 before skiff 2 executed its mission. The last conclusion that can be drawn is that if the skiffs are spotted too close to the merchant vessel ($t_{reach} = 100$ s), none of the Beagle defense strategies can stop them if the skiffs use fire RPG tactic. This means that spotting the skiffs in time is an important aspect to successfully repel the pirate attacks.

8-2-2 Simulation results group 2B: wreck Beagle and board Beagle

The first step of simulation round 2B is to expose the Beagle defense strategies to the pirate tactics: *wreck Beagle* & *board Beagle*, see Table 8-11. The results of these eight simulations are shown in Figure 8-10. For the Board Beagle versus MDS simulation the skiff ignored the Beagle bubble. The reason for this is because, in contrast to the water cannon and the LRAD, the skiffs could choose to ignore the presence of the MDS. The slippery goo might prevent them from boarding, but it does not scare them away. This resulted in a loss for the MDS.

Table 8-11: Simulation results group 2A: Wreck Beagle and board Beagle tactics with one skiff

	Beagle speed [kn]	Number of skiffs	Pirate tactic
Variation 1	35	1	Wreck Beagle
Variation 2	35	1	Board Beagle

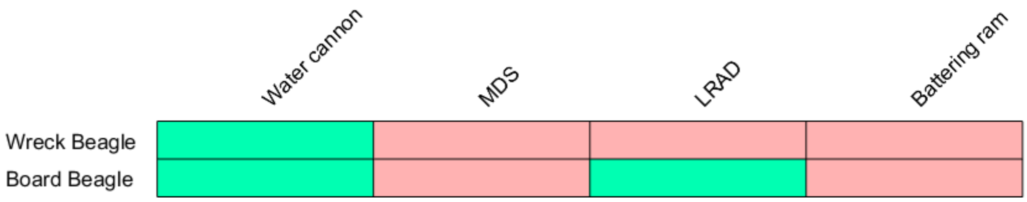


Figure 8-10: Results of simulations shown in Table 8-4

In Figure 8-10 one can see that only three out of eight simulation succeed. The MATLAB plot file for the wreck Beagle pirate tactic versus the MDS, LRAD and battering ram, has been analyzed. It can be concluded that the pirates are dynamic enough to keep the Beagle at a distance, just enough to shoot at the Beagle. After analyzing the board Beagle pirate tactic versus the MDS it can be concluded that the pirates have boarded the Beagle before the Beagle could successfully fill it with the slippery goo.
After analyzing this failed simulation of the board Beagle pirate tactic versus the MDS and battering ram tactic it became clear that this problem could be resolved. The Beagle needs a system that always keeps the pirates at at least a distance of 10 meters. This is modeled as a bubble around the pirates of 10 meters in which the Beagle does not want to operate. The battering ram needs to hit the skiff from behind, therefore, the bubble around the skiff is slightly adapted for the battering ram, see Figure 8-11.

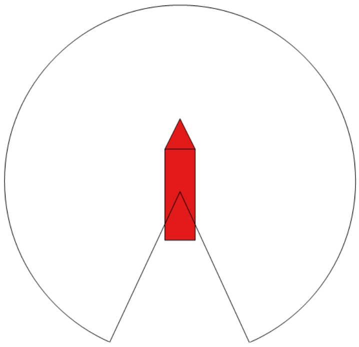


Figure 8-11: Bubble around the skiff for the battering ram

After implementing this system this simulation turned successful. The new figure for the results from the simulations of Table 8-11 are shown in Figure 8-12.

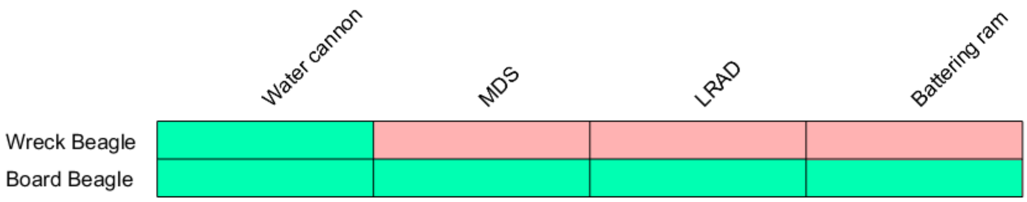


Figure 8-12: New results of simulations shown in Table 8-4

Since three out of eight simulations fail for one skiff, for those combination of Beagle defense strategy and pirate tactic, the simulations with two skiffs will not be done. Those are the red boxes shown in Figure 8-12. Since the Beagle weapon cannot be deployed at both skiffs at the same time, the simulations with two skiffs are interesting for the combination of pirate tactic and Beagle defense strategy with green boxes in Figure 8-12.
Tables 8-12 and 8-13 show the simulations that are done for simulation group 2B: *Wreck Beagle and board Beagle*. Under each of these tables, the results of these simulations are shown. These are Figures 8-13 and 8-14 respectively.

Table 8-12: Influence of Beagle speed versus wreck Beagle tactic (only done for water cannon)

	Beagle speed [kn]	Number of skiffs	Pirate tactic
Variation 1	40	2	Wreck Beagle
Variation 2	35	2	Wreck Beagle
Variation 3	30	2	Wreck Beagle
Variation 4	25	2	Wreck Beagle

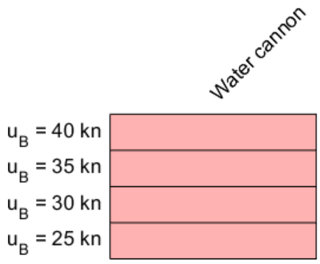


Figure 8-13: Influence of Beagle design speed versus wreck Beagle tactic

Table 8-13: Influence of Beagle speed versus board Beagle tactic (only done for water cannon, MDS and LRAD)

	Beagle speed [kn]	Number of skiffs	Pirate tactic
Variation 1	40	2	Board Beagle
Variation 2	35	2	Board Beagle
Variation 3	30	2	Board Beagle
Variation 4	25	2	Board Beagle

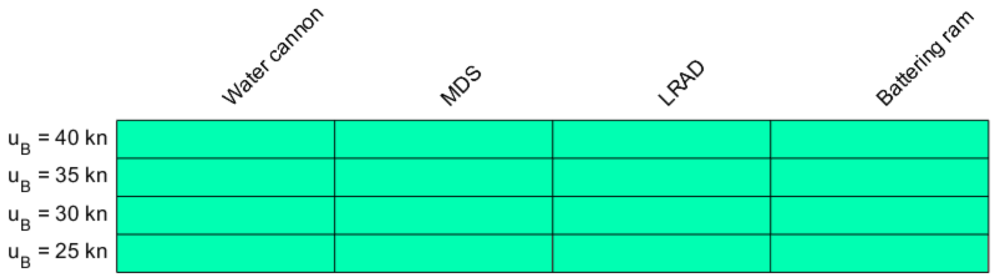


Figure 8-14: Influence of Beagle design speed versus board Beagle tactic

Conclusion wreck and board Beagle tactics From Figures 8-12, 8-13 and 8-14 a few conclusions can be drawn. First of all, Beagle design speed plays no part when the skiffs decide to focus on the Beagle instead of the merchant vessel. Furthermore, all Beagle defense strategies are resistant to the skiffs trying to board the merchant vessel, either due to the weapon (water cannon and LRAD) or the invisible bubble around the skiffs (MDS and battering ram). Finally, if the skiffs together decide to wreck the Beagle, no Beagle defense strategy will succeed. This suggests that the Beagle needs to be more robust against the pirates using Kalashnikov rifles than assumed in this research, or that this scenario needs to be avoided.

8-3 Conclusion

From the simulation results in this chapter a few conclusions can be drawn. These are conclusions about design speed, endurance, required skiff spotting distance and finally the chosen Beagle defense strategy.

Beagle design speed
The first conclusion that is drawn, is that the Beagle design speed needs to be around 5 knots faster than the skiffs. Otherwise the MDS cannot keep up with the skiffs, and the battering ram will not be able to accelerate enough to do damage to the skiff's engines. Furthermore, to sail from one side to the other side of the merchant vessel in time, the required Beagle speed is 30 knots. Otherwise, the pirates have too much time to intimidate the captain with their Rocket Propelled Grenades (RPGs). 30 knots should be sufficient for all Beagle defense strategies.

Endurance
It is desired that the Beagle has a larger endurance than the skiffs. A skiff is frequently fitted with a 60 hp engine. At full speed (25 knots) this engine consumes about 25 liters an hour, [36]. Assuming they carry around 50 liters of fuel an attack could last for about two hours, but no reports have been found of pirate attacks that took that long. Usually, if the element of surprise is gone, the pirates stop their attack, [37].

Skiff spotting distance
The second conclusion that can be drawn is that the pirates can always intimidate the captain with their RPG if they are spotted within 100 seconds of the merchant vessel. This means that it is important to spot the pirates outside the range shown in Figure 8-15 for the Beagle to succeed.

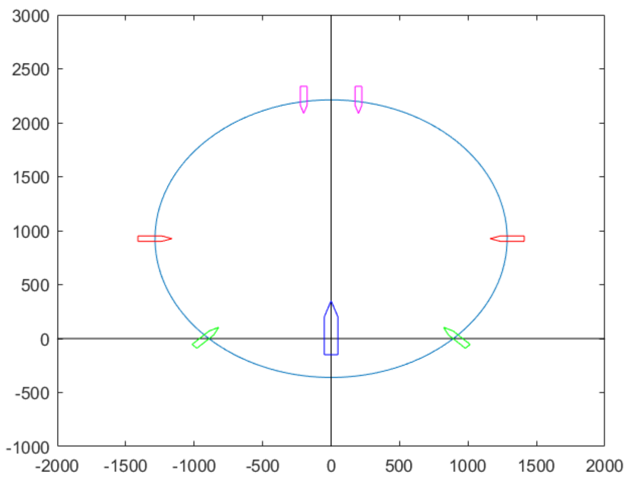


Figure 8-15: t_{reach} = 100 s circle
*vessels not on scale

Beagle defense strategy
The skiffs will not be able to board the Beagle, but, under the assumptions in the simulation, the pirates could wreck the Beagle if they both decide to shoot at the Beagle. This situation needs to be avoided. To do so, the Beagle will be equipped with an 'attack and neutralize threat' defense strategy; the battering ram. The philosophy behind this is that one or two skiffs will already be neutralized before the pirates get aggressive and start to shoot. The

battering ram is chosen over the other 'attack and neutralize threat' defense strategy; the MDS, since the battering ram neutralizes the threat quicker. Furthermore, once hit with the battering ram, a skiff drifts off. It will not be able to shoot at the Beagle anymore. While the MDS neutralizes the threat by making sure the pirates are too slippery to board, it does not stop them from sailing around and shooting at the Beagle. Which was exactly the scenario that needs to be avoided.

The 'attack and neutralize threat' defense strategies are not optimal in all situations. If the skiffs are spotted at a short reaching time to the merchant vessel (t_{reach}), the neutralize defense strategies fail. After analyzing the simulations, a reaching time (t_{reach}) of 150 seconds seems to be the lower working limit for the 'attack and neutralize threat' strategies. If the skiffs are getting to close to the merchant vessel, a 'defend and guard merchant vessel' strategy works better.

To have the ideal Beagle defense strategy in all situations a combination of an 'attack and neutralize threat' and 'defend and guard merchant vessel' strategy is chosen to be equipped on the Beagle. The water cannon and the LRAD have the same simulation results. The most convenient of the two is chosen as 'guard and defense merchant vessel' strategy. For the water cannon, a heavy pump installation (400-600 kilogram) is required. Furthermore, the Beagle needs to be adapted to suck water from the sea. The LRAD installation does not require large adaptions. The LRAD itself is not heavy and furthermore, only consumes around 1200 watts. The total system would be around 150 kilograms. It could easily be installed on the Beagle. Long-Range Acoustic Devices (LRADs) can be operated by hand, but also, remotely controlled units exists. The LRAD is chosen over the water cannon to serve as 'guard and defense merchant vessel' strategy.

What remains is to combine the battering ram, 'attack and neutralize threat' strategy with the LRAD, 'defend and guard merchant vessel' strategy. The skiff priority coefficient (c_p) will be a function of the positions of the skiffs with respect to the merchant vessel; A reaching time (t_{reach}) of 150 seconds was the lower bound for the battering ram to work. Furthermore, the Beagle deployment time is 120 seconds. 8-16 shows a circle around the merchant vessel that represents $t_{reach} = 150 - 120 = 30$ seconds.

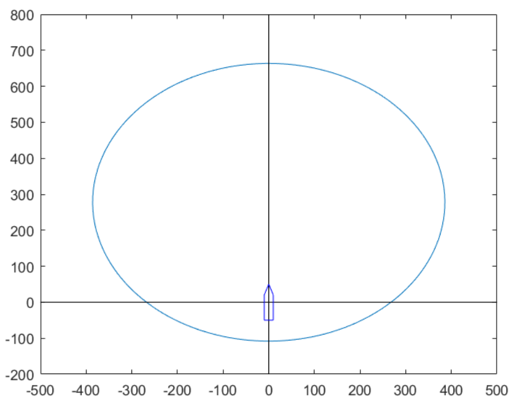


Figure 8-16: $t_{reach} = 30$ s circle

So if both skiffs are outside this circle the skiff priority coefficient (c_p) is 0.25. If one skiff is within this circle and one is outside, skiff priority coefficient (c_p) is 0.5. If both skiffs are within this circle, the skiff priority coefficient (c_p) is 0.75. The defense zone radius will be put on 1600 meter. Finally, if the priority skiff is outside the circle, the battering ram control will take over. If the priority skiff is within the circle the LRAD control will take over.

The requirements for the Beagle can be summed up:

- The design speed of the Beagle is at least 30 knots, but preferably more.
- The Beagle must be able to sail for 2 hours at design speed.
- The Beagle will be equipped with an LRAD.
- The Beagle will be equipped with a battering ram.
- The add-on plug and play system must be compatible with current, existing FRC.

Chapter 9

Feasibility study Beagle

Chapter 8 discussed the simulation results. This resulted into requirements for the Beagle:

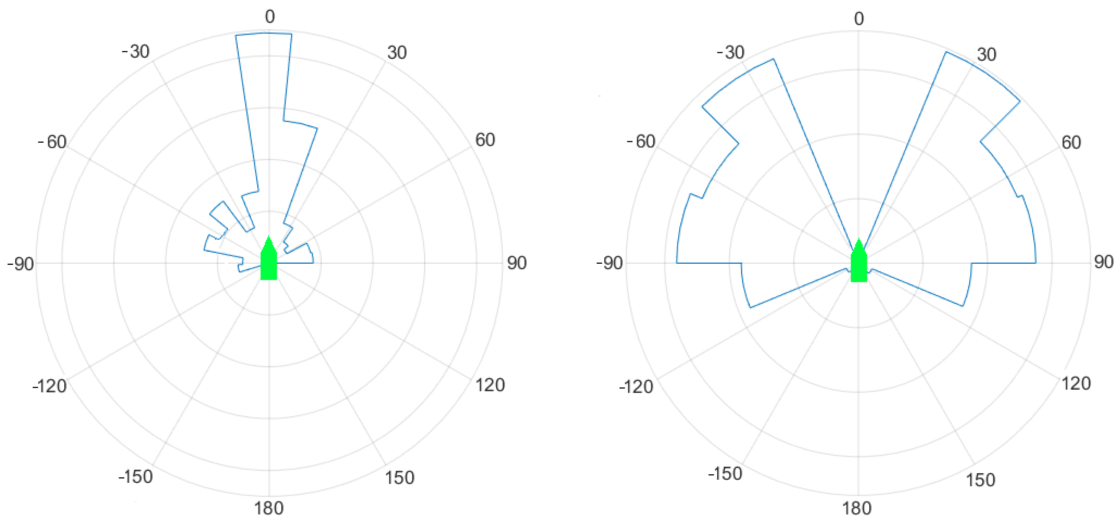
- The design speed of the Beagle is at least 30 knots, but preferably more.
- The Beagle must be able to sail for 2 hours at design speed.
- The Beagle will be equipped with an LRAD.
- The Beagle will be equipped with a battering ram.
- The add-on plug and play system must be compatible with current, existing FRC.

This chapter will discuss whether it is feasible to modify a Fast Rescue Craft (FRC) such that it complies with those requirements. The first two items are entirely dependent on the FRC that is chosen. When choosing a FRC to make an add-on plug and play system, these two items need to be checked off. The Palfinger FRSQ850 model is chosen as an example of a suitable, initial FRC. The FRSQ850 complies with the first two items. It has a design speed of 40 knots. Furthermore, it carries 360 liters of fuel, [1]. The engine of the FRSQ850 consumes about 140 liters of fuel per hour in design speed, [38]. This means that the FRSQ850 can sail for about 2 and a half hour at top speed. In Section 9-1 the arrangement of the subsystems, the Long-Range Acoustic Device (LRAD) and the battering ram, is discussed. Finally, this chapter will conclude the feasibility of the Beagle as an add-on system, that should be compatible with current, existing FRC. It will do this by discussing the aspects of the design spiral. The owners requirements is the starting point of this design spiral. In the conclusion of this chapter, Section 9-2, the first iteration of the design spiral will be discussed.

9-1 Add-on system arrangement

First an estimation of the weight and corresponding Length Centre of Gravity (LCG) and Vertical Centre of Gravity (VCG) of the new subsystems is made. Furthermore, a cost estimation will be made.

LRAD Long-Range Acoustic Devices (LRADs) come in different sizes, with prices ranging from 6,000 to 115,000 U.S. dollars. The sound intensity and costs of the LRAD increases if the size increases. What LRAD will be suitable to equip on the Beagle is not certain yet. For now, the assumption is made that it will be the heaviest (150 kilograms), [22]. This LRAD is chosen because first of all it is remotely controlled. Secondly, the LRAD is used as a non-lethal weapon. The lighter LRADs variants will not be capable to produce enough sound to scare away the pirates.
During the simulations a counter was set on the heading of the LRAD with respect to the Beagle's heading. The counter counted how many seconds the LRAD was turned on between 0 and 10 degrees, 10 to 20 degrees etc. The result are normalized and are shown in Figure 9-1. From this graph one can conclude that the LRAD is mostly deployed, with respect to the Beagle's heading, between -90 and 90 degrees. The LRAD will be placed on the bow of the FRC, facing alongside the heading of the FRC. Also, there is room for the LRAD system at the bow of an FRC.



(a) Board merchant vessel pirate tactic **(b)** Fire RPG pirate tactic

Figure 9-1: Angles at which the LRAD is deployed

Battering ram The battering ram will be located at the tip of the bow. A choice needs to be made whether this is under the waterline or above. The advantage of putting the battering ram under the waterline is that it can hit the skiff's propeller, which is easier to demolish than the outboard engine itself. The downside is that the underwater hull design of the FRC changes the characteristics of the FRC too much. Since, SeaState5 is focusing on an add-on system, compatible with current FRC, a battering ram above the waterline is more convenient. It is not the aim of this research to work out the structural details of the battering ram. The assumption is made that the battering ram and its structural reinforcements will not exceed a weight of 100 kilograms. An estimation of the costs of the battering ram would be around 5.000 USD. A large amount of this money does not go to the material costs, but to making the battering ram compatible with an FRC. This includes, making the bow of the FRC stronger for the impact an perhaps making an extra watertight compartment in the bow. This might be required since the battering ram increases the probability of damage. To keep the risk at the same level, the impact should decrease, since risk = probability · impact. The impact could be decreased by making an extra watertight compartment in the bow of the FRC. Nevertheless, the costs of the battering ram will be low compared to the LRAD.

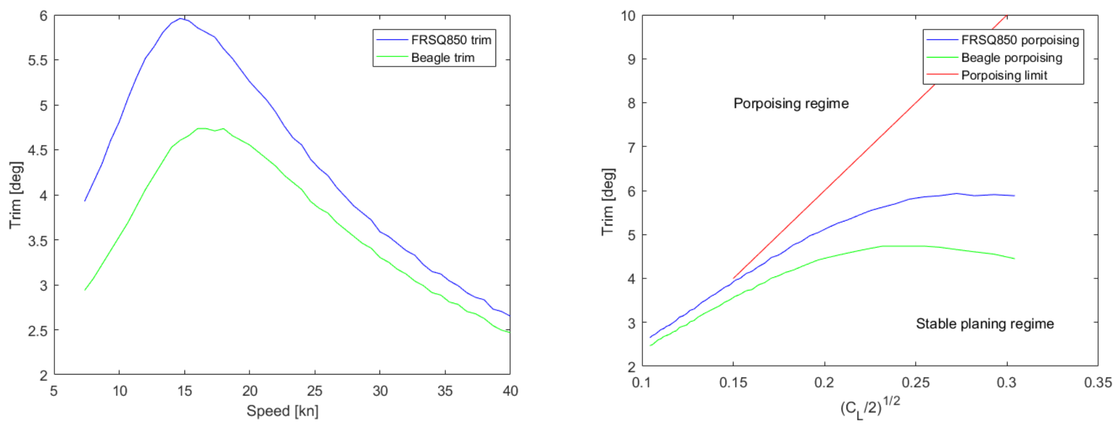
Table 9-1 shows the shift of the LCG and VCG as a result of adding the LRAD and battering ram subsystems.

Table 9-1: Shift of length and vertical centre of gravity

Part	Weight [kg]	LCG [m]	VCG [m]
FRSQ850	3200	3	1
LRAD system	150	7.5	3
Battering ram system	100	8	1
Beagle	3450	3.34	1.09

The FRSQ850 is designed to carry a payload of 21 persons with an equivalent of 1680 kilograms. The add-on system would add approximately 250 kilograms to the lightship weight, this increase could mean that less people could be taken aboard. This should not be a problem since the capacity rule on an FRC state: "The rescue boat shall be capable of carrying at least five seated persons and a person lying on a stretcher",[27]. This indicates that some of the payload can be shifted to the add-on system. Yet it is of importance to discuss this with an FRC manufacturer.

The change of the VCG is insignificant, so the change of the intact stability will be minimal. Since both subsystems are located at the bow of the craft, the change of the LCG is meaningful. This results in a change of trim, as shown in Figure 9-2a. This is not significant. For small planing craft porpoising is a problem. Porpoising is slamming of the bow on the water surface due to dynamic instabilities during planing. Usually it occurs when the LCG is located too far aft. Since the LCG is shifted forwards, the danger for porpoising should decrease. Savitsky's method has a way to check whether or not a vessel has a danger to porpoise. As shown in Figure 9-2b, the danger for porpoising decreases when the subsystems are added.



(a) Change of trim **(b)** Porpoising limit

Figure 9-2: Results of changing LCG

9-2 Conclusion

This conclusion will discuss all the items on the design spiral as shown in Figure 9-3.

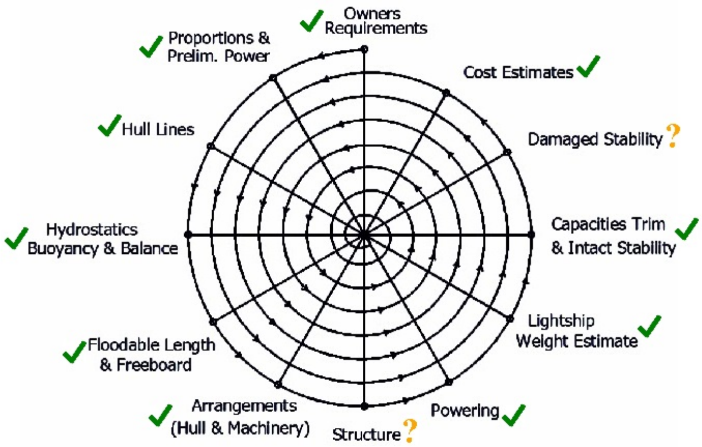


Figure 9-3: Naval architect design spiral, [2]

Most of the states of the design spiral could easily be checked of as shown in Figure 9-3. The reasons for this are discussed in Section 9-1. This will be summarized here. The FRSQ850 is designed to carry a payload of 21 people or 1680 kilograms. An FRC, by law, is obligated to carry at least five seated persons and a person lying on a stretcher, [27]. This indicates that some of the payload can be shifted to the add-on system, i.e. the LRAD and the battering ram in exchange for human payload. Furthermore, the change in VCG and LCG does not influence the maneuverability of the FRC. Yet there are two parts of the design spiral that requires extra attention. These are the structure and the damage stability part. It will not be a part of this research to work out the details of these two subjects. The structure part is an important aspect of the Beagle's strategy because it will be hitting the skiff's engine. Research should be done on how the battering ram will look like and what this does with the loads on the battering ram and the loads on the rest of the FRC. Furthermore, the damaged stability aspect is important to research further. This battering ram strategy leads to an increased probability of damage. To keep the risk at the same level, the impact should decrease. This could be done by adding a watertight compartment in the bow. Research should be done to investigate how this can be done best.

Chapter 10

Conclusion and recommendations

10-1 Conclusion

This thesis aims to answer the research question, "**What is the most suitable Beagle defense strategy to successfully counteract pirate attacks on merchant vessels?**". A suitable Beagle defense strategy repels the pirate attack in an effective way without being too costly. Furthermore, it needs to be compatible with current Fast Rescue Craft (FRC). In this section the important conclusions of this report will be discussed. This will be done by answering the sub-questions drafted in the introduction. Finally, the research question will be answered.

In Chapter 3 the non-lethal weapons suitable to neutralize the pirates are discussed. Furthermore, it elaborates upon how pirate operate. This answers sub-question 2:

> 2. *Which non-lethal weapons are available to successfully repel pirate attacks on merchant vessels with the Beagle?*

Only non-lethal weapons that are deemed to be suitable to neutralize the pirates and compatible with an FRC are simulated. These are:

Non-lethal weapon variations

1. Water cannon
2. Mobility Denial System (MDS)
3. Long-Range Acoustic Device (LRAD)
4. Battering ram

In Chapter 4 the Beagle defense strategies are defined, which answers sub-question 3:

> 3. *Which defense strategies can be used to successfully carry out the Beagle's mission?*

The Beagle defense strategy consists of four parameters; a Beagle defense strategy is a combination of variations of these parameters. The four parameters that define a Beagle defense strategy are:

Beagle defense strategy parameters

1. Non-lethal weapon
2. Skiff priority coefficient
3. Defense zone radius
4. Control strategy

Chapter 5 introduced the pirate attack scenarios. Together with Chapter 3, it gives an answer to sub-question 1:

1. *How do pirates operate and how can this be modeled?*

The pirates' operational behavior is defined by five pirate attack scenario parameters:

Pirate attack scenario parameters

1. Beagle design speed
2. Number of skiffs attacking
3. Pirate attack strategy
4. Time for the skiffs to reach the merchant vessel
5. Direction in which the pirates are spotted

Four different pirate attack strategies are simulated:

Pirate attack strategy variations

1. Skiffs will try to board the merchant vessel
2. Skiffs will intimidate the captain with an Rocket Propelled Grenade (RPG)
3. Skiffs will try to wreck the Beagle
4. Skiffs will try to board the Beagle

Chapter 4 and 5 are fundamental to the computer simulation explained in Chapter 6. The power and maneuvering model of the Beagle was based on and verified with an actual FRC; the Palfinger FRSQ850. In Chapter 7 the simulation setup is explained and in Chapter 8 the results of these simulations are discussed. It gives an answer to the fourth and final sub-question:

4. *How do different Beagle defense strategies perform in different attack scenarios?*

The non-lethal weapons can be divided into two groups:

Group 1. Attack and neutralize threat

1. Mobility Denial System (MDS)
2. Battering ram

Group 2. Defend and guard merchant vessel

1. Water cannon
2. Long-Range Acoustic Device (LRAD)

For group 1 and group 2, the best remaining parameters for the best Beagle defense strategy were found, i.e. the parameters that determine the trajectory of the Beagle. For group 1, the trajectory of the Beagle gave the best results if it focused relatively more on the skiff closest to the Beagle rather than the skiff closest to the merchant vessels, i.e. low values for skiff priority coefficient. Secondly, larger defense zone radii gave better results. The reasoning behind this is that the Beagle could intercept the skiffs at a larger distance from the merchant vessel and neutralize the threat in an early stage. Finally, the Pure Pursuit (PP) control was the most suitable control strategy for group 1. This way the Beagle gets as close to the skiff as possible, which is desired to neutralize it.

Group 2 functioned best for higher values for the skiff priority coefficient, i.e. it focused relatively more on the skiff closest to the merchant vessel, rather than the skiff closest to the Beagle itself. Secondly, the influence of the defense zone radius was small, the simulations converged into a scene around the merchant vessel in which the Beagle tries to push the skiffs away from the merchant vessel. Finally, the Line-Of-Sight (LOS) control was the best control strategy for group 2. The LOS control takes into consideration that the skiffs have a target as well, the merchant vessel. The Beagle intercepts the skiff on its way to the merchant vessel.

Next, each weapon with corresponding Beagle defense strategy was subjected to a range of pirate attack scenarios. From these simulations conclusions are drawn. There was no significant difference within the two strategy groups. The results will be treated per group.
For group 1, the simulations failed if the Beagle was as fast as the skiffs. The reason for this is that the Beagle can follow the skiffs but not overtake them, so it was too late to neutralize the threats. For group 2, the simulations failed if the Beagle design speed was under 30 knots. The reason for this is that the Beagle could not sail fast enough from one side of the merchant vessel to the other side. The minimal required design speed of the Beagle is 30 knots, but preferably more.

Group 1, 'attack and neutralize threat', neutralizes two skiffs in an effective way as long as they are spotted at a large reaching time. The reaching time is the time it takes the skiffs to get to the merchant vessel at the moment they are spotted. If the skiffs are spotted at a smaller reaching time (150 seconds or smaller), the Beagle has no time to neutralize the threat. The direction in which the skiffs attack has no significant influence here.
Group 2, 'defend and guard merchant vessel' reacts better than group 1 if the skiffs are spotted at a smaller reaching time, but there is a limit. It is preferable to spot the skiffs at at least 100 seconds from the merchant vessel. Otherwise the pirates could achieve their objective before the Beagle could intercept them. Again, the direction in which the pirates are spotted has no influence in this.

An anti-boarding mechanism is built into the Beagle to prevent to the skiffs from boarding. This is proven to be successful, even for two skiffs. If both skiffs decide to wreck the Beagle by shooting at it, the Beagle loses in every simulation, under the assumptions of the model. This means that this is an unwanted scenario and should be avoided.

This concludes the simulation results; the main question can be answered:

> "**What is the most suitable Beagle defense strategy to successfully counteract pirate attacks on merchant vessels?**"

The scenario in which both skiffs shoot at the Beagle needs to be prevented. This will be done by using an 'attack and neutralize threat' strategy to neutralize one skiff in an early stage. The battering ram is chosen over the MDS. The reason for this is once hit with the battering ram a skiff drifts off. It will not be able to shoot at the Beagle anymore. While the MDS prevent the skiffs from boarding, it does not stop them from sailing around and shooting at the Beagle. As concluded before, the 'attack and neutralize threat' strategies are not sufficient in scenarios where the skiffs are spotted with a small reaching time, i.e. if the skiffs get too close to the merchant vessel. That is why the battering ram will be combined with a non-lethal weapon from the 'defend and guard merchant vessel' strategy group. Since those two weapons had similar results the most convenient one to build on a FRC will be chosen, which is the LRAD.

The requirements for the Beagle are:

- The design speed of the Beagle is at least 30 knots, but preferably more.
- The Beagle must be able to sail for 2 hours at design speed.
- The Beagle will be equipped with an LRAD.
- The Beagle will be equipped with a battering ram.
- The add-on plug and play system must be compatible with current, existing FRC.

Chapter 9 treats the last aspect of this study, the feasibility of the Beagle. In this chapter it is concluded that it is feasible to equip an existing FRC with the necessary equipment to counteract maritime piracy on merchant vessels.

10-2 Recommendations

In this section the recommendations for the future development of the Beagle will be treated in chronological order.

The computer simulation showed promising results for counteracting piracy with an unmanned, non-lethal, anti-piracy craft, but it was based on a number of assumptions. The primary assumption of the computer model was the assumption of perfect sensors. This assumption leads to perfect knowledge for the Beagle about the whereabouts of all vessels. Due to this perfect knowledge the Beagle could intercept the skiffs exactly at the right position.

Furthermore, it could keep up with the skiffs, follow it properly and even hit the skiffs' engines. It is not unthinkable that the effect and feasibility of the Beagle defense strategies would change due to sensor uncertainty. For instance; With what accuracy can the Beagle hit a skiff's engine if there is no perfect knowledge? Within SeaState5, a research project is going on to study the use of sensors for situational awareness. The first and most important recommendation is:

1. Add sensor uncertainties to the computer model and find out whether the defense strategies are still feasible and suitable.

The results of the situational awareness research, combined with the computer model, will give a conclusion about the theoretical feasibility of the Beagle. If the conclusions of this report remain unchanged, the researcher suggests a collaboration with the manufacturer of LRADs, LRADx. This company manufactures LRADs in varies sizes, ranging from 6,000 to 115,000 dollars. LRADx is interested for the use of Long-Range Acoustic Devices (LRADs) in counteracting piracy, [39]. The performance is measured in the capability to carry a message over a large distance, [22]. The offensive range of the alarm tone capability per LRAD is unknown, although victims describe the exposure of the alarm tone as a kind of psychological torture and were unable to move or think. The researcher suggests a collaboration to find a suitable LRAD to integrate in the FRC. Suitable means a consideration between price and effective offensive range:

2. Is there an LRAD suitable to integrate in an FRC, with the goal to counteract pirate attacks on merchant vessels?

The battering ram is the most suitable Beagle defense strategy to have a quick neutralization of skiffs. If the battering ram is still deemed a suitable Beagle defense strategy after the sensor uncertainty is added to the model, two more aspects need to be worked out in detail:

3. What is the structure of the battering ram going to be and what is the structural impact on the rest of the FRC?

4. What does the presence of the battering ram mean for the damaged stability of the FRC?

If the Beagle is still theoretical feasible it is time for the last step: To make a prototype of the Beagle and test the feasibility in real life. As shown in section 6-5, the modeled physics of the Beagle came close to the real life tests of Palfinger. The researcher suggests that the computer model can act as a tool to find a suitable controller for the Beagle and provide initial controller values. The effectiveness of the presented model will be higher if environmental forces are added to the model. The last two recommendations are:

5. Add environmental forces to the computer model.

6. Use the computer model to find a suitable controller for the real life prototype of the Beagle.

Appendix A

State diagrams

In this appendix the state diagrams for both the Beagle and the pirates are elaborated.

A-1 Beagle state machine

The Beagle state machine that is used for the weapons, water cannon, Mobility Denial System (MDS) and Long-Range Acoustic Device (LRAD) is already explained in section 6-2-1. This section will elaborate on the last remaining state machine, the state machine used for the battering ram. This state machine is different from the others since it has a specific task; hitting the engines of the skiffs. Figure A-1 shows the this state diagram. Figures A-2, A-3, A-4, A-5 and A-6 are states 1, 2, 3, 4 and 0 respectively.

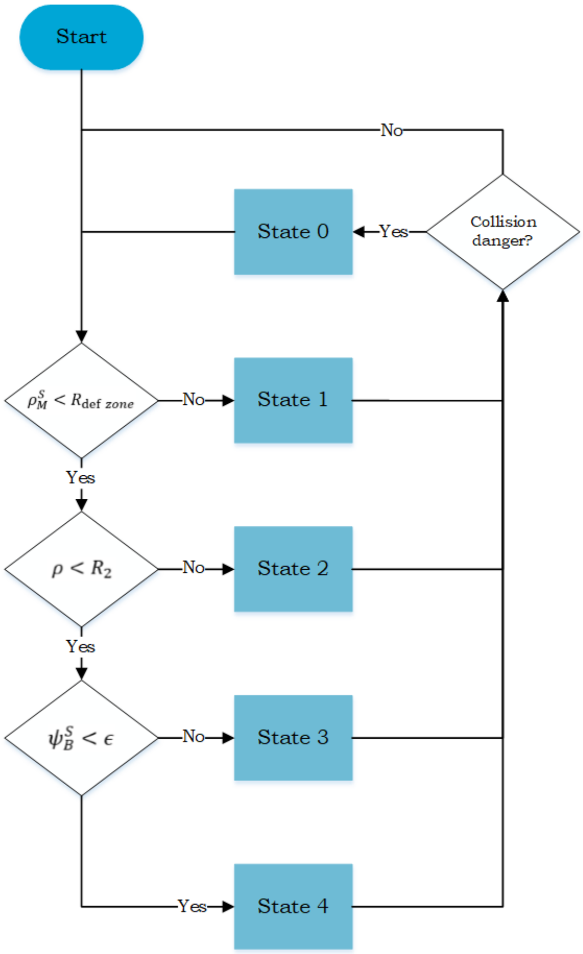


Figure A-1: State diagram battering ram

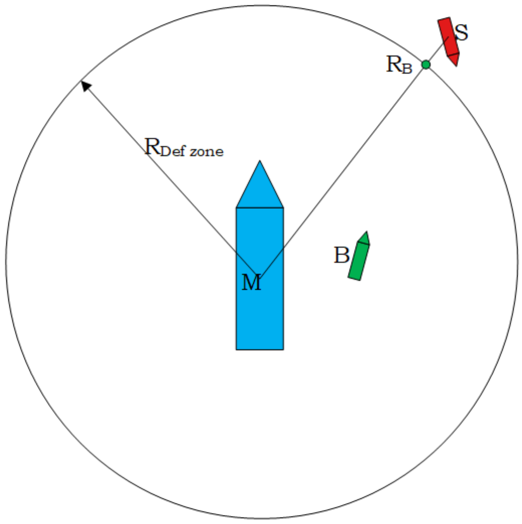
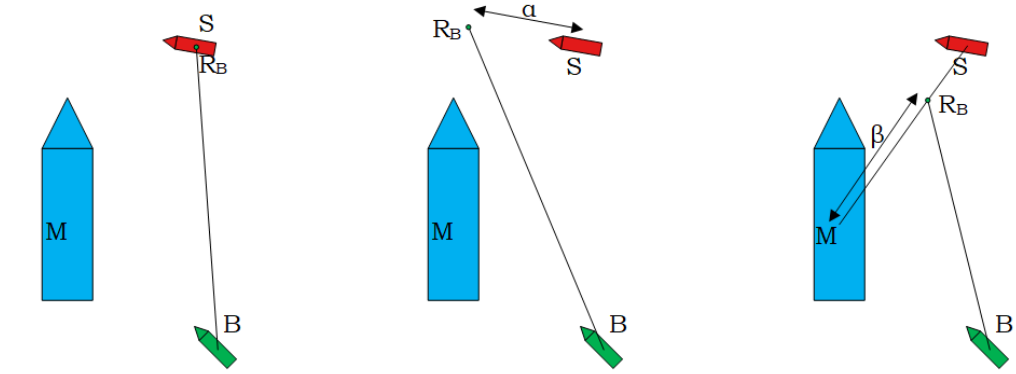


Figure A-2: Beagle battering ram: State 1



(a) Pure Pursuit control **(b)** Constant Bearing control **(c)** Line-Of-Sight control

Figure A-3: State 2: Depends on control strategy

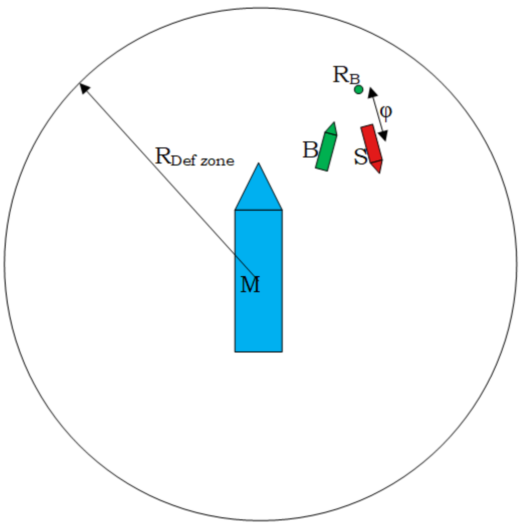


Figure A-4: Beagle battering ram: State 3

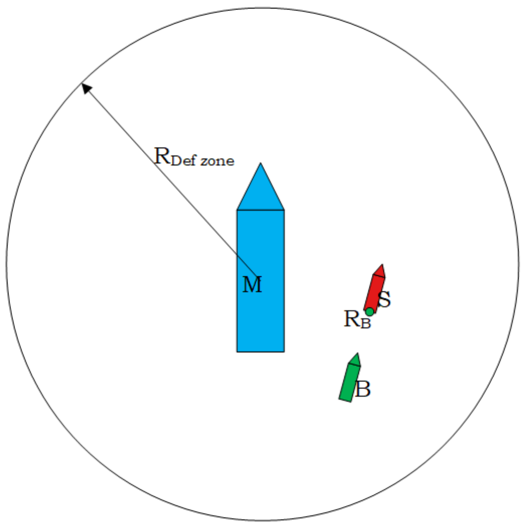


Figure A-5: Beagle battering ram: State 4

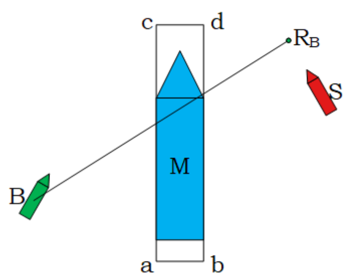


Figure A-6: Beagle battering ram: State 0

A-2 Pirate state machines

Now that the Beagle state machines are explained the four pirate state machines will be explained.

A-2-1 Board merchant vessel

In Figure A-7 the state diagram of a pirate trying to board the merchant vessel is shown. In Figures A-13, A-14, A-10 and A-11 the states corresponding this state diagram are shown.

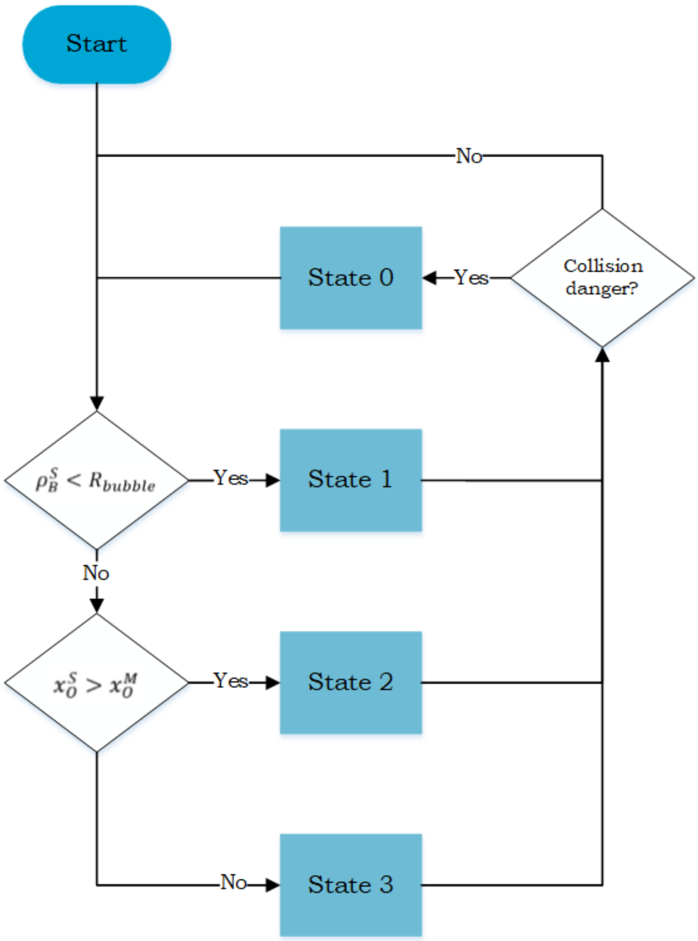


Figure A-7: State diagram board merchant vessel

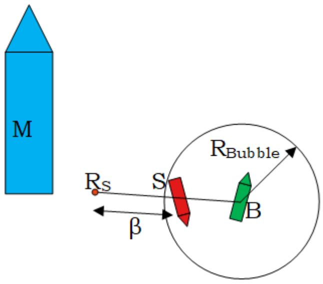


Figure A-8: Boarding merchant vessel: State 1

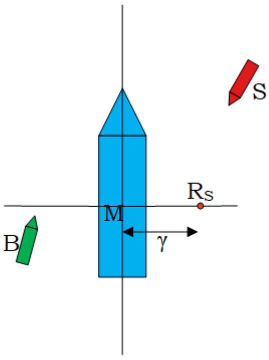


Figure A-9: Boarding merchant vessel: State 2

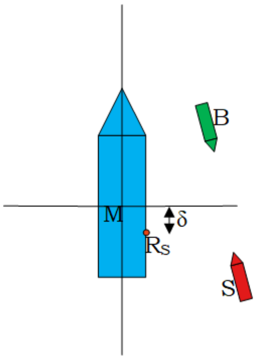


Figure A-10: Boarding merchant vessel: State 3

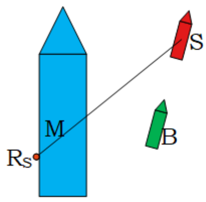


Figure A-11: Boarding merchant vessel: State 0

A-2-2 Fire RPG at merchant vessel

In Figure A-12 the state diagram of a pirate trying to fire a Rocket Propelled Grenade (RPG) at the merchant vessel is shown. In Figures A-13, A-14, A-10 and A-11 the states corresponding this state diagram are shown.

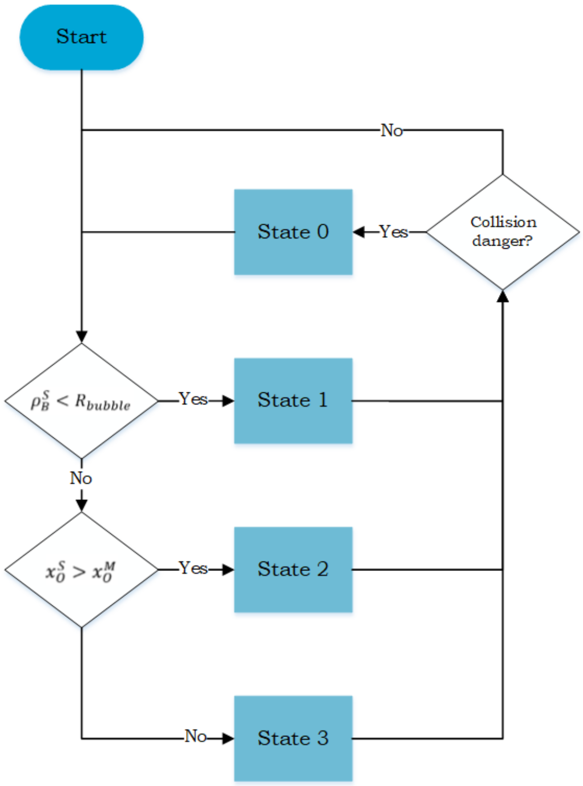


Figure A-12: State diagram fire RPG at merchant vessel

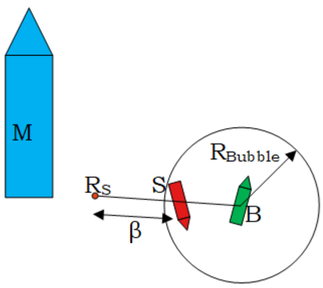


Figure A-13: Fire RPG at merchant vessel: State 1

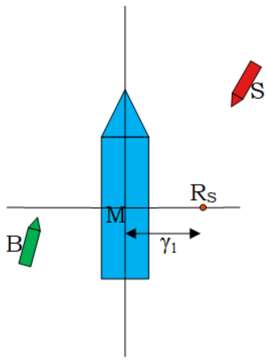


Figure A-14: Fire RPG at merchant vessel: State 2

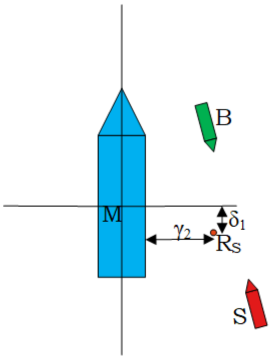


Figure A-15: Fire RPG at merchant vessel: State 3

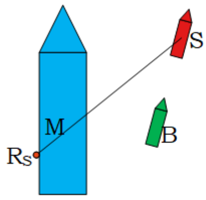


Figure A-16: Fire RPG at merchant vessel: State 0

A-2-3 Wreck Beagle

In Figure A-17 the state diagram of a pirate trying to board the merchant vessel is shown. In Figures A-18, A-19 and A-20 the states corresponding this state diagram are shown.

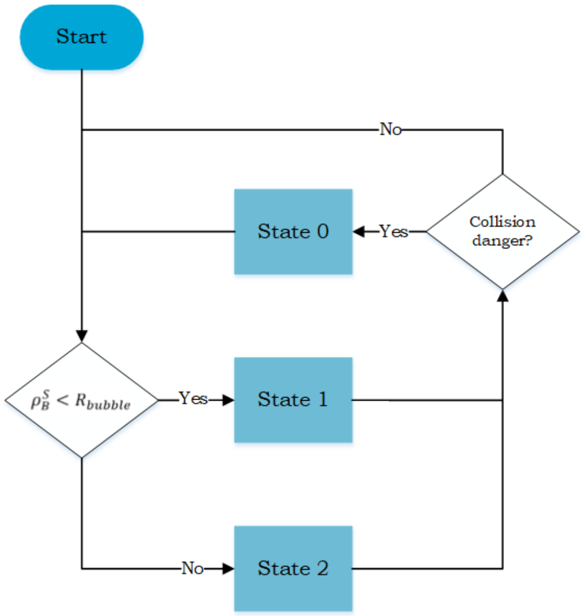


Figure A-17: State diagram wreck Beagle

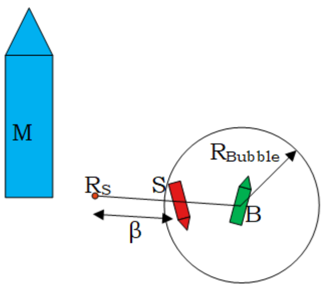


Figure A-18: Wreck Beagle: State 1

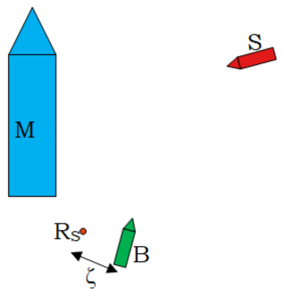


Figure A-19: Wreck Beagle: State 2

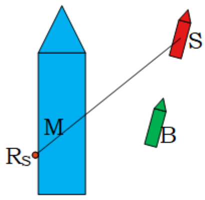


Figure A-20: Wreck Beagle: State 0

A-2-4 Board Beagle

In Figure A-21 the state diagram of a pirate trying to board the merchant vessel is shown. In Figures A-22, A-23 and A-24 the states corresponding this state diagram are shown.

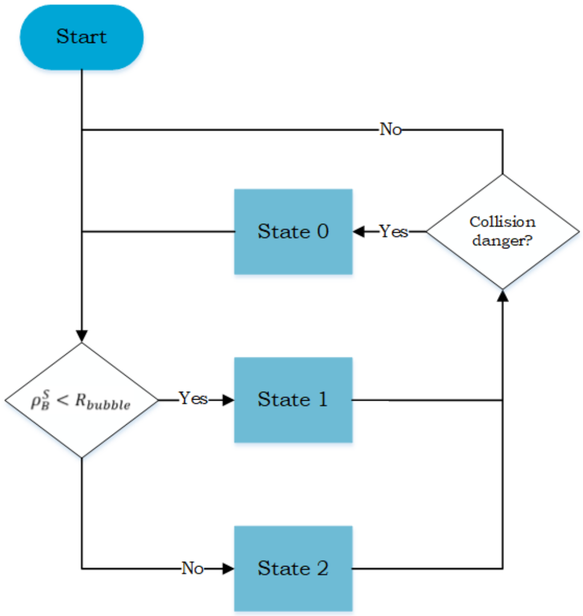


Figure A-21: State diagram board Beagle

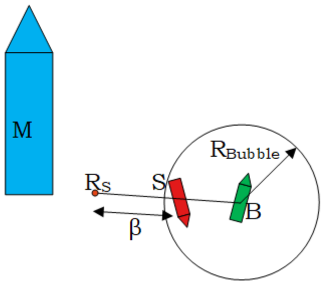


Figure A-22: Board Beagle: State 1

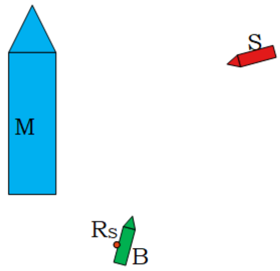


Figure A-23: Board Beagle: State 2

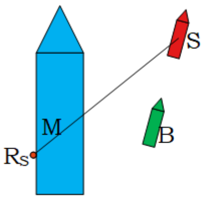


Figure A-24: Wreck Beagle: State 0

A-3 Decision model constants

These are the values of the variables shown in Sections A-1 and A-2.

Table A-1: Overview of decision model constants

Constant	Unit	Value
β	[m]	60
γ	[m]	100
γ_1	[m]	100
γ_2	[m]	80
δ	[m]	20
δ_1	[m]	20
ϵ	[deg]	1
ϕ	[m]	20
ζ	[m]	40

Appendix B

Ship equations of motion

In this appendix the ship equations of motions are elaborated. The ship equations of motions can be divided into three groups:

1. Propulsion forces
2. Hull forces
3. Inertia forces

The inertia forces are equal to the hull forces and the propulsion forces added:

$$\begin{bmatrix} X_{in} \\ Y_{in} \\ N_{in} \end{bmatrix} = \begin{bmatrix} X_{hull} + X_{prop} \\ Y_{hull} + Y_{prop} \\ N_{hull} + N_{prop} \end{bmatrix}. \tag{B-1}$$

1. Propulsion forces

The propulsion forces are explained in Section 6-3. The thrust direction is a function of the thrust (T) and the waterjet steering angle (α):

$$\begin{bmatrix} X_{prop} \\ Y_{prop} \\ N_{prop} \end{bmatrix} = \begin{bmatrix} T\cos(\alpha) \\ T\sin(\alpha) \\ T\sin(\alpha)LCG \end{bmatrix}. \tag{B-2}$$

2. Hull forces

The hull forces are described with the Abkowitz model:

$$\begin{bmatrix} X_{hull} \\ Y_{hull} \\ N_{hull} \end{bmatrix} = \begin{bmatrix} X_{uu}u^2 + X_{vv}v^2 + X_{rr}r^2 + X_{uv}u|v| + X_{ur}u|r| + X_{vr}vr + X_{\dot{u}}\dot{u} \\ Y_{vv}v|v| + Y_{rr}r|r| + Y_{uv}uv + Y_{ur}ur + Y_{vr}v|r| + Y_{rv}r|v| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} \\ N_{rr}r|r| + N_{vv}v|v| + N_{uv}uv + N_{ur}ur + N_{vr}v|r| + N_{rv}r|v| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + Y_{hull}r_a \end{bmatrix}. \tag{B-3}$$

However, the following of these variables are negligible, [40].

- Because of the x-symmetry of the ship X_{uv} X_{ur} are 0.
- Since the velocities (v) and (r) are small Y_{rr} Y_{vr} Y_{ur} Y_{rv} and N_{vv} N_{vr} N_{rv} are negligible.

$Y_{hull}r_a$ is an extra moment introduced on the vessel due to the fact that the underwater forces work on the back side of the vessel. r_a is the distance between Length Centre of Gravity (LCG) and the aerodynamic center of the underwater vessel. For delta wings, this is usually located behind the center of gravity of the wing. As seen from the stern this is located at $0.25L_{wl}$.

A turning test have been done where residual Abkowitz coefficients have been left out one by one systematically. In each test at least one of the results, maximum speed and turning circle radius, changed significantly. From this, one can conclude that all residual Abkowitz coefficients are necessary for a realistic and stable maneuvering model.

3. Inertia forces
In the left side of the equations of motion contains the inertia forces, for the three degrees of freedom (surge, sway and yaw). They can be describes as:

$$\begin{bmatrix} X_{in} \\ Y_{in} \\ N_{in} \end{bmatrix} = \begin{bmatrix} m(\dot{u} - vr - X_g r^2) \\ m(\dot{v} + ur + X_g \dot{r}) \\ I_{zz}\dot{r} + m x_G(\dot{v} + ur) \end{bmatrix}. \tag{B-4}$$

Final equations of motion
The final implicit equations of motion are:

$$\begin{bmatrix} m(\dot{u} - vr - x_g r^2) \\ m(\dot{v} + ur + x_g \dot{r}) \\ I_{zz}\dot{r} + m x_g(\dot{v} + ru) \end{bmatrix} = \begin{bmatrix} X_{uu}u^2 + X_{vv}vv + X_{rr}rr + X_{vr}vr + X_{\dot{u}}\dot{u} + T\cos(\alpha) \\ Y_{vv}v|v| + Y_{uv}uv + Y_{ur}ur + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + T\sin(\alpha) \\ N_{rr}r|r| + N_{uv}uv + N_{ur}ur + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + Y_{hull}r_a + T\sin(\alpha)\mathrm{LCG} \end{bmatrix}. \tag{B-5}$$

Those implicit equations of motions can not be solved yet, all the accelerations will be written in the left side of the equation and the rest will be written in the right side:

$$\begin{bmatrix} (m - X_{\dot{u}})\dot{u} \\ (m - Y_{\dot{v}})\dot{v} + (m x_G - Y_{\dot{r}})\dot{r} \\ (m x_G - N_{\dot{v}})\dot{v} + (I_{zz} - N_{\dot{r}})\dot{r} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}. \tag{B-6}$$

With,

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} X_{uu}u^2 + X_{vr}vr + T\cos(\alpha) + mvr + m x_G r^2 \\ Y_{vv}v|v| + Y_{uv}uv + Y_{ur}ur + T\sin(\alpha) - mur \\ N_{rr}r|r| + N_{vv}v|v| + N_{uv}uv + N_{ur}ur + T\sin(\alpha)LCF - m x_G ru \end{bmatrix}. \tag{B-7}$$

The explicit acceleration terms are:

$$\dot{u} = \frac{f_1}{m - X_{\dot{u}}},$$
$$\dot{v} = \frac{(I_{zz} - N_{\dot{r}})f_2 - (mx_G - Y_{\dot{r}})f_3}{(m - Y_{\dot{v}})(I_{zz} - N_{\dot{r}}) - (mx_G - Y_{\dot{r}})(mx_G - N_{\dot{v}})}, \tag{B-8}$$

and

$$\dot{r} = \frac{(m - Y_{\dot{v}})f_3 - (m - N_{\dot{v}})f_2}{(m - Y_{\dot{v}})(I_{zz} - N_{\dot{r}}) - (mx_G - Y_{\dot{r}})(mx_g - N_{\dot{v}})}. \tag{B-9}$$

Integrating those will result in the local speeds, u, v and r. To obtain the global displacement (C_O^B) from the local speeds the following transformation has been applied:

$$C_O^B = \begin{bmatrix} x_O^B \\ y_O^B \\ \psi_O^B \end{bmatrix} = \begin{bmatrix} \int (u \ \cos(\int r \ dt) - v \ \sin(\int r \ dt)) \ dt \\ \int (u \ \sin(\int r \ dt) + v \ \cos(\int r \ dt)) \ dt \\ \int r \ dt \end{bmatrix}. \tag{B-10}$$

Appendix C

Coefficients of the Abkowitz model

In this appendix the coefficients that are used in the Abkowitz model are explained. The coefficients are from the Principle of Naval Architecture part 3, [33] and a function of L_{wl}, B_{max}, T and trim (t). The unknown coefficients are:

X_{uu}, X_{vv}, X_{rr}, $X_{\dot{u}}$, X_{vr}, Y_{vv}, Y_{uv}, Y_{ur}, $Y_{\dot{v}}$, $Y_{\dot{r}}$, N_{rr}, N_{vv}, N_{uv}, N_{ur}, $N_{\dot{v}}$ and $N_{\dot{r}}$.

X_{uu} is the resistance component in x direction, Savitsky's method is used to obtain this coefficient, it can be found in appendix D. $X_{\dot{u}}$ is not explained by, [33]. According to [41] distinction should be made between the added mass in surge for planing and non-planing modes. For the non-planing area the added mass will be around 50 percent of the total mass of the vessel, due to the large trim a lot of water is displaced at the stern of the ship during this non-planing area. In the planing areas the added mass for surge is far less and around 10 percent. The other coefficients are determined according the follow formulas:

$$X_{vr} = -\frac{2Y_{uv}Y_{ur}}{\frac{1}{2}\rho\pi T^2}, \tag{C-1}$$

$$X_{rr} = -\frac{Y_{ur}^2}{\frac{1}{2}\rho\pi T^2}, \tag{C-2}$$

$$X_{vv} = -\frac{Y_{uv}^2}{\frac{1}{2}\rho\pi T^2}, \tag{C-3}$$

$$Y_{vv} = \frac{1}{2}c_D L_{wl} T, \tag{C-4}$$

$$Y_{uv} = \frac{\rho}{2}L_{wl}^2 Y_v'(t), \tag{C-5}$$

$$Y_{ur} = \frac{\rho}{2} L_{wl}^3 Y_r'(t), \tag{C-6}$$

$$N_{rr} = \frac{c_D T \rho L_{wl}^4}{64}, \tag{C-7}$$

$$N_{uv} = \frac{\rho}{2} L_{wl}^3 N_v'(t) \tag{C-8}$$

and

$$N_{ur} = \frac{\rho}{2} L_{wl}^4 N_r'(t). \tag{C-9}$$

With:

$$\begin{aligned} Y_v'(0) &= -\pi(\frac{T}{L_{wl}})^2(1 + 0.4 c_b \frac{B}{T}), \\ Y_r'(0) &= -\pi(\frac{T}{L_{wl}})^2(-0.5 + 2.2\frac{B}{L} - 0.08\frac{B}{T}), \\ N_v'(0) &= -\pi(\frac{T}{L_{wl}})^2(0.5 + 2.40\frac{T}{L}, \end{aligned} \tag{C-10}$$

and

$$N_r'(0) = -\pi(\frac{T}{L_{wl}})^2(0.25 + 0.039\frac{B}{T} - 0.56\frac{B}{L}). \tag{C-11}$$

When a trim is present and defined as:

$$t = T_{ap} - T_{fp}, \tag{C-12}$$

than the correction according to Inoue and Kijima are:

$$\begin{aligned} Y_v'(t) &= Y_v'(0)(1 + 0.67\frac{t}{T}), \\ Y_r'(t) &= Y_r'(0)(1 + 0.80\frac{t}{T}), \\ N_v'(t) &= N_v'(0)(1 - 0.27\frac{t}{T}\frac{Y_v'(0)}{N_v'(0)}), \end{aligned} \tag{C-13}$$

and

$$N_r'(t) = N_r'(0)(1 + 0.30\frac{t}{T}). \tag{C-14}$$

Finally, the added mass coefficients are:

$$\begin{aligned} Y_{\dot{v}} &= \frac{\rho}{2} L^3 Y_{\dot{v}'}, \\ Y_{\dot{r}} &= \frac{\rho}{2} L^4 Y_{\dot{r}'}, \\ N_{\dot{v}} &= \frac{\rho}{2} L^4 N_{\dot{v}'} \end{aligned} \tag{C-15}$$

and

$$N_{\dot{r}} = \frac{\rho}{2} L^5 N_{\dot{r}'}. \tag{C-16}$$

With:

$$\begin{aligned}
Y_{\dot{v}'} &= -\pi(\frac{T}{L_{wl}})^2(1 + 0.16c_b\frac{B}{T} - 5.1(\frac{B}{L})^2), \\
Y_{\dot{r}'} &= -\pi(\frac{T}{L_{wl}})^2(0.67\frac{B}{L} - 0.0033\frac{B}{T}), \\
N_{\dot{v}'} &= -\pi(\frac{T}{L_{wl}})^2(1.1\frac{B}{L_{wl}} - 0.041\frac{B}{T}
\end{aligned} \tag{C-17}$$

and

$$N_{\dot{r}'} = -\pi(\frac{T}{L_{wl}})^2(\frac{1}{12} + 0.017c_b\frac{B}{T} - 0.33\frac{B}{L}). \tag{C-18}$$

Appendix D

Savitsky's method

Savitsky's method uses basic ship parameters to make an estimation of the resistance and underwater hull form of a planing vessel. It is used to get insights on the resistance (R) and the change of the design parameters required for the Abkowitz model coefficients (L_{wl}, B_{max}, T and t) as a function of ship speed (u), [34]. Palfinger marine provided the input variables necessary for Savitsky's method (L_{oa}, B_{max}, β, Δ, f, ϵ, LCG and VCG). The Savitsky input parameters are, [1]:

Table D-1: Savitsky input variables

B [m]	β [deg]	[ton]	f [m]	ϵ [deg]	LCG [m]	VCG [m]
3	25	4.8	0.5	5	3.2	1

The output variables (L_{wl}, T, t, r_a, and $R/X_{uu}u^2$) are shown in Figures D-1, D-2, D-3a and D-3b. In Figure D-1 the resistance at maximum capacity is shown. Also, the resistance prediction of Palfinger is shown. This validates the correct use of Savitsky's method.

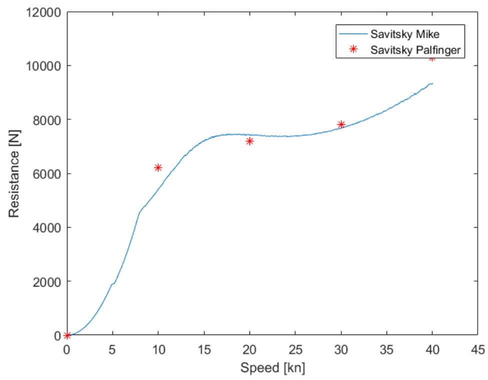


Figure D-1: Resistance determined with Savitsky and Maxsurf

In Figure D-2 the trim of the vessel is shown as a function of the speed. It shows exactly the kind of behaviour one would expect from a small planing vessel. At zero speed it has a certain positive trim. When accelerating the trim will grow. It will grow until the semi-planing starts. In this case this is around 6 meters per second or Froude number 0.7. After this hump the vessel will straighten again and the trim will drop significantly, although it will stay positive.

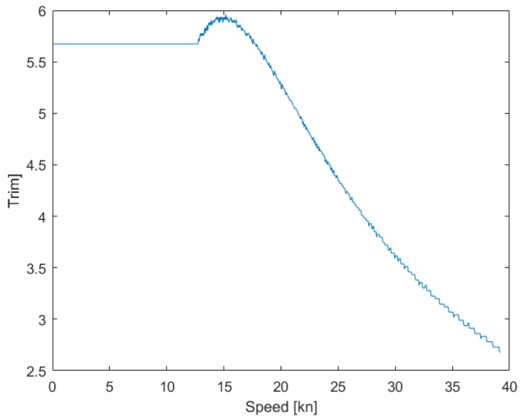
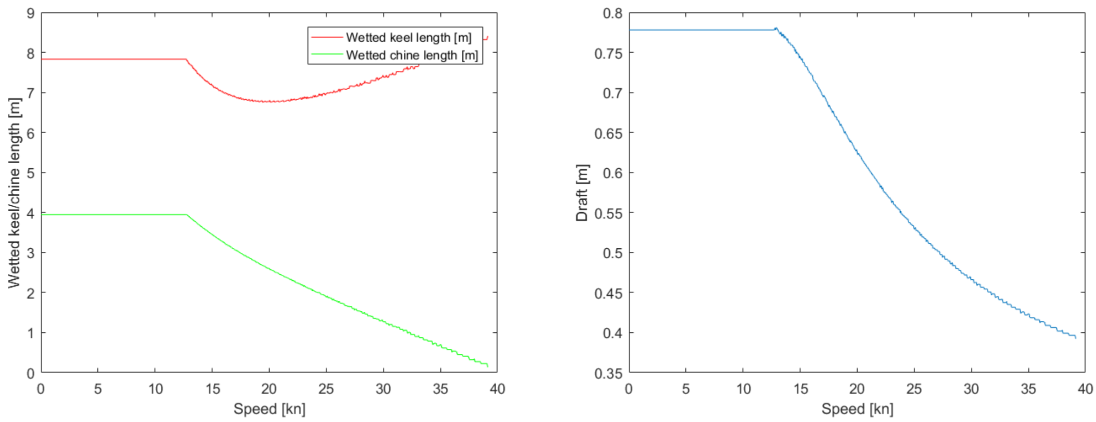


Figure D-2: Trim as a function of speed

In Figures D-3a and D-3b the result of this trim is shown. Because of the trim the length of the waterline (L_{wl}) will decrease. After the trim hump the length of the waterline (L_{wl}) will again increase and the draft (T) will decrease. The draft (T) will decrease more than the original draft at zero speed. At this point the vessel is lifting out of the water.



(a) L_{wl} as a function of speed

(b) Draft as a function of speed

Figure D-3: Savitsky's results

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Glossary

List of Acronyms

BMP4 Best Management Practices for Protection against Somalia Based Piracy

CB Constant Bearing

FRC Fast Rescue Craft

ICC International Chamber of Commerce

IMB International Maritime Bureau

KPI Key Performance Indicator

KPIs Key Performance Indicators

LCG Length Centre of Gravity

LOS Line-Of-Sight

LRAD Long-Range Acoustic Device

LRADs Long-Range Acoustic Devices

MDS Mobility Denial System

PMSC Private Maritime Security Contractors

PP Pure Pursuit

RPG Rocket Propelled Grenade

RPGs Rocket Propelled Grenades

RPS Revolutions Per Second

VCG Vertical Centre of Gravity

List of Symbols

A_{nozzle}	[m^2]	Nozzle area
B	[m]	Beam of a vessel
C_b	[-]	Block coefficient
C_D	[-]	Draft coefficient
C_S^M	[-]	Skiff decision factor
c_θ	[-]	Steering angle controller input constant
D	[-]	Derivative gain
f	[m]	Length between thrust and VCG
g	[m/s^2]	Gravitational constant
h_j	[m]	Nozzle elevation above the waterline
H	[m]	Pump head
i	[-]	Number of cylinders
i_{gb}	[-]	Gearbox ratio
I_{TRM}	[kg m^2]	Transmission system mass moment of inertia
I_{zz}	[kg m^2]	Mass moment of inertia
J	[-]	Advanced velocity
k	[-]	Engine type, k = 1 for 2-stroke engine | k = 2 for 4-stroke engine
K_M	[-]	Waterjet dimensionless torque coefficient
LCG	[m]	Length centre of gravity
LHV	[J/kg]	Lower heating value
L_{wl}	[m]	Length waterline of a vessel
m	[kg]	Ships mass
M_B	[Nm]	Brake torque
M_P	[Nm]	Impeller torque
M_f	[kg]	Mass of fuel (per cylinder and per cycle)
M_{fnom}	[kg]	Nominal mass of fuel (per cylinder and per cycle)
n_e	[omw/s]	Engine RPS
n_p	[omw/s]	Waterjet RPS
n_ω	[-]	Specific pump speed
P	[-]	Proportional gain
P_B	[W]	Brake power
P_P	[W]	Impeller power

Q	[m^3/s]	Volume flow rate through the waterjet
r	[rad/s]	Speed of a vessel in yaw direction
r_a	[m]	Shifting of LCF as a function of speed
R	[N]	Resistance of a ship
R_{AK}	[m]	Range in which Kalashnikov is still effective
R_{bubble}	[m]	Radius of the bubble around the Beagle
$R_{def\ zone}$	[m]	Defense zone radius
t_{bubble}	[s]	Time skiff needs to be in the bubble to be dismantled
t	[m]	Trim of a vessel
T	[m]	Draft of a vessel
T	[N]	Thrust generated by the waterjet
T_{ap}	[m]	Draft aft perpendicular of a vessel
T_{fp}	[m]	Draft front perpendicular of a vessel
u	[m/s]	Speed of a vessel in x direction
v	[m/s]	Speed of a vessel in y direction
v_{in}	[m/s]	Mass averaged ingested velocity at duct inlet
v_{out}	[m/s]	Mass averaged outlet velocity at the nozzle
VCG	[m]	Vertical centre of gravity
w	[-]	Wake factor
X_{set}	[-]	Position of the throttle
x_G	[m]	Distance centre of gravity to mid ship
α	[deg]	Waterjet steering angle
α	[m]	Distance used in the CB control
β	[deg]	Dead rise angle
β	[m]	Distance used in the LOS control
δ	[kg]	Ships displacement
ϵ	[-]	Waterjet inlet loss coefficient
ϵ	[deg]	Shaft inclination angle
η_e	[-]	Engine efficiency
η_{pump}	[-]	Waterjet efficiency
ρ_{sw}	[kg/m^3]	Density of sea water
ϕ	[-]	Waterjet nozzle loss coefficient