

The Future of Unmanned Naval Systems: An Overview Of Efficiency Enhancements and Warfare Upgrades for Maritime Drones

UNIVERSITY OF TURKU
Department of Computing
Master of Science in Technology Thesis
Robotics and Autonomous Systems
June 2025
Jere Leman

Supervisors:
Paavo Nevalainen

UNIVERSITY OF TURKU
Department of Computing

JERE LEMAN: The Future of Unmanned Naval Systems: An Overview Of Efficiency Enhancements and Warfare Upgrades for Maritime Drones

Master of Science in Technology Thesis, 75 p.
Robotics and Autonomous Systems
June 2025

The dramatic rise of tensions between various countries has been escalating since the larger-scale Russian invasion of Ukraine in 2022. At the same time, the robotics and autonomous systems fields are blooming with new inventions and technology for both civilian and military applications. Most of the existing autonomous systems are built on ground, air, or space platforms. However, in this thesis, maritime drones will be explored comprehensively to improve their efficiency and military aspects, considering that the field of marine robotics lags behind other robotics fields. The development of autonomous weapon systems is highly connected to the advancements in AI technology, which allows the fundamentals for such maritime drone systems. The two largest competitors, the United States of America and China, bolster billions annually to fund research and development of maritime drones. However, Ukraine and its innovative solutions offer more concrete use cases and developments that have come to the public's attention during their asymmetric warfare against Russia. Ukraine has effectively defended its territorial waters using maritime drones alongside its much smaller navy compared to the Russian naval fleet.

The reasoning for this thesis is to address three research questions:

- 1. What are the strategic and tactical implications of maritime drones in modern warfare?**
- 2. How can maritime drones be optimized and equipped better?**
- 3. What are the ethical and environmental considerations surrounding the deployment of maritime drones? And what kind of regulatory measures have been set for maritime drones?**

The thesis will present various maritime drones and their properties. Additionally, it will feature a maritime drone developed in collaboration with the Finnish National Defence University, the University of Turku, and the Turku University of Applied Sciences. The Meri-Turso is a maritime drone that improves efficiency and affordability through innovative design. The role of naval drones in modern warfare will be examined through an analysis of current conflicts.

Keywords: Maritime, Naval, USV, UUV, Autonomous Weapon Systems, Warfare

0.1 Acknowledgement

I express my gratitude to my thesis supervisor, **Paavo Nevalainen**, my internship supervisor, **Tomi Westerlund**, and my colleagues for allowing me to work with the type of technology I am genuinely interested in. I value the opportunity to showcase my skills and fully participate in the development of these systems for future use. Working with the **TIERS (Turku Intelligent Embedded and Robotic Systems)** team at the **University of Turku** provided hands-on experience that significantly deepened my understanding of robotics, autonomous systems, and the defense sector.

To note the use of artificial intelligence, Grammarly's AI has been used to proof-read and improve the thesis's grammar.

Contents

0.1	Acknowledgement	i
1	Introduction	1
1.1	Thesis Motivation	2
1.2	Thesis Research Questions	3
1.3	Thesis Objectives	4
1.4	Thesis Structure	5
2	Background and Theory	6
2.1	Terminology of Maritime Drones (USVs, UUVs, ROVs, etc.)	6
2.2	History of Unmanned Naval Systems	9
2.2.1	USVs - Unmanned Surface Vehicles	10
2.2.2	UUVs - Unmanned Underwater Vehicles	15
2.3	Current Applications Sectors	20
2.4	Maritime Drone Market	21
2.5	Technical Foundations	23
2.6	Maritime Drone Challenges	26
3	Evaluating and Developing Maritime Drones	29
3.1	Analyzing Efficiency Improvements	29
3.2	Key Performance Metrics	30
3.3	Tools, Models, and Frameworks Used in Development	32

4	Improving Military Maritime Drones	35
4.1	Energy Optimization and Advancements	35
4.2	Hydrodynamics and Design	36
4.3	AI and Hardware	42
4.4	Stealth Features and Communications	43
4.4.1	Stealth Technologies	44
4.4.2	Communication Security and Innovation	47
5	Maritime Drones in Modern Warfare	50
5.1	The Black Sea: Russo-Ukraine War	50
5.2	The Gray Zone: The Red Sea, Persian Gulf, and the Israel–Gaza Conflict	54
5.3	South and East China Sea: The Brewing Storm Between The U.S, China, and Taiwan	58
6	Results	61
6.1	Strategic Implications	61
6.2	Tactical Implications	63
6.3	Emerging Technologies and Improvements	64
6.4	Ethical and Environmental Concerns	66
6.5	Policy and Regulatory Considerations	68
6.5.1	European Union	69
6.5.2	National-Level Regulations	70
7	Conclusion	73
7.1	Summary	73
7.2	Future Work	74
	References	76

List of Figures

2.1	Unmanned surface vehicle classes defined by NAVSEA. [11]	8
2.2	Unmanned underwater vehicle classes defined by NAVSEA. [11]	9
2.3	The first USV, Fernlenkboot, developed by the German Imperial Navy. [5]	11
2.4	The Protector USV on display at the National Museum of Singapore in February 2014. [14]	12
2.5	The U.S. Navy’s Sea Hunter USV, developed by Vigor Industries. [15]	13
2.6	Ukraine’s first USV, the Mykola. [18]	14
2.7	Marlin, the first electronic warfare maritime drone. [16]	14
2.8	The first UUV, SPURV (1957), developed by the University of Washington. [21]	16
2.9	NMRS system developed by the U.S. Navy. [22]	17
2.10	The REMUS 100 UUV, used by the Finnish Navy, on display in Turku, 2016. [24]	18
2.11	The Toloka-TLK150 UUV, developed by Brave1. [18]	19
2.12	Copperhead UUVs, developed by Anduril Industries. [26]	20
2.13	Projected growth of the global unmanned marine vehicles market. [27]	22
2.14	Key end-use segments in the unmanned marine vehicles market. [27]	22
2.15	Navigation pipelines examples from the Rolls-Royce AAWA report. [35]	26

4.1	Side profile of the Wave Rider drone. [40]	37
4.2	The Manta Ray drone as seen in Google Earth satellite imagery. [41]	38
4.3	The Manta Ray during testing in 2024. [25]	39
4.4	The world's first hybrid drone, Triton. [42]	40
4.5	From left: Petteri Hemminki, Walteri Soininen, and Lauri Vasankari presenting the Meri-Turso maritime drone board at the MPKK. [43]	41
4.6	The Meri-Turso maritime drone prototype presented at the SecD-day by Cpt. Jan Joutsu. [44]	42
4.7	BAE Systems' Adaptiv camouflage system rendered on a warship. [46]	45
4.8	Taiwan's first military maritime drone. [49]	47
4.9	6G Maritime relay network concept. [52]	49
5.1	Known Russian maritime drones used in the Black-Sea. [56]	51
5.2	Known Ukrainian maritime drones used in the Black-Sea. [56]	52
5.3	Damage inflicted to the Kerch Bridge by a Ukrainian maritime drone. [57]	52
5.4	Ukrainian maritime drone during an attack on Olenegorsky Gornyak. [55]	53
5.5	Drone attacks in Ukraine during 2022-2023. [37]	54
5.6	Known maritime drones used by the Houthis. [60]	56
5.7	The Blue Whale UUV, developed by Israeli Elta Systems. [61]	57
5.8	Successful Houthi attack on the Greek tanker MV Tutor, June 12, 2024 [6]	57
5.9	Chinese military maritime activity during the August 2022 drill. [64]	59
6.1	Ukraine's maritime drone, the Katran Venom. [65]	65

List of Tables

3.1	Key performance metrics for maritime drones.	31
3.2	Comparison of simulators for maritime robotics.	34

1 Introduction

We have entered the beginning stages of the *age of autonomous warfare*, and no end is in sight. The Russo-Ukrainian war is an excellent example of how these weapons perform in real-life use cases in the modern era. The Russo-Ukrainian war has been a pivotal testing field for such systems and their development. Large private robotics companies are deploying their products to Ukraine for experiments on actual humans and enemy systems. Autonomous weapon systems are gathering large amounts of data to improve their capabilities for potential future conflicts. We have already seen the first fully unmanned multi-robot attack on Ukrainian soil and many unmanned drones fighting against each other [1]. Ukraine's Minister of Digital Transformation, Mykhailo Fedorov, announced on May 29, 2025, that Ukraine paved the way for fully autonomous strikes by conducting the first-ever fully autonomous aerial drone attack [2]. Autonomous warfare will become a reality.

The field of autonomous drones has been growing staggeringly in research and development. The required technology behind these systems has been available for a long time. However, these have only gained popularity recently, primarily driven by advancements in artificial intelligence and sensor technology.

This thesis explores the field of maritime drones, which are categorized based on their operating environments or capabilities. The two main categories are **Unmanned Surface Vehicles (USVs)** and **Unmanned Underwater Vehicles (UUVs)**. Chapter 2 provides a more detailed discussion of these terms and other

categorizations.

Maritime drones have transformed modern naval warfare by providing capabilities such as logistics, intelligence, surveillance, reconnaissance, mine detection, mine laying, anti-submarine warfare, and even offensive operations.

The challenges these types of drones have generated for the field have exploded in quantity. They must navigate complex and harsh marine environments, support long operational endurance, and function with minimal human intervention. However, technological constraints such as power limitations, communication challenges, and security vulnerabilities can hinder their full potential.

We can see from history that these systems date back to World War I. However, the systems back then were not autonomous; they were remote-controlled. The development of advanced autonomous maritime drones gained increased popularity in the late 20th century. [3], [4] The recent conflicts between Russia and Ukraine, as well as those between the Houthis and coalition forces, demonstrate how these systems can significantly influence **asymmetric warfare**. [5], [6] Asymmetric warfare means that one belligerent of the war is less equipped than the other. However, this does not imply that they cannot be used in **symmetric warfare** where the opposing forces are nearly equal in military power.

1.1 Thesis Motivation

Maritime drones play an important role in modern warfare, and their significance is becoming clearer as we witness advancements in their development and their ability to operate effectively in various scenarios, like in the cases of the Black Sea, the Red Sea, and the East and South China Seas. A key point to understand is that maritime drones are used in many fields, which means there are various use cases beyond military applications, including research, security, transportation, and other commercial applications. Their ability to operate in the harsh marine environment makes them

perfect for these use cases. Despite the recent advancements in the maritime drone field, there are remaining challenges in areas such as navigation, endurance, sensor integration, and real-time data processing, which limit their full potential. While a lot of research has been conducted mainly on aerial and ground drones, these maritime drones present unique technological and operational challenges due to their complex underwater and surface conditions.

My interest in these types of systems comes from both academic and practical experience in this field. My bachelor's thesis, *Tekoälyavusteiset asejärjestelmät nykyaikaisessa sodankäynnissä*, or *AI-assisted weapon systems in modern warfare* in English, was an overview of all types of **Lethal Autonomous Weapon Systems (LAWS)** in modern warfare [7]. In this thesis, I decided to focus exclusively on maritime drones. Additionally, my role as a reserve officer and my interest in **Open-Source Intelligence (OSINT)** have led me to research the operational needs of maritime drones for the defense sector. Overall, all of these experiences have shaped my motivation to explore innovative solutions that can bridge the existing technological gaps related to maritime drones.

1.2 Thesis Research Questions

This thesis will answer three research questions on maritime drones, which are:

1. **What are the strategic and tactical implications of maritime drones in modern warfare?**
2. **How can maritime drones be optimized and equipped better?**
3. **What are the ethical and environmental considerations surrounding the deployment of maritime drones? And what kind of regulatory measures have been set for maritime drones?**

These research questions are necessary for defining the scope of the thesis. These questions will serve as a guide for both the theoretical and the practical exploration of the topic. The primary goal of this thesis is to understand the implications that maritime drones have on the nature of modern warfare. This thesis aims to contribute to the development of maritime drone systems that are more effective, efficient, and ethically responsible, with benefits for both military and civilian applications.

1.3 Thesis Objectives

The main objectives of the thesis are:

1. Investigate the underlying technologies, systems, and processes involved in maritime drone design, development, and deployment to deepen understanding of them.
2. Study the use cases and influence of maritime drones currently used across several sectors, including scientific, industrial, commercial, defense, and war, but keep the main focus on warfare.
3. Explore potential improvements and changes in the design, efficiency, and operational standards of maritime drones. Propose recommendations that could contribute to more sustainable, affordable, and scalable solutions.
4. Provide a foundation for future studies by giving an overview of the current situation, identifying current challenges, and recommending areas where further research and innovation could advance the field of maritime drone technology.

1.4 Thesis Structure

In this thesis, maritime drones, including USVs and UUVs, will be examined. The focus will be on how these technologies have reshaped modern warfare, illustrated through real-world case studies.

In Chapter 2, the technical properties for developing maritime drones, a historical overview of their origins, and the terminology surrounding them will be explained. Furthermore, it introduces the current challenges of maritime drones, the global market, and their application fields.

In Chapter 3, approaches to evaluating maritime drones, considering features like energy efficiency, lifespan, cost, and performance, will be explored. It will also review tools, models, and frameworks used in developing maritime drones.

In Chapter 4, an overview of how maritime drones can be improved through energy optimization, hydrodynamics, artificial intelligence, stealth features, and communication systems will be provided. This will be achieved mainly by comparing different innovative maritime drones.

In Chapter 5, the use of maritime drones in modern warfare will be analyzed by looking at ongoing conflicts worldwide. It will showcase the impact of them on enemy assets, trade routes, and the rising tensions between nations.

In Chapter 6, the research questions set for the thesis will be answered. The chapter will discuss the strategic and tactical impacts of maritime drones on modern warfare, efficiency improvements and combat enhancements, ethical and environmental issues, and regulatory measures such as the Geneva Convention, EU regulations, and national laws.

In Chapter 7, the thesis will be concluded by summarizing the work done and providing recommendations and final thoughts on future research, military applications, and the role of unmanned naval systems.

2 Background and Theory

This chapter will cover the fundamentals of maritime drones, exploring their origins, various use cases, and the challenges associated with their development. Discuss the environmental factors that contribute to these challenges. Moreover, the chapter will examine the core technologies that enable the creation of naval maritime drones.

2.1 Terminology of Maritime Drones (USVs, UUVs, ROVs, etc.)

Surrounding terminology of maritime drones can quickly become confusing due to the various terms available. However, the main two categories are **Unmanned Surface Vehicles (USVs)** and **Unmanned Underwater Vehicles (UUVs)**. The term *autonomous* can also be used instead of *unmanned*, leading to designations such as **Autonomous Underwater Vehicles (AUVs)** and **Autonomous Surface Vehicles (ASVs)**. *Autonomous* often implies that the vehicle possesses self-decision capability, whereas *unmanned* may suggest that it is primarily operated by a human but without an onboard crew. [3], [4]

Additionally, the term **Remotely Operated Vehicle (ROV)** is common in the marine field. This term can be preceded by different prefixes, such as **Remotely Operated Underwater Vehicle (ROUV)** or **Remotely Operated Surface Vehicle (ROSV)**. The prefix can also appear at the beginning, resulting in terms

like **UROV** or **SROV**. [4], [8]

NATO (North Atlantic Treaty Organization) has adopted the term **Maritime Unmanned Systems (MUS)** to cover all maritime-related drones in a single category. However, it is essential to note that MUS also includes aerial, ground, and space systems related to maritime operations. [9] The EDA (European Defence Agency) has used the term **Unmanned Marine Systems (UMS)**, also including air, sea, and space systems. [10]

Lastly, maritime drones can be categorized by both their mode of movement and their size. This includes classifications such as gliders, bio-inspired robots, and crawlers. Moreover, categorizing by size is widely used since drones can come in various sizes. The Naval Sea Systems Command (NAVSEA) has categorized USVs and UUVs into four classes by size, which can be seen in Figures 2.1 and 2.2 [11].

2.1 TERMINOLOGY OF MARITIME DRONES (USVS, UUVS, ROVS, ETC.)8

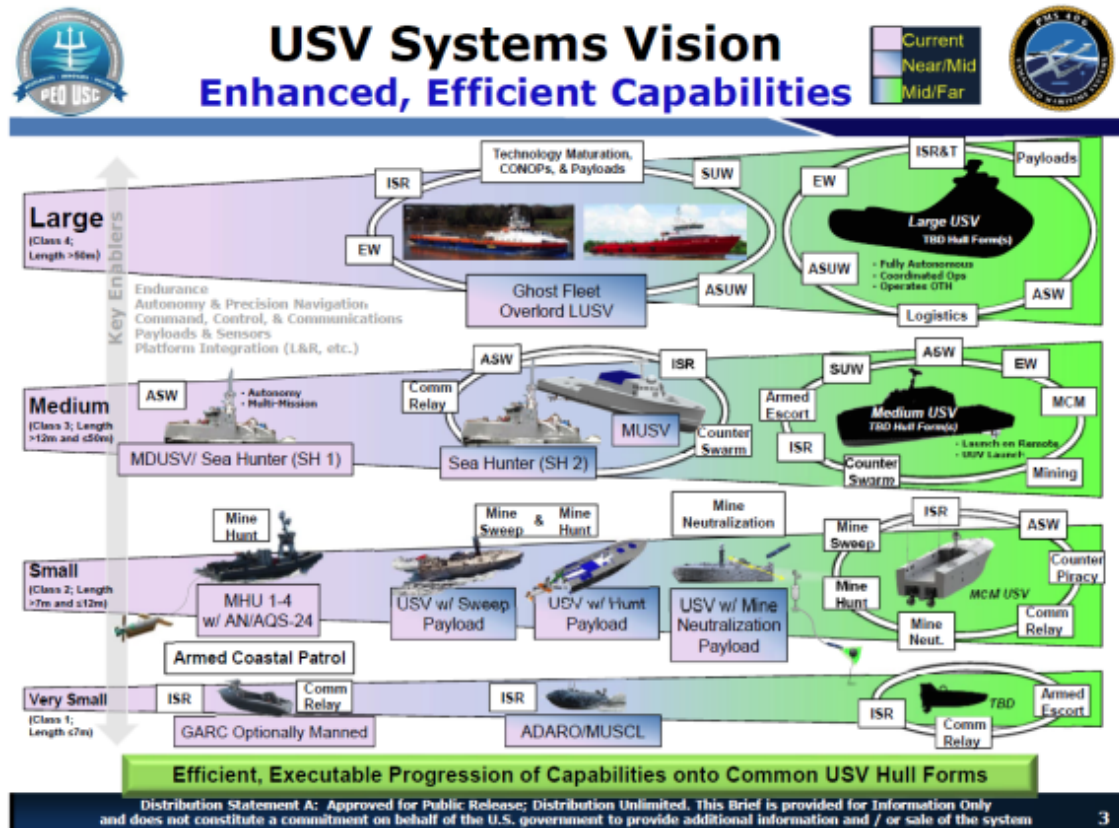


Figure 2.1: Unmanned surface vehicle classes defined by NAVSEA. [11]

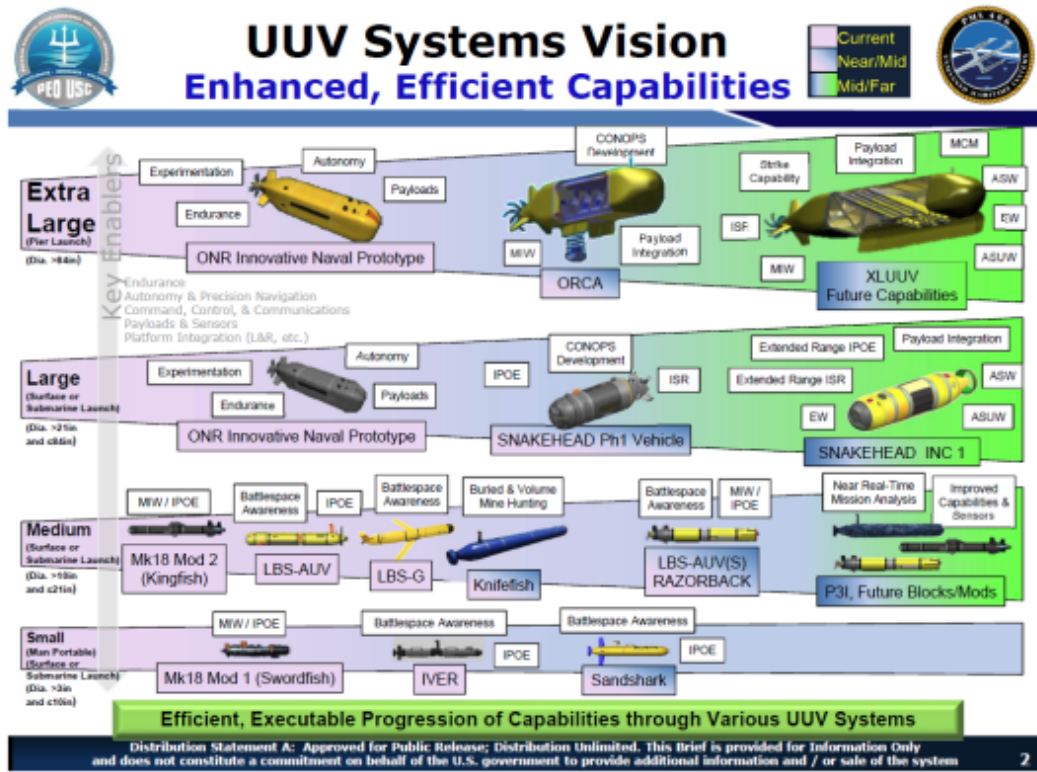


Figure 2.2: Unmanned underwater vehicle classes defined by NAVSEA. [11]

Given the multitude of terms, it is more beneficial to focus on the capabilities and specifications of each maritime drone rather than relying solely on the terminology. Some maritime drones are classified as hybrid drones, capable of operating on the surface, underwater, or even in the air. Additionally, maritime drones may have specific terminology beyond what has already been introduced here.

2.2 History of Unmanned Naval Systems

To make it clear, only maritime drones that were or are remotely controlled or autonomously operated will be covered here. The history of these systems date

back to World War I [5], which is quite impressive. Some have categorized human-operated explosive suicide boats as maritime drones [5]. However, in this thesis, they will not be covered. The same goes for ancient fireships that were lit and sent towards a target [3]. This thesis will focus primarily on military maritime drones.

2.2.1 USVs - Unmanned Surface Vehicles

The first military maritime drones were remote-controlled, and already in 1898, Nikola Tesla received a patent for a radio-controlled unmanned surface vehicle [12]. During World War I, remote-controlled boats carrying explosives were deployed in the English Channel. The German Imperial Navy developed its version, called the **Fernlenkboot**, as seen in Figure 2.3. At the same time, the British also experimented with radio-controlled attacks on German naval ports. The Ferlenkboot was not very successful during the war due to its limited range. Its 20-kilometer tether restricted the range, and it had delay problems with the remote control. However, despite these issues, it managed to strike two targets in 1917: the Nieuwpoort pier and the HMS Erebus monitor of the Royal Navy of the United Kingdom of Great Britain and Northern Ireland. Similar tactics continued in World War II. [5], [13]



Figure 2.3: The first USV, Fernlenkboot, developed by the German Imperial Navy. [5]

After World War I, the development of military-based USVs almost halted. Significant progress resumed in the early 2000s, notably in 2005 when Israel introduced the **Protector USV** for the coalition forces operating in the Persian Gulf. The Protector (see Figure 2.4) is built on a motorboat platform and is equipped with a lightweight machine gun. [14]



Figure 2.4: The Protector USV on display at the National Museum of Singapore in February 2014. [14]

In 2016, a serious step was taken by the Defense Advanced Research Projects Agency (DARPA) when they introduced the **Sea Hunter** (see Figure 2.5), an anti-submarine USV prototype, showing significant advancement in autonomous maritime technology. The Sea Hunter can operate for months and travel thousands of kilometers without any human involvement, making it fully autonomous. [15]



Figure 2.5: The U.S. Navy’s Sea Hunter USV, developed by Vigor Industries. [15]

In the 2020s, a lot of USV development from various parties started rapidly. In 2020, Turkey developed their first armed USV prototype, the **ULAQ** [3], and later in 2022, the world’s first-ever electronic warfare maritime drone, the **Marlin** (see Figure 2.7) [16]. Additionally, in 2022, Ukraine developed its first kamikaze maritime drones by introducing their first-generation USV, the **Mykola** (see Figure 2.6). In 2023, Russia developed its first kamikaze maritime drone, the **Oduvanchik**, or Dandelion in English, which has similar capabilities to the Ukrainian **SeaBaby** USV [17]. Ukraine has been developing kamikaze drones since the start of the larger-scale attack from Russia in 2022. Russia has used maritime drones far less frequently than Ukraine, despite having developed several of its own, since it is using more of its traditional naval vessels.



Figure 2.6: Ukraine's first USV, the Mykola. [18]



Figure 2.7: Marlin, the first electronic warfare maritime drone. [16]

Currently, there are hundreds of USVs developed by governments, militaries, private companies, hobbyists, and researchers for various applications.

2.2.2 UUVs - Unmanned Underwater Vehicles

The development of military unmanned underwater vehicles started later than USVs, with the **Self-Propelled Underwater Research Vehicle (SPURV)** by the University of Washington in 1957 to research the arctic waters. This drone could operate for four hours and was like a small-scale submarine. [4], [19] Figure 2.8 shows the SPURV. After the SPURV, similar projects continued to appear from various institutes. **The Autonomous and Remote-Controlled Submarine (ARCS)** by ISE Ltd. was developed together with the Canadian Department of Defence and Hydrographic Service in 1983. [20] Despite its name, it was only remote-controlled, but it was able to operate for 35 hours with real-time communications, enabling longer operations.



Figure 2.8: The first UUV, SPURV (1957), developed by the University of Washington. [21]

In the 1990s, the UUVs became more autonomous and capable after the Russian Institute of Marine Technology started the development of the **Solar Autonomous Underwater Vehicle (SAUV I and SAUV II)**. The solar panels made it possible to have longer operations and equip them with more technology and payloads. In 1995, the first glider UUVs appeared. Gliders were capable of operating for several months since battery life was improved, and they used the ocean waves as a way of moving and collecting energy back. [4] These two were primarily research-focused, but they still considered military applications, as extended operational time remained a key requirement. More on the military side, the U.S. Navy developed

the **Near-Term Mine Reconnaissance System (NMRS)** (see Figure 2.9), a two-vehicle system launched from a submarine's torpedo tube in 1996.

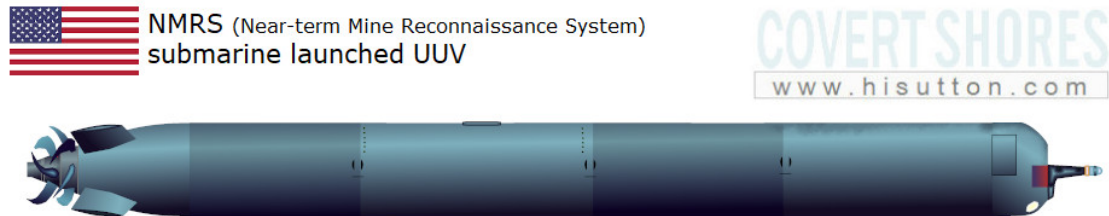


Figure 2.9: NMRS system developed by the U.S. Navy. [22]

In the 2000s, the first use cases in conflict were seen. A UUV was first utilized in combat in 2003 during Operation Iraqi Freedom. The United States employed a **REMUS** UUV to assist in the removal of sea mines from the region near the Umm Qasr port. [23] For example, the Finnish Navy operates one version of this type of UUV, the REMUS 100 UUV, as shown in Figure 2.10.



Figure 2.10: The REMUS 100 UUV, used by the Finnish Navy, on display in Turku, 2016. [24]

The 2020s is the most significant time for the development of UUVs and the first broad use in modern warfare. In 2022, the successful attacks with USVs prompted Ukraine to also develop UUVs. In 2023, the Ukrainian government-led agency Brave1 developed three different-sized UUVs, called **Toloka-TLK150**, **Toloka-TLK400**, and **Toloka-TLK1000**. The smallest model has a range of 100 kilometers, while the largest can exceed 1,900 kilometers. In Figure 2.11, the smallest Toloka-TLK150 is shown. [4]



Figure 2.11: The Toloka-TLK150 UUV, developed by Brave1. [18]

The industry in the United States followed after with their modern UUVs. First with the **Manta Ray** by Northrop Grumman in 2024 and the **Copperhead** by Anduril Industries in 2025. The manta ray is a bio-inspired extra-large maritime drone, and the Copperhead family consists of two UUVs, the Copperhead-100 and Copperhead-500, with the key difference being size, which introduces more room for additional payloads and longer operational time. Copperheads can be launched from Anduril's **Dive-LD** and **Dive-XL** UUVs; both can carry multiple Copperheads. Opening the possibility of a fully connected autonomous fleet. Anduril is already collaborating with military partners on developing even more capable systems, such as the **Ghost Shark XL-AUV**, which is expected to be operational in June 2025. [25], [26]



Figure 2.12: Copperhead UUVs, developed by Anduril Industries. [26]

2.3 Current Applications Sectors

Today, the maritime drone sector spans various sectors, and the capabilities of such systems can differ. These drones play an increasingly important role in nearly all aspects of the marine environment. Maritime drones are mostly employed currently in [3], [4]:

- **Military:** Intelligence, surveillance, reconnaissance, mine detection and neutralization, electronic warfare, logistics support, and force protection.
- **Scientific:** Oceanographic research, climate monitoring, and marine biodiversity assessment.

- **Industrial:** Inspection of offshore infrastructure, monitoring of undersea cables, and detailed seabed mapping.
- **Transportation:** Autonomous ferries and logistics platforms.

The combination of autonomy, endurance, and adaptability makes them especially valuable in environments that are dangerous or inaccessible to human operators. Larger vessels can also use this type of autonomy. However, there is debate about whether an autonomous ferry or cruise ship can be considered a drone; therefore, I will not specifically count them in this thesis as autonomous maritime drones.

2.4 Maritime Drone Market

The future of the maritime drone market, according to a recent report by Global Market Insights, indicates that the market was valued at USD 4.8 billion in 2024 and is projected to grow at a **compound annual growth rate (CAGR)** of over 6.8% from 2025 to 2034 [27]. The growth of the maritime market is shown in Figure 2.13.

The market's expansion is a result of a combination of technological advancements, increasing defense budgets, and rising demand for ocean data collection and offshore oil & gas exploration. Autonomous systems offer a low-cost and safer alternative to traditional manned operations in harsh or inaccessible marine environments. Furthermore, they provide a chart on how the market value is shared according to the end application. From Figure 2.14, it is clear that the defense sector dominates the maritime drone market by over half, with a percentage of 56.8%. [27]

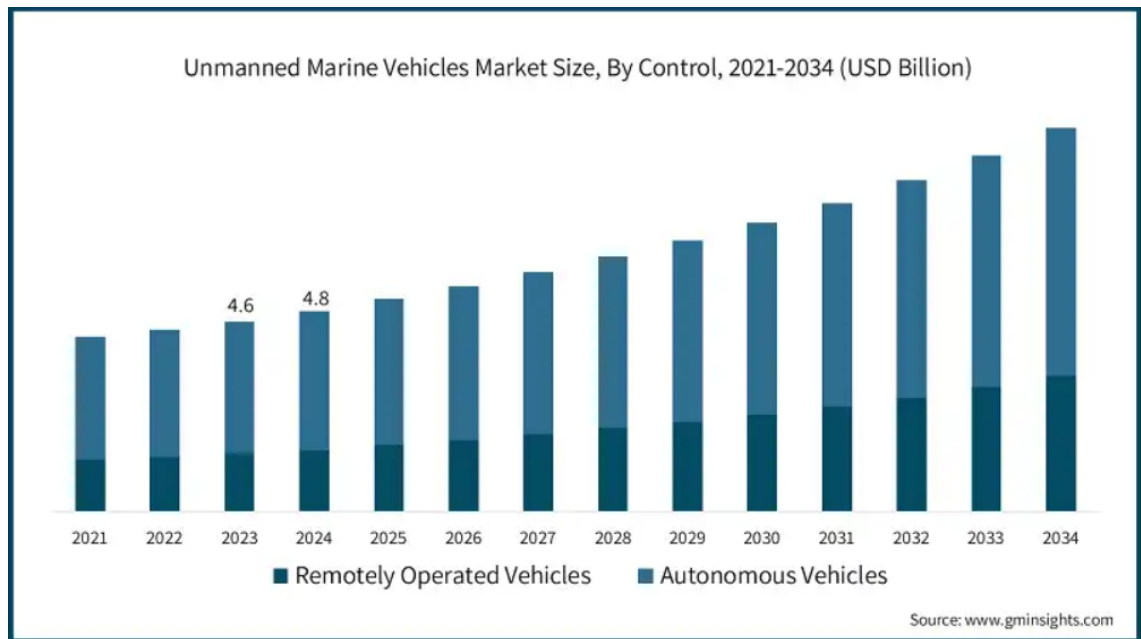


Figure 2.13: Projected growth of the global unmanned marine vehicles market. [27]

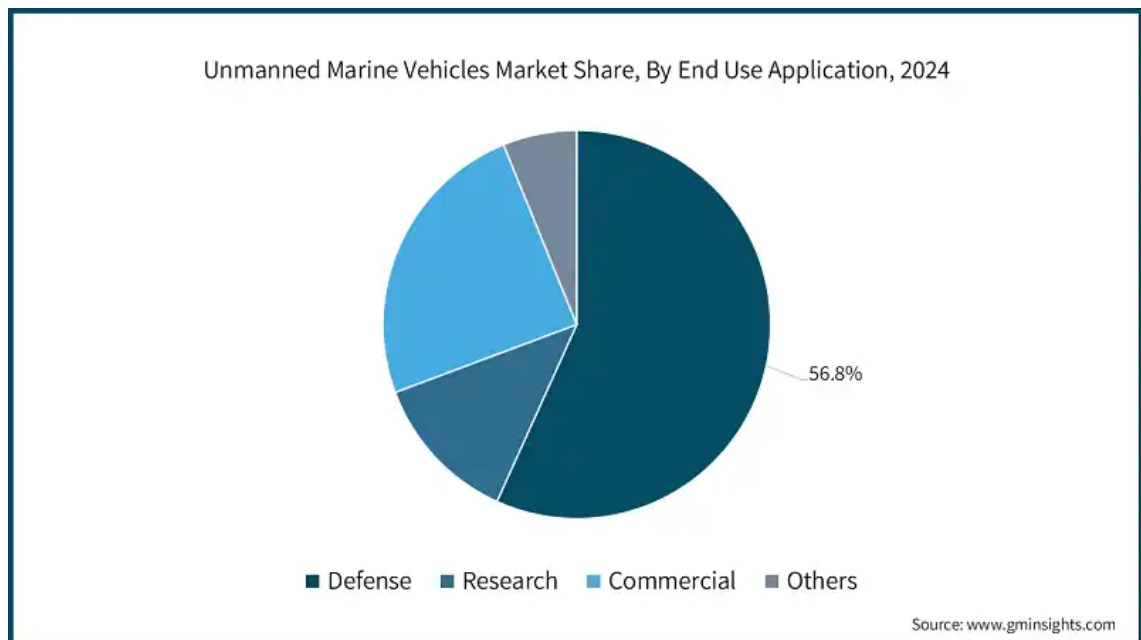


Figure 2.14: Key end-use segments in the unmanned marine vehicles market. [27]

These graphs illustrate the potential of maritime drones globally, not only in military applications, though that remains the largest sector by far.

2.5 Technical Foundations

There are several core technologies used in maritime drones that are typical to any robotics field: a mix of mechanical design, electronics, and software engineering. The primary difference that lies in the maritime field is adapting these traditional technologies to operate effectively in challenging and unpredictable marine environments. Key technologies that are used in maritime drones:

- **Sensors and Data Acquisition:**

Maritime drones rely on a variety of sensors, such as sonar, lidar, radar, GNSS, and optical or thermal cameras. All of these are used to perceive and interpret their environment. Sensors are foundational to real-time navigation, obstacle avoidance, and mission-critical data collection. Sensors are integrated for sensor fusion for more accurate and fail-proof systems. [28], [29]

- **Communication Systems:**

Effective communication is a critical component in the deployment of maritime drones. In maritime drones, typical radio frequency (RF) communication is used. While RF communication is effective at or above the water surface, it becomes unreliable underwater. Therefore, underwater vehicles often depend on acoustic communication. [28]

- **Autonomous Navigation and AI:**

Autonomous maritime drones integrate machine learning algorithms and AI-driven control architectures to support decision-making, path planning, and environment interpretation. These systems process sensor data using techniques such as Simultaneous Localization and Mapping (SLAM), probabilistic

reasoning, and reinforcement learning. Computer vision plays a vital role, enabling tasks like object recognition, horizon stabilization, and visual tracking in dynamic marine settings. [30]

- **Control Systems:**

To ensure dynamic stability and accurate maneuverability, maritime drones utilize control systems grounded in feedback principles. One of the most widely used approaches is the Proportional–Integral–Derivative (PID) controller, which continuously corrects system behavior based on deviations from desired states. These controllers are mathematically robust and computationally efficient, making them suitable for stabilizing depth, heading, and velocity in turbulent marine environments. [29]

- **Propulsion and Actuation:**

Propulsion systems in maritime drones commonly include electric or gas-powered motors driving propellers or thrusters. Often supplemented by control surfaces such as rudders, fins, or vectored thrust mechanisms to allow precise maneuvering. For underwater drones, propulsion systems are optimized for minimal noise and efficient energy use to support stealth and long-duration missions. [29]

- **Power Systems:**

Energy management is vital for prolonged, autonomous operation. Maritime drones typically use rechargeable lithium-based batteries due to their high energy density and stability. Some systems also incorporate renewable energy sources like solar panels or energy harvesting from wave motion to enhance endurance and reduce logistical dependence. [29] Efficient power distribution and low-power computing hardware further improve operational longevity.

- **Materials and Structural Design:**

The structural integrity of maritime drones is maintained through the use of specialized materials such as marine-grade stainless steel, fiberglass composites, and high-performance polymers. These materials offer resistance to corrosion and biofouling while maintaining structural strength against water pressure. Design considerations also focus on hydrodynamics, pressure tolerance, and modularity to facilitate maintenance and upgrades. [31]

- **Software and Simulation:**

Software ecosystems for maritime robotics often adapt general-purpose frameworks, such as the Robot Operating System 2 (ROS2) or Mission Oriented Operating Suite - Interval Programming (MOOS-IvP) for marine applications. These platforms support mission scripting, autonomy modules, sensor integration, and real-time diagnostics. Simulation environments are widely used to test navigation algorithms, assess control systems, and validate mission scenarios within virtual models of marine settings, helping to reduce risks before real-world deployment. [32], [33]

- **Cybersecurity:**

As maritime drones become more connected, especially in military or commercial contexts, cybersecurity is increasingly critical. Potential threats include unauthorized access, signal spoofing, and data interception. Secure communication protocols, hardware encryption, and intrusion detection systems must be integrated to ensure mission integrity and asset protection. [34]

The Rolls-Royce-led program, the Advanced Autonomous Waterborne Applications (AAWA) Initiative 2015-2017, has captured the similarity between ground-based autonomous vehicles and maritime vessels quite well in their research on the development of maritime autonomous vehicles. Looking at Figure 2.15, we can see the two pipeline examples of an autonomous car and a maritime vessel. The two are

similar, with mainly a difference in some sensors and the environmental differences requiring different types of maps and charts. [35]

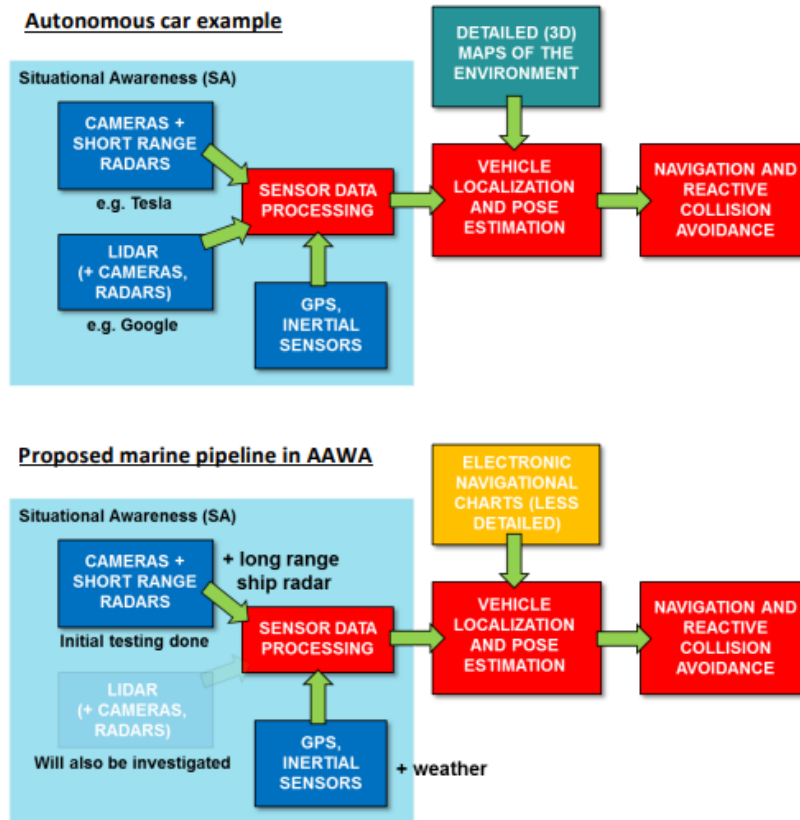


Figure 2.15: Navigation pipelines examples from the Rolls-Royce AAWA report. [35]

The technology for maritime drones is already available. However, further development and innovation are still necessary.

2.6 Maritime Drone Challenges

Maritime drones come with challenges. The harsh marine environment can change rapidly, and it introduces critical aspects that need to be taken into account when

developing maritime drones. To list common challenges:

Navigation and communication are some of the main challenges maritime drones present. Most maritime drones depend on GPS navigation, which can be unreliable in various situations. This is particularly true for underwater vehicles that cannot effectively use GPS. As a result, these vehicles often need to rely on acoustic signals, which can also be susceptible to interference. Maritime drones rely on network connections to stay linked with their operators, process data via cloud computing, or communicate and coordinate with other drones. Without stable connectivity, tasks like remote control, real-time monitoring, and collaborative missions become challenging to manage.

Power management and retrieving maritime drones is the next challenge. Maritime drones operate far from shore, making it extremely difficult to recharge, perform maintenance, or retrieve them. For the maritime drones that are designed to be expendable, like kamikaze types, retrieval is not an issue. Power management is an issue, especially with naval drones that need to perform long-term operations or have a lot of power consumption.

Temperature change and sensor accuracy are significant challenges for maritime drones operating in both polar and equatorial waters, as they encounter conditions ranging from freezing temperatures to extreme heat. Heat change, sediments, and marine debris can affect the sensor's performance. Additionally, high-pressure environments are a challenge, as the intense pressure can crush the vehicle. [28], [29]

Military applications pose additional challenges for maritime drones. The military forces of the enemy will often have similar maritime drones and counter systems for them. Stealth and detection are critical factors to consider, as the drones must operate without being detected while effectively carrying out the tasks assigned to them. To achieve this, developers can minimize sensor output and prioritize the use of more passive components to reduce electromagnetic signatures. Furthermore,

materials that conceal temperature signatures or reduce radar detection are also important considerations. Cyberattacks or hijacking attempts by adversaries seeking to gain control or sabotage the system should also be considered, not just in military contexts. [34], [36]

The development process of maritime drones can be expensive. It follows a standard software engineering approach while also emphasizing rapid innovation. This means the product may undergo multiple prototype versions and several testing phases to ensure everything operates seamlessly. After the product has proven to work, in most cases, the development process will continue with improvements and software updates. Even small-scale maritime drones can still exceed hundreds of thousands in unit costs, not taking the development cost into account, like some of Ukraine's kamikaze drones [37].

Lastly, there are challenges regarding the application of regulatory measures to maritime drones, as many regulations do not specifically mention them. Some regulations may apply, but their enforcement largely depends on each nation's willingness to adhere to them. [38]

3 Evaluating and Developing Maritime Drones

This chapter will cover the core metrics to evaluate the performance of maritime drones and popular models, tools, and frameworks that assist in the development process of maritime drones.

3.1 Analyzing Efficiency Improvements

When evaluating maritime drones, especially for military operations, certain main features are sought after. Efficiency in maritime drones can refer to a range of factors, including energy consumption, mission duration, navigation accuracy, data throughput, and responsiveness to environmental conditions. When analyzing potential improvements, the evaluation should be driven by the drone's intended mission profile, whether it is a kamikaze drone, a USV or UUV, or some stationary platform.

For military operations in particular, efficiency is closely tied to the following aspects:

- **Stealth:** Acoustic signature, radar visibility, and heat emissions.
- **Endurance:** Battery or fuel efficiency for long-range deployment.

- **Responsiveness:** Ability to react and reroute based on dynamic threats or changes in mission parameters.
- **Modularity:** Payload adaptability for missions such as surveillance, reconnaissance, attack, and mine operations.

Analyzing the efficiency involves simulating and testing these parameters under realistic environmental and operational scenarios. Additionally, specialized maritime simulators, or wargaming, can be used.

3.2 Key Performance Metrics

To analyze maritime drone performance, I have gathered a Table 3.1 with some of the main performance metrics that are looked after when analyzing maritime drone capabilities and efficiency.

Feature Category	Description
Hull design	Stable and hydrodynamic shape, lightweight and corrosion-resistant materials
Propulsion system	Electric, fuel, or hybrid systems with efficient propellers or thrusters
Navigation	GPS/INS systems, sonar/lidar for obstacle detection, autonomous path planning
Communication	Satellite, RF, or acoustic links for control and data transmission
Sensors and payload	Cameras, sonar, radar, lidar; modular payload configurations
Autonomy	AI for mission planning, obstacle avoidance, and adaptive behavior
Power management	Long battery life, solar or wave energy, and smart power allocation
Deployment	Launch/recovery from ship or shore, modular and portable design
Safety	Emergency protocols, backup systems, maritime safety compliance
Cost	Low-cost is essential for maritime drones

Table 3.1: Key performance metrics for maritime drones.

These performance metrics are perfect for assessing design trade-offs and for benchmarking different maritime drones from various parties.

3.3 Tools, Models, and Frameworks Used in Development

Developing maritime drones requires several tools. Generally, the process follows a standard software engineering process from the development perspective.

Frameworks are the starting point of developing a maritime drone. Frameworks that are extremely popular currently for developing robots include Robotic Operating System 2 (ROS2), which is currently the biggest and most popular open-source robotics framework. ROS2 is amazingly straightforward to use, and they have extensive documentation. [32] The basic architecture behind ROS2 is that nodes transfer data between each other. Nodes are either publishers or subscribers, and they can be extended to servers for more complex functionality. Another excellent framework especially designed for maritime drones is Mission Oriented Operating Suite-Interval Programming (MOOS-IvP). MOOS-IvP is a comprehensive, modular, open-source, C++-based autonomy framework developed and maintained by the MIT Marine Robotics Laboratory [33]. MOOS-IvP's highly modular architecture makes it an excellent choice, but it requires far more knowledge than ROS2. Moreover, one choice is to program everything without any framework. However, doing it this way will require much more development, which increases the cost and time used immediately.

Simulators are useful for testing robots before they operate in the real world. There are universal simulators, and some simulators have been specially developed for the maritime robotics community. The main simulators used in robotics are Gazebo, Webots, RViz, and Unity, which have compatibility with ROS2. Addition-

ally, smaller open-source simulators exist, such as Stonefish and HoloOcean, which are more physics-based and try to capture the actual hydrodynamical physics. Each simulator has its pros and cons. Simulators accelerate the development process by eliminating the need for actual hardware, allowing a single developer to test various scenarios and environments. Simulators can emulate various sensors, making them excellent tools to try different configurations. During my research, I explored various simulators and summarized my findings in Table 3.2.

When simulating robots, a robot model is necessary. In ROS2, for instance, the **Unified Robot Description Format (URDF)** is used to create 3D models of robots [32]. Robotics engineers mostly use professional **computer-aided design (CAD)** programs for designing mechanical and electrical parts. The most popular mechanical CAD programs are SolidWorks, Catia, and Autodesk. Additional plugins are available to convert these designs to URDF or include them in ROS2 simulators. Some simulators can use various CAD file extensions.

Some robots might need custom PCBs and electrical design. Popular electrical CAD programs are KiCad, Altium Designer, Eagle, and EasyEDA. These are by far the most prominent and easiest to learn for beginners. These tools allow designers to create custom PCBs, design electrical schematics, and simulate them to verify functionality before building the robot.

Simulator	Advantages	Limitations
Gazebo	<ul style="list-style-type: none"> – Native integration with ROS2 – Robust sensor simulation and modular architecture – Extensive plugin support 	<ul style="list-style-type: none"> – Computationally intensive – Requires custom extensions for realistic marine physics
HoloOcean	<ul style="list-style-type: none"> – Built especially for underwater environments – Includes most maritime sensors – Multi-agent setups 	<ul style="list-style-type: none"> – Complex setup and dependency management – Limited documentation
Unity + MARUS	<ul style="list-style-type: none"> – High-quality graphics – Customizable 3D environments – Real-time simulation capabilities 	<ul style="list-style-type: none"> – Low physical realism – Requires scripting for accurate marine physics
Webots	<ul style="list-style-type: none"> – Lightweight and user-friendly – Open-source and well-documented 	<ul style="list-style-type: none"> – Simplified hydrodynamic modeling – Limited graphical and sensor realism
Stonefish	<ul style="list-style-type: none"> – Designed specifically for marine robotics – Modular and integrates with ROS2 	<ul style="list-style-type: none"> – Still under active development – Smaller ecosystem compared to legacy platforms

Table 3.2: Comparison of simulators for maritime robotics.

4 Improving Military Maritime Drones

This chapter will explore a range of practical advancements that have been implemented to enhance the operational efficiency of maritime drones. These improvements will be categorized into seven distinct areas, each addressing a key aspect of performance optimization, technological innovation, or environmental adaptability.

4.1 Energy Optimization and Advancements

Maritime drones mostly rely on traditional energy sources for power. The demand for longer operation times and the integration of additional devices and weapons necessitates an increase in power consumption. Therefore, it is important to consider each individual component since they play a role in the scheme of everything. Well, one could think that there is no way of optimizing energy efficiency, but that is not true. Despite humanity having found various ways of generating power, there is still a long road ahead for improvements to come. Some areas currently under heavy innovation are battery technology, solar power, wave energy harvesting, hydrogen cells, and thermal energy. All of these methods can be used on maritime drones to enhance their energy efficiency.

The improvement does not need to be a physical feature. Energy optimization can be achieved by developing more efficient software. AI tasks can be sent to

the cloud, which is called task offloading, and path planning can be designed in an energy-efficient way [28]. Different power management modes and scheduling can be implemented. Sensors can be strategically disabled, or dynamic loading can be utilized, meaning the system only consumes the necessary power. Additionally, multi-robot systems can influence energy efficiency by sharing information to collaborate in optimizing paths, potentially leading to more effective energy distribution [28].

On the hardware side, sensors can be designed for low power consumption to minimize energy usage; excellent examples of these are Field Programmable Gate Arrays (FPGAs) and neuromorphic processors. Furthermore, actuators can be picked with minimal power consumption, and energy can be collected back with energy harvesting from solar, wind, and wave energy [29].

4.2 Hydrodynamics and Design

To improve the efficiency of maritime drones, the principles of hydrodynamics can be applied. Hydrodynamics is an excellent way to affect the behavioral aspects of a maritime drone with water. [39] Hydrodynamics can be used in clever ways, and I will introduce four different maritime drones that have been specially designed with hydrodynamics and efficiency in mind.

The Wave Glider (Figure 4.1), developed by Liquid Robotics, a subsidiary of The Boeing Company, uses an innovative propulsion method that harnesses the energy of ocean waves. It has two main sections. The top section stays on the surface, and it can have various payloads. The bottom section is tethered to the top section, and the bottom section is submerged eight meters underwater. The bottom section is responsible for utilizing the wave energy to glide the drone to its target. Liquid Robotics states that the Wave Glider can operate for several months. [40]

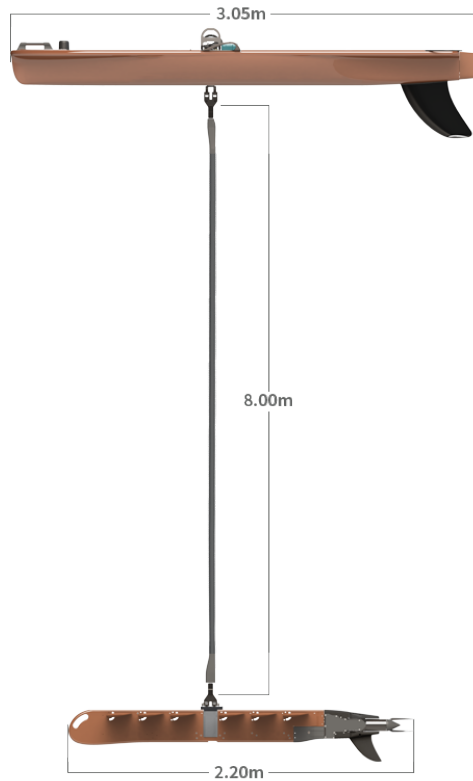


Figure 4.1: Side profile of the Wave Rider drone. [40]

The Manta Ray UUV (Figure 4.3) by Northrop Grumman that was developed in 2024 is shaped like a manta ray due to their efficient movement underwater. Manta Ray is an excellent example of a biology-based maritime drone. While the Manta Ray cannot flex its body like a real manta ray, it mimics the animal's hydrodynamic movement. The manta ray can operate autonomously for long periods, and it can be customized to different sizes and operations, mainly to be used as a logistics drone. [25]

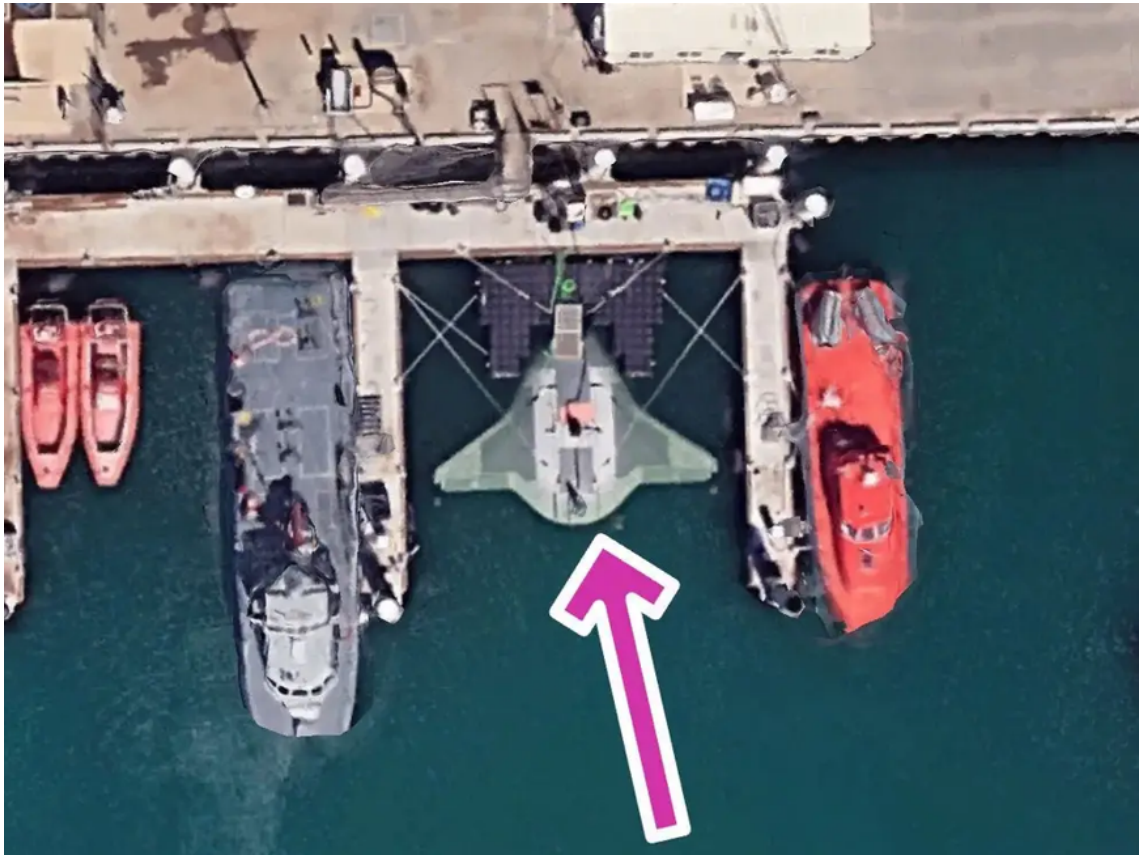


Figure 4.2: The Manta Ray drone as seen in Google Earth satellite imagery. [41]



Figure 4.3: The Manta Ray during testing in 2024. [25]

The Triton (Figure 4.4) is one of the first hybrid maritime drones that can operate both on the surface and underwater. It has been fully developed by OceanAero in the United States. The drone has a foldable sail and is fully covered with solar panels, enabling it to sail for up to three months. By folding the sail down, it can operate for five days underwater. OceanAero themselves describe the Triton as the world's first Autonomous Underwater and Surface Vehicle (AUSV), and it has also been referred to as the *Sail Submarine*. The main purpose of Triton for military applications is to provide intelligence, surveillance, reconnaissance, mine countermeasures, and anti-submarine warfare. [42]



Figure 4.4: The world’s first hybrid drone, Triton. [42]

The Finnish National Defense University (MPKK), together with our team from **Turku University** and **Turku University of Applied Sciences**, has developed an efoil board-based maritime drone, the **Meri-Turso**. Figure 4.5 shows the bottom section of the Meri-Turso drone [43]. From this view, it is clear that the design of Meri-Turso supports efficient hydrodynamic performance. The design is based on flying atop a submerged wing, which generates lift to keep the vehicle above the water. This configuration minimizes the contact with water, thereby significantly reducing drag. This design also helps to remove cavitation in the case that Meri-Turso is always moving at the optimal depth. Traditional propellers are often placed near the surface, or they spin too fast, which causes cavitation. Cavitation can be problematic for military maritime drones, as the hissing and bubble popping can be detected by enemy passive sensors. A noisy drone is more

likely to be detected, tracked, or targeted. Meri-Turso's low-rpm and high-torque motor minimizes cavitation, providing a constant flow in water.

The main purpose of Meri-Turso is to provide remote surveillance. However, use cases can vary from mission to mission, and the drone could even be equipped with an explosive payload to function as a kamikaze drone. Additionally, it could operate in swarms, making it almost impossible to counter. Meri-Turso uses intelligent control systems to stabilize itself in various situations and can navigate with ease. The first built prototype (see Figure 4.6) by our team of universities was presented to the public at the SecD-day event in Helsinki Expo & Convention Center on 29-30 January 2025 [44].



Figure 4.5: From left: Petteri Hemminki, Waltteri Soininen, and Lauri Vasankari presenting the Meri-Turso maritime drone board at the MPKK. [43]



Figure 4.6: The Meri-Turso maritime drone prototype presented at the SecD-day by Cpt. Jan Joutsu. [44]

4.3 AI and Hardware

Since the beginning of artificial intelligence (AI) in the 1950s, the field has progressed dramatically due to advances in both computing platforms and algorithmic design. Better computing platforms and algorithms have been pivotal for the research and development of AI and autonomy in robotics. As a core element of naval drones, artificial intelligence significantly improves system efficiency. In such systems, AI is critical to achieving efficient navigation, localization, object detection, threat assessment, and mission execution. Numerous ways to implement AI algorithms, each with trade-offs in terms of speed, accuracy, and computational cost, are available [30]. As these algorithms continue to evolve, they are increasingly well optimized for performance and robustness in real-world conditions.

AI tasks demand a significant amount of processing power, especially for real-

time inference tasks such as computer vision and sensor fusion, and therefore, optimal hardware is needed. In the context of military maritime drones, these need to be relatively cheap and capable of handling rough environments and possible jamming from electronic warfare systems.

Single-board computers (SBCs) are a common choice in robotics due to their compact size and integrated capabilities. Two widely used SBC platforms are the NVIDIA Jetson series and the Raspberry Pi. The Jetson family shows better performance in graphically intensive applications because it is designed for AI tasks. In contrast, the Raspberry Pi is considered more a hobbyist-level SBC, but it has also proven successful in various robotics projects. [45]

For defense applications, ruggedized embedded computing platforms designed especially for military environments are often preferable. These systems are typically tested and rated for shock, vibration, temperature extremes, and electromagnetic compatibility. In the case of kamikaze drones, the cost should be minimized. Therefore, rugged computers might not be the right choice for that use case.

Ultimately, the choice of computational hardware in maritime drones must consider at least three core aspects: computational requirements, environmental resilience, and cost-effectiveness. The future of AI-powered naval systems will depend heavily on continued development in both software and hardware platforms.

4.4 Stealth Features and Communications

Stealth and secure communication technologies are critical features for modern military operations. As unmanned systems become more prevalent in naval warfare, ensuring their survivability, discretion, and secure command and control capabilities is essential. Maritime drones, especially those intended for reconnaissance, surveillance, or offensive operations, must be equipped with sophisticated stealth features to avoid detection and advanced communication systems to function in contested or

denied environments. I will introduce three points for each section.

4.4.1 Stealth Technologies

The marine environment again poses unique challenges for stealth due to factors such as sonar, radar, infrared detection, and electromagnetic signature tracking. In response, several advanced stealth techniques are being explored or are to be implemented in maritime drones:

1. **Adaptive Thermal Camouflage**

Adaptive thermal camouflage would enable unmanned vessels to regulate or disguise their heat signatures to evade infrared detection from enemy sensors. Using materials or coatings that respond dynamically to environmental temperatures would allow drones to blend into the sea surface's thermal background. Adaptive thermal camouflage would be particularly useful in avoiding thermal imaging sensors used by enemy aircraft, satellites, or coastal surveillance systems. The ADAPTIV camouflage was introduced in 2011 by BAE Systems AB in Sweden, and it has been tested on CV90 infantry fighting vehicles with excellent results. Figure 4.7, provided by BAE Systems, illustrates how ADAPTIV technology could be applied to a warship, suggesting its potential use on maritime drones as well.



Figure 4.7: BAE Systems' Adaptive camouflage system rendered on a warship. [46]

2. Electromagnetic Signature Reduction

Naval vessels emit a range of electromagnetic signals. Electromagnetic signals can be emitted from propulsion systems, onboard electronics, and communication equipment. To remain undetected, maritime systems should be engineered with electromagnetic shielding and emission control protocols (EMCON) in mind. [47] Features like these help reduce or mask emissions, making it harder to trigger radar or electronic surveillance systems. Signaling can be configured in timed bursts or limited windows to avoid continuous transmission. Additionally, to reduce the electromagnetic signature, more passive sensors that do not emit signals can be used.

3. Radar cross-section (RCS) reduction

Radar cross section can be minimized in four ways [48]:

- (a) Shaping

- (b) Radar-absorbing materials (RAM)
- (c) Passive cancellation
- (d) Active cancellation

Maritime drones may be constructed using composites or coatings that absorb rather than reflect radar waves. Radar-absorbing materials help reduce the RCS, making unmanned vessels more difficult to track or identify using conventional radar systems. These materials are already in use on stealth aircraft and submarines and should be adapted for small surface and subsurface drones. Another way of reducing RCS is to have low-profile or wave-skimming hull designs. Some maritime drones employ small radar cross-section hulls or semi-submersible profiles that allow them to stay below the horizon and radar line of sight, further increasing stealth in secret operations. Passive and active cancellation can be used to either echo the waves back or generate waves that counter the radar's waves. Passive and active cancellation could be used for maritime drones. Shaping can be seen in many traditional naval vessels but is not yet in broad use for maritime drones. However, for example, Taiwan's first maritime drone or the U.S. Navy's Sea Hunter are excellent examples of such shaping; see Figures 4.8 and 2.5. These RCS improvements usually also come with the negative aspects of reduced payload, reduced range, added weight, and possibly increased maintenance [48].



Figure 4.8: Taiwan’s first military maritime drone. [49]

4.4.2 Communication Security and Innovation

Reliable and secure communications are essential for unmanned or autonomous drones, especially in high-risk settings. However, traditional communication methods are vulnerable to jamming, interception, and spoofing. A few advanced technologies are being developed to mitigate these vulnerabilities:

1. Adaptive AI-Based Communication Protocols

Artificial intelligence could be used to manage drone communication systems more flexibly and intelligently. AI can autonomously shift frequencies, detect interference, and reroute communication paths to maintain the network as operational [50]. This capability would allow maritime drones to maintain command-and-control links even under an electronic attack. These systems

can adapt in real-time to emerging threats and environmental conditions.

2. Mesh Networking Among Other Drones

Next-generation drones should be equipped with more mesh networking capabilities, allowing them to communicate with each other directly. Enabling data relays over large distances, improves redundancy, and reduces reliance on a single ground control station, which is especially valuable for coordinated fleet operations. In 2023, one such 5G mesh networking system was tested by NATO in the Dynamic Messenger test [51]. This type of mesh connection can be seen in Figure 4.9, where especially the UUVs are connected with each other.

3. 4G - 6G, Satellite, and Other Communication Integrations

Modern maritime drones often switch between traditional radio frequency communications and satellite uplinks depending on range and environment. The integration of multiple channels allows for redundancy and greater resilience to signal loss or jamming. Both Ukraine and Russia have used the Starlink terminals developed by SpaceX on their maritime drones [3]. Starlink works by providing internet access through satellite communication. If satellite communication is unavailable, the system will fall back to a Long-Term Evolution (LTE) or, as it is known, 4G connection. Furthermore, since 5G and 6G networks have proved to work quite well in other fields, they should be utilized more in maritime drones by having special maritime drones to relay the signal or link buoys. Figure 4.9 illustrates a relay-based 6G network for maritime drones.

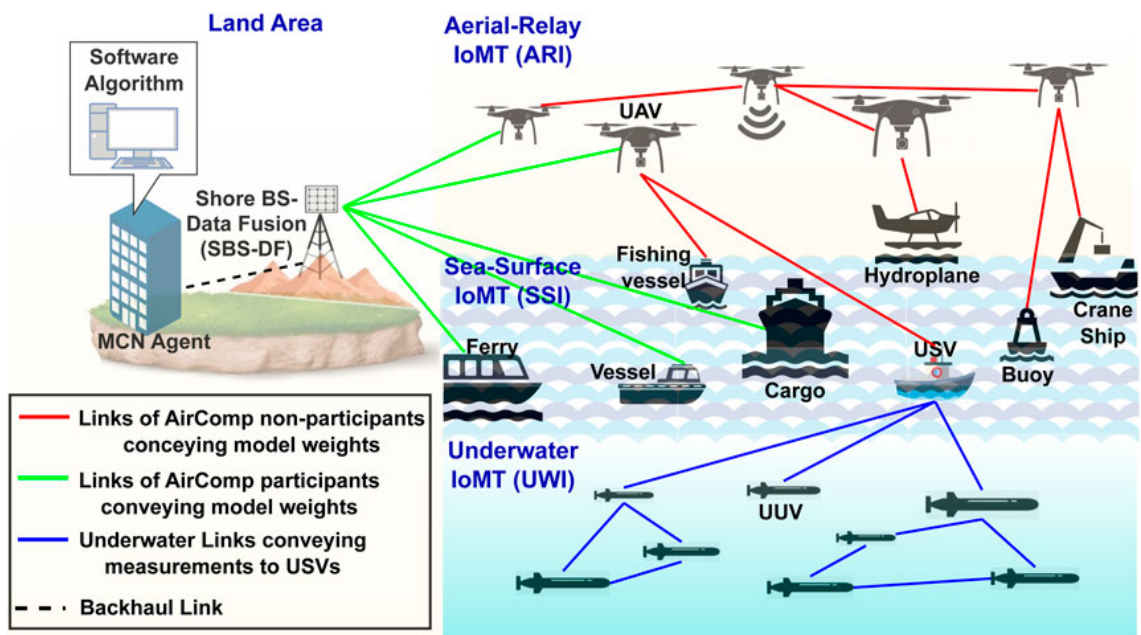


Figure 4.9: 6G Maritime relay network concept. [52]

5 Maritime Drones in Modern Warfare

5.1 The Black Sea: Russo-Ukraine War

Ukraine has countered the Russian naval fleet with a range of maritime drones. Ukraine does not have a well-equipped navy since Russian forces have captured most of the Ukrainian naval bases during the battles from 2014 to 2025. Therefore, Ukraine developed maritime drones to combat Russian vessels and even established a specialized brigade for USVs in August 2023, the 385th Unmanned Surface Vehicles Brigade [53]. Ukraine has already managed to destroy a third of the Russian naval fleet with maritime drones and missiles, according to the Security Service of Ukraine (SBU) [54].

Some larger-scale operations were so significant that the Russian naval fleet decided to move their vessels back to their home bases. In 2023, Ukraine sank the Russian landing ship *Olenegorsky Gornyak* by attacking it with several USVs [55]. In 2024, two notable maritime drone attacks were successfully carried out: the downing of a Russian Mi-8 helicopter and an attack on the Kerch Bridge. The damage inflicted by these maritime drones to the Kerch Bridge and the landing ship *Olenegorsky Gornyak* are shown in Figures 5.3 and 5.4. Numerous other successful operations have also targeted Russian oil platforms, military seaports, and various

strategic assets throughout the war. Moreover, on May 2, 2025, we saw yet more downings of two Russian SU-30 fighter jets from Ukraine’s MAGURA-7 USV with U.S.-made AIM-9 Sidewinder Missiles [54].

The use of maritime drones in Ukraine is, by far, the most extensively documented example of their deployment in a real-world asymmetric modern conflict. The tactics Ukraine has used are marine drone swarms and explosive-laden USVs, with the help of remote piloting via Starlink and similar satellite-based communication systems. All successful attacks from 2022 to 2023 are shown in Figure 5.5. Although only five attacks were reported during this period, the figure illustrates that maritime drones have been effective in Ukraine, primarily due to the strategic importance of each operation.

Furthermore, the drones currently known to be used by Ukraine and Russia can be seen in Figures 5.1 and 5.2. By looking at these figures, it is clear that the Ukrainian armed forces have utilized more maritime drones and equipped them with a greater variety of weapon systems than Russia.



Figure 5.1: Known Russian maritime drones used in the Black-Sea. [56]

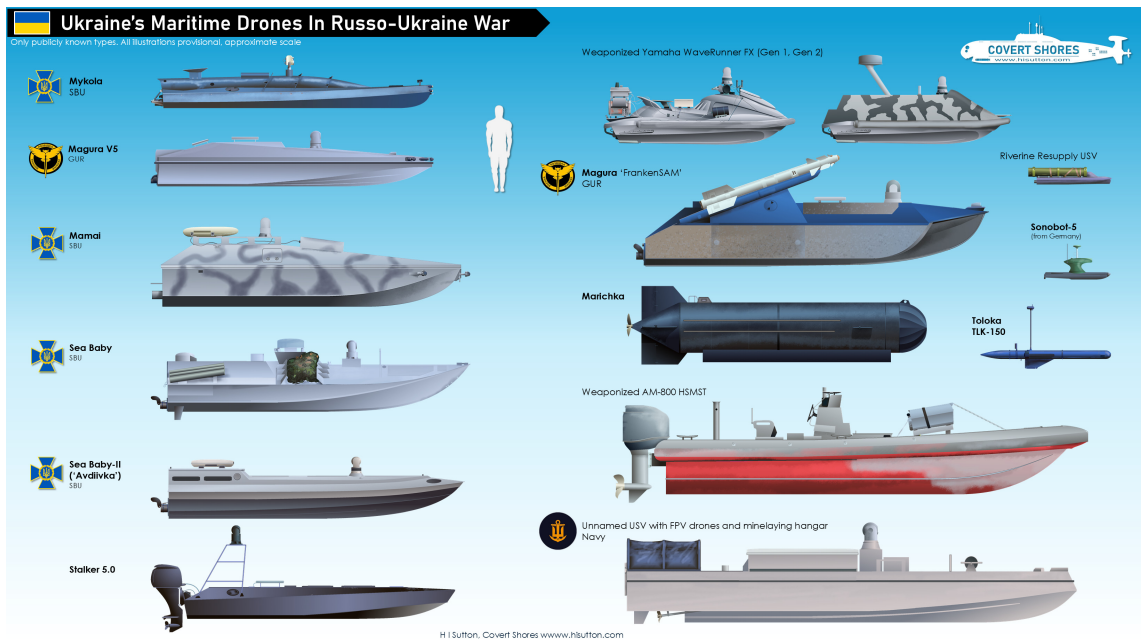


Figure 5.2: Known Ukrainian maritime drones used in the Black-Sea. [56]



Figure 5.3: Damage inflicted to the Kerch Bridge by a Ukrainian maritime drone. [57]

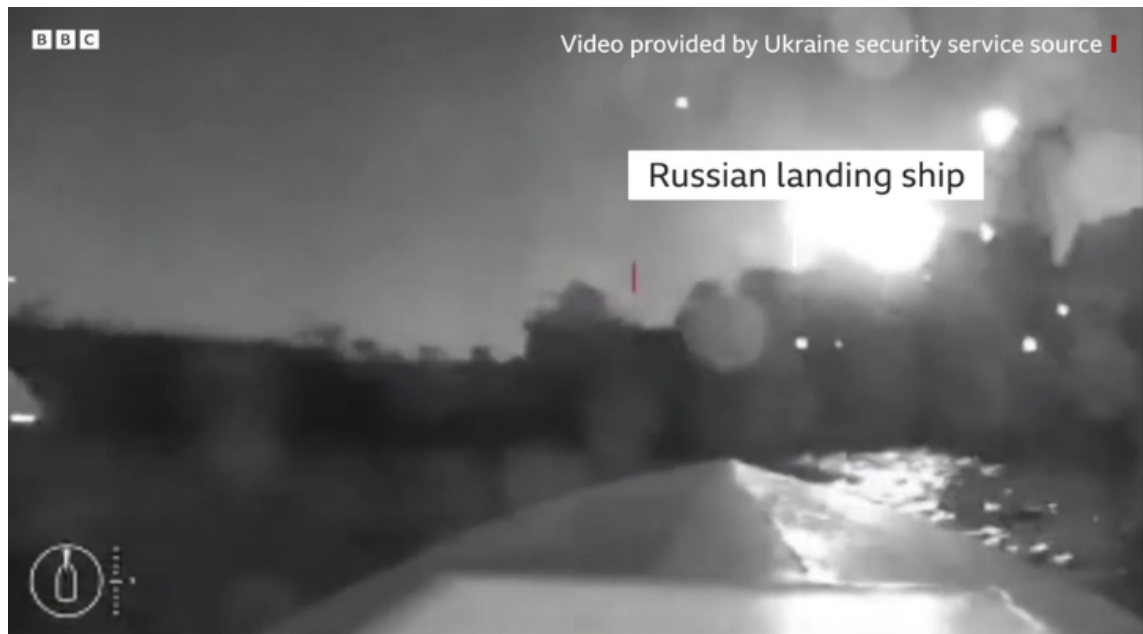


Figure 5.4: Ukrainian maritime drone during an attack on Olenegorsky Gornyak.

[55]

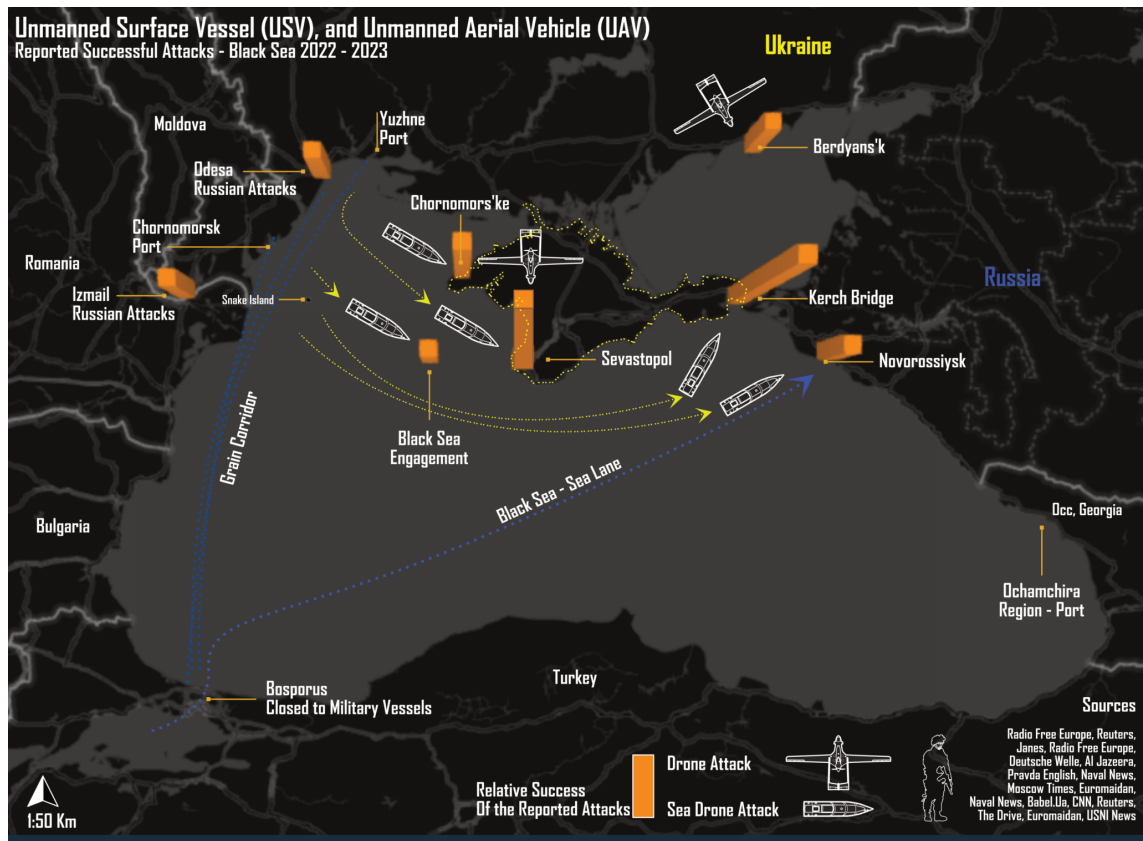


Figure 5.5: Drone attacks in Ukraine during 2022-2023. [37]

5.2 The Gray Zone: The Red Sea, Persian Gulf, and the Israel–Gaza Conflict

In the context of escalating regional tensions following the Israel-Gaza conflict, Yemen’s Houthi movement has intensified its maritime warfare strategy by also incorporating maritime drones into its operational toolkit. The currently known arsenal used by the Houthis is shown in Figure 5.6. A report by Reuters in 2024 details the group’s shift toward deploying explosive-laden maritime drones to target commercial shipping transiting the southern Red Sea and Bab al-Mandab Strait, a globally critical maritime corridor since 12-15% of worldwide trade goes through the

strait and the Red Sea.

Since November 2023, the Houthis have conducted numerous maritime drone attacks, with at least forty-three vessels targeted and twenty-one confirmed as damaged by direct strikes. However, only thirteen reported being attacked by a drone. While their earlier operations relied on boarding actions and projectile weaponry, the use of USVs marked a notable evolution in their asymmetric maritime tactics. Operating in the confined waters of the Red Sea and exploiting the dense shipping traffic in the Bab al-Mandab Strait, the drones are difficult to detect and intercept and can be launched from concealed coastal or mobile platforms. The success of such attacks has not only inflicted material damage, including the sinking of at least one bulk carrier, but also severely disrupted international maritime logistics. Major shipping companies have diverted their ships around the Cape of Good Hope, adding substantial costs and delays to global trade. [58]

A large supporter of the Houthis is Iran, which uses them as a proxy. The Houthis have also targeted the U.S. Navy multiple times, but none of the attacks have been successful since the U.S. Navy has countered every attack with ease. Iran has done its attacks more in the Persian Gulf area, also targeting international cargo ships and oil tankers or even the U.S. Navy. On June 12, 2024, the Houthis attacked the U.S. Navy and a Greek-owned MV-Tutor tanker. The U.S. Navy was able to destroy six of the maritime drones launched by the Houthis, but one managed to strike the Greek tanker, which can be seen in Figure 5.8.

Israel has sabotaged and surveilled Gaza's Hezbollah maritime supply lines with UUVs during the larger conflict. And likewise, Hamas and Hezbollah have received maritime drones from Iran. These drones are constructed with materials designed to evade radar detection and are capable of approaching Israeli coastal targets. Hamas has also been developing maritime drones for potential attacks on Israeli maritime assets. Israel has been able to counter the proxies quite well with its marine drone

fleet. One notable attack allegedly attributed to Hamas was the cutting of underwater communication cables in the Red Sea, which disrupted 25% of the region’s internet connectivity. However, no official confirmation has been issued regarding who was responsible for the incident. On the other hand, Israel, with a much smaller navy compared to Iran, has effectively repelled attacks and is developing its UUVs. **Blue Whale** (see Figure 5.7) is probably the best-known drone they have developed for intelligence, submarine detection, and reconnaissance. Additionally, the maritime drones that Iran produces are cheaper and faster to build than the ones that Israel is building. [59]



Figure 5.6: Known maritime drones used by the Houthis. [60]



Figure 5.7: The Blue Whale UUV, developed by Israeli Elta Systems. [61]



Figure 5.8: Successful Houthi attack on the Greek tanker MV Tutor, June 12, 2024 [6]

5.3 South and East China Sea: The Brewing Storm Between The U.S, China, and Taiwan

Tensions in the South and East China Seas have seen interceptions and shadowing involving USVs and UUVs, but not full-on attacks yet. In this region, maritime drones are already being prepared for possible future conflicts. Sitting at the crossroads of major sea lanes and near contested maritime zones, Taiwan would be a central player in any U.S.-China conflict, especially given the United States' heavy reliance on Taiwan for advanced electronics and semiconductor production. Taiwan is responsible for manufacturing at least 90% of the world's computer chips [62].

China continues to expand its drone capabilities in the region, while Taiwan is developing its unmanned systems for coastal defense. In the event of a crisis, these sea areas would likely serve as a key operational zone, making maritime drones vital tools for surveillance, denial, and early warning on all sides. The U.S. Navy maintains a significant presence in the region, leading to encounters between Chinese authorities and U.S. Navy maritime drones. In December 2016, tensions sparked quickly when China decided to seize one of the U.S. Navy's UUVs from international waters [63].

The tensions have been rising steadily between the nations, and Chinese military forces have been training for the occupation of Taiwan multiple times with various military drills. Furthermore, the Chinese forces have tried to scare Taiwan by operating maritime drones around the country. Figure 5.9 shows how the Chinese military utilized maritime drones in their military drills in August 2022. From the image, we can see that China launched the drones from the East China Sea and used the Japanese islands as cover to initiate their simulated attack and operations on the eastern side of Taiwan before returning via the same route. Once again, violating Taiwan's territorial waters. [64]



Figure 5.9: Chinese military maritime activity during the August 2022 drill. [64]

I included this case study because this region has the potential to become a new area of maritime warfare. Some military experts warn that it could even serve as a potential flashpoint for World War III. It is important to emphasize that there is currently no active conflict in the area. However, the ongoing arms race between nations is evident. Military developments are visible on both sides, and China's drills are increasingly hostile toward Taiwan. Furthermore, relations between China

and the United States remain tense.

6 Results

This chapter will address the research questions outlined in Chapter 1 by examining emerging technologies for maritime drones and their strategic and tactical implications. Additionally, it will provide a brief overview of the ethical and environmental issues associated with maritime drones, as well as the regulatory measures that have been established for their use.

6.1 Strategic Implications

By looking at the use of maritime drones in modern warfare settings, I have divided the strategic and tactical implications into four smaller categories. As seen from the previously presented drones and use cases in modern warfare in Chapter 5, it can be concluded that maritime drones play a significant role in both strategic and tactical implications. The surface and underwater domains have opened two new fronts in warfare for autonomous drones. Furthermore, this and the following section should be considered as an answer to the first research question: **1. What are the strategic and tactical implications of maritime drones in modern warfare?**

1. Shift in Naval Power Dynamics

Maritime drones are enabling the redistribution of influence. Unlike traditional warships, which require substantial investment, maintenance, and personnel, maritime drones are relatively inexpensive and accessible. Allowing smaller

states, and even non-state actors, to bear maritime drones. Resulting in traditional naval power being more vulnerable to threats posed by these drones. This shift is evident in recent conflicts, where smaller forces have effectively employed maritime drones to challenge naval powers.

2. Deterrence and Escalation

The expansion of the maritime drone field complicates the strategic calculus around deterrence and escalation. These systems are well suited for so-called *gray zone* operations. These are actions that fall below the threshold of an open conflict but can still alter the strategic balance, such as seen in the Red Sea and East and South China Seas. Since these drones can operate without direct human risk and with plausible deniability, they offer states a tool to probe, harass, and even damage adversaries without necessarily provoking a full-scale military response. This blurring of boundaries raises new discussions about intent, attribution, and proportionality in maritime conflict.

3. Strategic Surveillance and Sea Denial

One of the most significant strategic implications of maritime drones is their ability to conduct persistent intelligence, surveillance, and reconnaissance operations. UUVs, in particular, can operate for long periods while remaining undetectable. This capability improves maritime domain awareness, especially in contested regions or near strategic chokepoints. By integrating maritime drones into anti-access/area denial operations, states can bolster their ability to deter or obstruct hostile naval activity within critical sea lanes and their territorial waters.

4. Arms Race and Naval Modernization

The development and use of maritime drones are fueling a new naval arms race. Major military nations, including the United States, China, and Russia, are

investing billions in autonomous naval systems. This advancement applies not only to hardware but also to the integration of artificial intelligence, swarming capabilities, and advanced underwater navigation and communication systems. As this arms race intensifies, there is a risk of destabilization, especially as these technologies become more autonomous and less predictable *black boxes*.

6.2 Tactical Implications

Once again, I have divided the tactical implications into four categories, which I consider to be the most significant:

1. Force Multiplication

At the tactical level, maritime drones offer an excellent force multiplier effect. Multiple of drones can be deployed simultaneously to perform coordinated maneuvers, reconnaissance, or attacks. In swarm configurations, they can overwhelm traditional naval defenses, saturate enemy sensors and weapon systems, and complicate targeting decisions. Changing the calculus of engagement, especially in coastal environments or during rapid-response operations.

2. Covert Operations and Sabotage

Maritime drones enable new forms of covert action. Their small size and stealth features allow them to infiltrate harbors, lay mines, and damage critical infrastructure such as undersea cables or energy pipelines. These operations can be carried out with minimal risk to personnel and may remain undetected until the effects are noticed. Opening new possibilities for sabotage, subversion, and strategic disruption, especially when attribution is uncertain or contested.

3. Logistics and Resupply

In addition to traditional combat applications, maritime drones are being

adapted for logistical tasks. Maritime drones can transport supplies, ammunition, and equipment to deployed forces, reducing the risk to traditional vessels and supporting sustained operations. Additionally, some drones are designed for autonomous search-and-rescue missions or recovery operations in hazardous conditions.

4. Counter-Drone Operations

Increased use of maritime drones creates a need for new defensive measures. Various parties are currently developing counter-drone systems, including electronic warfare techniques, directed energy weapons, and drone-on-drone interception strategies. As these systems become increasingly interconnected and reliant on software, cybersecurity rises as a critical vulnerability. A compromised drone system could mislead, disable, or turn against its fleet.

6.3 Emerging Technologies and Improvements

Looking at the innovations from Chapter 4, we can observe that maritime drones have undergone a lengthy process of improvement in terms of efficiency and modular payload capabilities. This section will answer the second research question: **2. How can maritime drones be optimized and equipped better?**

The maritime robotics field is currently experiencing rapid growth, with innovations emerging every month. These advancements have taken the world by surprise in various ways. For instance, on the military side, traditional fighter jet carriers are being replaced by fully autonomous drone carriers able to transport hundreds of drones. Additionally, there are motherships designed to contain smaller drones that can be deployed for their missions, as well as connected drone swarms.

A notable aspect of developing military applications is the modularity of these systems, allowing them to be equipped with almost any payload. Military appli-

cations require a variety of payloads, ranging from traditional to electronic warfare payloads. The diverse range of maritime drones presented provided us with a clear view of these capabilities.

Maritime drones are increasingly being outfitted with advanced weapon systems to enhance their capabilities to the fullest extent. An excellent example is one of the newest maritime drones from Ukraine, the Katran Venom. This drone is equipped with two torpedoes, two air defense missiles, and two machine guns: a 7.62-caliber minigun and a 50-caliber Browning M2 machine gun. Additionally, it includes electronic warfare equipment and smoke and heat decoy systems. Furthermore, Katran can carry a range of additional payloads, including aerial drones and various weapon systems. Katran Venom is shown in Figure 6.1. [65]



Figure 6.1: Ukraine's maritime drone, the Katran Venom. [65]

On the efficiency side, maritime drones are being optimized with innovative designs that prioritize hydrodynamic performance, incorporate more efficient and alternative battery technologies and advanced software, improve power management

systems, and integrate better sensors.

These enhancements will increase the capabilities of maritime drones, enabling them to operate more effectively in swarms and to carry a greater arsenal of lethal and non-lethal weapon systems. Enable longer operational time and range. To predict the future, multi-domain robot attacks are likely the next wave of operations to be seen, involving synchronized autonomous or unmanned attacks using ground, air, and sea drones simultaneously.

6.4 Ethical and Environmental Concerns

This and the following sections will answer the third research question: **3. What are the ethical and environmental considerations surrounding the deployment of maritime drones? And what kind of regulatory measures have been set for maritime drones?**

Maritime drones have already caused ethical and security concerns and will continue to do so in the future. In the article published in the Ukrainian open-access law scientific journal *Maritime Autonomous Weapon Systems from the Standpoint of International Humanitarian Law*, possible ethical impacts of maritime drones in the view of International Humanitarian Law (IHL) are presented. Usmanov and Chernychka explain that the main reason why this topic is debated is that the use of lethal force is moving more toward autonomy. Therefore, meaning that autonomous weapon systems can remove humans completely from the loop of decision. Usmanov and Chernychka present legal issues that the use of autonomous weapon systems can have even though we have seen deployment of such systems from various countries. [38]

The most known and debated issue that is presented is the ethical concern of delegating life-and-death decisions to autonomous machines. This issue is universal for all autonomous machines that can be responsible for human life. [38] Who will

take the blame for killing the human or destroying the asset? Would it be the operator who launched it, the company that built it, or even a single programmer who made the algorithm to kill and destroy? Furthermore, to continue on this topic, a critical point is that these systems need to distinguish between civilians and combatants, and by doing so, they should try to do so in a way that produces minimal harm since it is guaranteed that in a total war situation, there will be civilian casualties. And what to do if a civilian is using some uniform that can be mistaken for a military uniform? Additionally, there is a large issue with the definitions and classification of these systems, and therefore it is hard to establish new regulations and oversight on AWS. [38]

Regarding general security, these systems can both enhance and undermine it, particularly due to privacy concerns [38]. Maritime drones are equipped with multiple sensors, such as cameras, and may record individuals without their consent. This raises important legal and ethical questions: while it is generally legal to film people in public spaces, recording private property or tracking someone's movements can be more problematic. So, where should we draw the line?

On the environmental side, maritime drones are pretty unnoticeable. However, the greater issue is explosive-laden military maritime drones that scatter pieces all around the area of explosion; this can be anything from oil, gasoline, plastics, electronics, explosive materials, et cetera. Everyone knows this is an issue, but nothing can really be done to minimize it other than forbidding all of them. On the other hand, there are maritime drones that are designed to clean the oceans, so this is an endless cat-and-mouse race. Furthermore, maritime drones can affect sea life in a negative way, since the noise and debris can affect sensitive animals and other sea life.

6.5 Policy and Regulatory Considerations

The regulation of AWS remains an evolving field. The first step toward global regulation of such technologies was taken in 2019 when a set of eleven guiding principles was introduced by the Governmental Expert Group (GGE). These principles marked the initial attempt to provide a normative framework for the development and deployment of lethal AWS. However, many countries have not adopted it. Usmanov and Chernychka explain that there is no need to ban autonomous weapons since they do not cause unnecessary suffering. The stance of maritime drones within the framework of international humanitarian law is that they can only be subject to it if they operate under human control and decision-making. [38]

The Geneva Conventions have historically functioned as the foundation of international humanitarian law during armed conflict. Applying it to emerging maritime drones presents significant challenges. For example, in order to fall under the existing wartime legal framework, they would first need to be classified as *ships*. Only after this initial categorization could they potentially be recognized as *warships*, a designation that comes with stringent legal and structural requirements that most autonomous maritime systems do not meet. [66]

One illustrative example of this legal complexity is found in Article 18 of the Second Geneva Convention, which requires parties of a conflict to actively search for and assist the wounded, shipwrecked, and sick after naval engagements:

1. "**Article 18 – Search for casualties after an engagement:** After each engagement, Parties to the conflict shall, without delay, take all possible measures to search for and collect the shipwrecked, wounded and sick, to protect them against pillage and ill-treatment, to ensure their adequate care, and to search for the dead and prevent their being despoiled." [67]

This becomes operationally impractical in the context of small, autonomous mar-

itime drones, particularly those designed for kamikaze-style attacks, which lack any capability for rescue or post-conflict engagement. While there is ongoing research and development into specialized unmanned systems intended for maritime search and rescue, these technologies have not yet matured to a stage where they can be reliably deployed in real-world operations.

Among the existing legal instruments, Article 36 of the First Additional Protocol to the Geneva Conventions may be the most applicable to autonomous maritime systems. This provision mandates that each state must conduct legal reviews of new weapons to ensure compliance with international law:

1. "**Article 36 – New weapons:** In the study, development, acquisition or adoption of a new weapon, means or method of warfare, a High Contracting Party is under an obligation to determine whether its employment would, in some or all circumstances, be prohibited by this Protocol or by any other rule of international law applicable to the High Contracting Party." [67]

This article creates a legal obligation for states to assess whether new technologies, including maritime drones, conform to existing laws and norms before deployment. However, the application of Article 36 is still ambiguous in the context of autonomous systems, as it leaves significant room for interpretation regarding what constitutes a *new method of warfare* and whether current legal standards are sufficient.

6.5.1 European Union

While international frameworks such as the Geneva Conventions and the previously mentioned guiding principles offer general reference points, they are insufficient for comprehensively regulating autonomous maritime systems. Consequently, the European Union and individual states have begun to explore region-specific and national

regulatory approaches to address the legal and ethical challenges posed by these technologies.

In 2021, the European Commission introduced the Artificial Intelligence Act (AI Act). It is a proposed legal framework aimed at ensuring trustworthy and human-centric AI development across member states. While primarily focused on civilian applications, the regulation identifies high-risk AI systems and encourages transparency, oversight, and accountability mechanisms. [68] It does not specifically take into account military applications. However, it can have a negative effect during the development of dual-use applications.

Furthermore, the EU Code of Conduct for Artificial Intelligence in Defense, published by the European Defence Agency (EDA) in May 2025, outlines voluntary commitments for the ethical use of AI in military contexts. This code emphasizes aspects such as human responsibility, accountability, and compliance with international humanitarian law. Although non-binding, it shows the EU's recognition of the risks associated with integrating AI into autonomous systems. Additionally, it is quite broad since it takes different levels of warfare into account and how AI should be used at given levels. [69]

6.5.2 National-Level Regulations

On the national level, regulatory responses vary widely depending on each country's technological capabilities, defense policies, and legal traditions. For instance, looking at a few of the larger military powers [70]:

Germany has taken a cautious approach, consistently advocating for international bans or strict regulation of lethal autonomous weapon systems. The German government supports the principle that human decision-making must remain central in the use of force, aligning closely with ethical constraints grounded in international humanitarian law.

France has supported further development of military AI but also stresses the importance of human oversight. French defense doctrine emphasizes *meaningful human control* over weapon systems, and the country has actively participated in international forums discussing the regulation of LAWS. Additionally, China and Russia highlight the principle of meaningful human control in AWS but are quite permissive with the development of these systems.

The United Kingdom and the United States, on the other hand, have shown a more permissive stance, emphasizing innovation and operational effectiveness. While the UK upholds international legal obligations, it has not endorsed proposals for a binding international ban on autonomous weapons. British policy documents often refer to *autonomous systems* within a framework that prioritizes their military utility. In the U.S., the Department of Defense Directive 3000.09 is a regulation for AWS. The original was established in 2012 and revised in 2023. The U.S. has quite a different stance compared to others since they state that AWS should have *appropriate levels of human judgment*, which can be interpreted very differently from *meaningful human control or human control*. The 2012 version of this directive is one of the first-ever national-level regulations for AWS. [71] This directive allows the U.S. to develop AWS that may require no more than human supervision.

These national-level efforts reflect a fragmented regulatory environment, where states adopt different interpretations of their legal obligations and ethical responsibilities. This inconsistency complicates efforts to develop a harmonized global or even regional framework. The regulation report [70] states that 195 countries have issued statements on AWS. Of these, 129 support regulating AWS, while 12 oppose such regulation. The remaining 54 have not taken a clear stance. This means that approximately 66% of the countries favor regulating AWS.

In conclusion, there is currently no unified or comprehensive legal framework that adequately addresses the classification and regulation of maritime drones. Their

varied sizes, functionalities, and intended uses ranging from reconnaissance to direct engagement or search and rescue complicate attempts at universal categorization. However, some similarities can be seen, especially in the aspect of keeping the decision-making in the hands of humans.

7 Conclusion

This chapter concludes the thesis by summarizing the work completed and outlining potential directions for future research.

7.1 Summary

This thesis explored methods to enhance the efficiency of maritime drones and examined emerging trends and innovations in the future of naval drones. It examined the evolution of maritime drones and their development from the early days of World War I to the modern 21st century, with warfare as the key focus point.

The thesis introduced popular robotics tools for developing maritime drones, such as Robot Operating System and Mission Oriented Operating Suite Interval Programming. This thesis also explored various simulators and core technical foundations for developing maritime drones, along with current challenges, the global market, and future forecasts and estimations.

This thesis addresses the defined research questions, which include examining the tactical and strategic impacts of maritime drones in modern warfare, exploring how they can be better equipped and optimized, identifying the environmental and ethical challenges they pose, and reviewing the current regulatory frameworks.

The alarming reality of these military systems showcases the need for improved countermeasures, more advanced drones, and further innovations. The importance of unmanned naval systems is now evident. They serve as cost-effective weapons

on multiple levels of warfare. Nations with even no naval force can rely on a maritime drone fleet to attack enemy vessels. And we are just at the beginning of these systems. Initially, we saw only kamikaze drones. Currently, maritime drones can be equipped with air support, additional drones, torpedoes, electronic warfare equipment, and small arms. Maritime drones represent a transformative shift in naval warfare, with implications that extend from the tactical battlefield to the global strategic environment. Their affordability, flexibility, and autonomy make them a disruptive force that empowers new actors, enables covert operations, and challenges established doctrines of naval power. As different parties adapt to these technologies, the maritime domain is assured to become more contested, automated, and complex. The implications for deterrence, escalation, and global security are profound and will only grow as maritime drones continue to evolve.

7.2 Future Work

As mentioned earlier, marine robotics is not as advanced as other fields of robotics. Therefore, governments and private companies should invest more in these systems, as we have seen them successfully applied in real-life scenarios. Further research and innovation in maritime drone technology are essential on a global scale. This is especially true for Finland, which remains significantly behind other Nordic nations in advancing this sector. It is my perspective that the Finnish Defense Forces could contribute to this development far more without interfering with their regular activities. Collaborating with Ukraine has already led to some advancements in the field. The use of this technology in Finland is not new, as the Finnish Navy has employed it, but on a limited scale. Additionally, maritime drones developed in Western nations should adhere to NATO and EU standards. This standardization is crucial for guaranteed interoperability among maritime drone systems, which is vital for the collective defense of Western countries.

Furthermore, all developed maritime drones should have dual-use capabilities, allowing them to be modular and accommodate both military and civilian payloads. Currently, the largest joint military exercise on maritime drones is Robotic Experimentation and Prototyping Maritime Unmanned Systems Exercise (REPMUS), which takes place annually. In the REPMUS 2024 exercise, 2000 participants from 30 NATO and partner countries participated [72]. The next REPMUS will take place on the 25th of September, 2025, and participants are expected to demonstrate an even wider range of new maritime capabilities [73]. This joint exercise is a clear sign of the increased development and interest in these drones. The first fully autonomous war has yet to occur, but each technological advancement brings us closer to that reality.

References

- [1] D. Axe, “Ukraine’s All-Robot Assault Force Just Won Its First Battle”, en, *Forbes*, 2024. [Online]. Available: <https://www.forbes.com/sites/davidaxe/2024/12/21/ukraines-first-all-robot-assault-force-just-won-its-first-battle/> (visited on 05/30/2025).
- [2] A. Fratsyvir, “Ukraine’s AI-powered ‘mother drone’ sees first combat use, minister says”, en, *The Kyiv Independent*, 2025. [Online]. Available: <https://kyivindependent.com/ukraines-ai-powered-mother-drone-sees-first-combat-use-minister-says/> (visited on 05/30/2025).
- [3] *Unmanned surface vehicle - USV*, en. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Unmanned_surface_vehicle (visited on 05/25/2025).
- [4] *Unmanned underwater vehicle - UUV*, en. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Unmanned_underwater_vehicle (visited on 05/25/2025).
- [5] O. Danylov, “Naval strike drones: From ancient brigands to modern times”, en, *Mezha.Media*, 2023. [Online]. Available: <https://mezha.media/en/articles/naval-strike-drones-from-ancient-brigands-to-modern-times/> (visited on 03/17/2025).
- [6] J. Saul and R. Maltezoou, “Houthi explosive drone boat attacks escalate Red Sea danger”, en, *Reuters*, 2024. [Online]. Available: <https://www.reuters.com>

- om/world/middle-east/houthi-explosive-drone-boat-attacks-escalate-red-sea-danger-2024-07-03/ (visited on 05/21/2025).
- [7] J. Leman, “Tekoälyavusteiset asejärjestelmät nykyaikaisessa sodankäynnissä”, fi, 2023. [Online]. Available: <https://www.utupub.fi/handle/10024/179850> (visited on 05/25/2025).
- [8] *Remotely operated underwater vehicle*, en. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Remotely_operated_underwater_vehicle (visited on 05/25/2025).
- [9] *Nato marine unmanned systems*, en, 2020. [Online]. Available: https://www.nato.int/nato_static_fl2014/assets/pdf/2020/11/pdf/2011-factheet-mus.pdf (visited on 05/25/2025).
- [10] *European defense agency - UMS*, en. [Online]. Available: [https://eda.europa.eu/what-we-do/all-activities/activities-search/unmanned-maritime-systems-\(ums\)-research](https://eda.europa.eu/what-we-do/all-activities/activities-search/unmanned-maritime-systems-(ums)-research) (visited on 05/16/2025).
- [11] P. Small, *Unmanned maritime systems*, en, 2019. [Online]. Available: <https://www.navsea.navy.mil/Portals/103/Documents/Exhibits/SNA2019/UnmannedMaritimeSys-Small.pdf?ver=2019-01-15-165105-297> (visited on 05/26/2025).
- [12] T. Nikola, “Method of and apparatus for controlling mechanism of moving vessels or vehicles”, en, US613809A, 1898. [Online]. Available: <https://patents.google.com/patent/US613809/en> (visited on 05/25/2025).
- [13] *FL-boat*, en. [Online]. Available: <https://en.wikipedia.org/w/index.php?title=FL-boat> (visited on 05/25/2025).
- [14] *Protector USV*, en. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Protector_USV (visited on 05/25/2025).

- [15] “ACTUV “Sea Hunter” Prototype Transitions to Office of Naval Research for Further Development”, en, 2018. [Online]. Available: <https://www.darpa.mil/news/2018/sea-hunter-prototype> (visited on 05/27/2025).
- [16] T. Ozberk, “MARLIN USV: Meet Turkiye’s Latest Drone Ship”, en, *Naval News*, 2022. [Online]. Available: <https://www.navalnews.com/naval-news/2022/09/marlin-usv-meet-turkiyes-latest-drone-ship/> (visited on 05/21/2025).
- [17] A. Mazurenko, “Russia creates marine drone similar to Ukrainian SeaBaby”, en, *Ukrainska Pravda*, 2023. [Online]. Available: <https://www.pravda.com.ua/eng/news/2023/12/15/7433230/> (visited on 05/25/2025).
- [18] H. Sutton, *Russia faces new threat: Ukraine’s ‘Toloka’ underwater maritime drone*, en, 2023. [Online]. Available: <http://www.hisutton.com/New-Ukraine-Underwater-Maritime-Drone.html> (visited on 05/22/2025).
- [19] H. R. Widditsch, “SPURV - The First Decade:” en, Defense Technical Information Center, Fort Belvoir, VA, Tech. Rep., 1973. DOI: 10.21236/ADA050816. (visited on 05/26/2025).
- [20] A. Bursuc *et al.*, “Overview on Sea Drones Evolution and their Use in Modern Warfare”, en, *Land Forces Academy Review*, vol. 29, no. 2, pp. 195–209, 2024. DOI: 10.2478/raft-2024-0021. (visited on 03/27/2025).
- [21] *History of UUV | Exploring NUSTEM*, en. [Online]. Available: <https://nustem.bridgeport.edu/history-of-uuv/> (visited on 05/26/2025).
- [22] H. Sutton, *Captured UUV in Pyongyang North Korea*, en, 2020. [Online]. Available: <http://www.hisutton.com/Captured-UUV-in-Pyongyang-North-Korea.html> (visited on 06/02/2025).

-
- [23] E. Ciobanu, *The History of Underwater Drones - Droneblog*, en, 2018. [Online]. Available: <https://www.droneblog.com/the-history-of-underwater-drones/> (visited on 06/02/2025).
- [24] *REMUS (vehicle)*, en. [Online]. Available: [https://en.wikipedia.org/w/index.php?title=REMUS_\(vehicle\)](https://en.wikipedia.org/w/index.php?title=REMUS_(vehicle)) (visited on 06/02/2025).
- [25] *Manta Ray*, en. [Online]. Available: <https://www.northropgrumman.com/what-we-do/sea/manta-ray> (visited on 04/14/2025).
- [26] *Anduril industries, inc.* en. [Online]. Available: <https://www.anduril.com> (visited on 05/25/2025).
- [27] S. Gujar and P. Paul, “Unmanned marine vehicles market size, share & analysis – 2034”, en, *Global Market Insights Inc.*, 2024. [Online]. Available: <https://www.gminsights.com/industry-analysis/unmanned-marine-vehicles-market> (visited on 04/11/2025).
- [28] A. Miller, B. Miller, and G. Miller, “Navigation of Underwater Drones and Integration of Acoustic Sensing with Onboard Inertial Navigation System”, en, *Drones*, vol. 5, no. 3, p. 83, 2021. DOI: 10.3390/drones5030083. (visited on 03/10/2025).
- [29] E. Zereik *et al.*, “Challenges and future trends in marine robotics”, en, *Annual Reviews in Control*, vol. 46, pp. 350–368, 2018. DOI: 10.1016/j.arcontrol.2018.10.002. (visited on 05/30/2025).
- [30] Y. Wu *et al.*, “A Review of Path Planning Methods for Marine Autonomous Surface Vehicles”, en, *Journal of Marine Science and Engineering*, vol. 12, no. 5, p. 833, 2024. DOI: 10.3390/jmse12050833. (visited on 03/09/2025).
- [31] F. Rubino *et al.*, “Marine Application of Fiber Reinforced Composites: A Review”, en, *Journal of Marine Science and Engineering*, vol. 8, no. 1, p. 26, 2020. DOI: 10.3390/jmse8010026. (visited on 06/01/2025).

- [32] *ROS 2 Documentation: Kilted documentation*, en. [Online]. Available: <https://docs.ros.org/en/kilted/index.html> (visited on 05/27/2025).
- [33] *MOOS-IvP Documentation*, en. [Online]. Available: <https://oceanai.mit.edu/moos-ivp> (visited on 06/01/2025).
- [34] M. E. Orye *et al.*, “Enhancing the Cyber Resilience of Sea Drones”, en, in *2024 16th International Conference on Cyber Conflict: Over the Horizon (CyCon)*, Tallinn, Estonia: IEEE, 2024, pp. 83–102. DOI: 10.23919/CyCon62501.2024.10685581. (visited on 06/01/2025).
- [35] E. Jokioinen *et al.*, “Rolls Royce AAWA Report”, en, Tech. Rep., 2016. [Online]. Available: <https://www.utupub.fi/handle/10024/157117> (visited on 05/21/2025).
- [36] T. McMillan, *Stealth Technology Breakthrough By Navy Researchers Could Revolutionize Underwater Drone Capabilities*, en, 2025. [Online]. Available: <https://thedebrief.org/stealth-technology-breakthrough-by-navy-researchers-could-revolutionize-underwater-drone-capabilities/> (visited on 06/01/2025).
- [37] P. Giangiuseppe, *Sea drones at war: Tactical, operational and strategic analysis of maritime uncrewed systems*, en, 2024. [Online]. Available: <https://euro-sd.com/2024/09/articles/40191> (visited on 03/18/2025).
- [38] I. Usmanov and M. Chernychka, “Maritime autonomous weapon systems from the standpoint of international humanitarian law”, en, *Lex Portus*, 2022. DOI: 10.26886/2524-101X.8.2.2022.2. (visited on 03/20/2025).
- [39] *Fluid dynamics*, en. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Fluid_dynamics (visited on 05/27/2025).

- [40] *The Wave Glider / Unmanned Surface Vehicle by Liquid Robotics*, en. [Online]. Available: <https://www.liquid-robotics.com/wave-glider/overview/> (visited on 04/14/2025).
- [41] N. Rennolds, "Huge US military 'Manta Ray' sea drone spotted on Google Earth at California naval base", en, *Business Insider*, 2024. [Online]. Available: <https://www.businessinsider.com/us-navy-manta-ray-sea-drone-california-coast-google-earth-2024-6> (visited on 04/14/2025).
- [42] *The TRITON*, en. [Online]. Available: <https://www.oceanaero.com/the-triton> (visited on 04/14/2025).
- [43] M. Tanner, "Tällainen on Suomessa kehitetty moottoroitu ja aseistettava taistelusrffilauta "Meri-Turso"", fi, *Tekniikka&Talous*, 2024. [Online]. Available: <https://www.tekniikkatalous.fi/uutiset/tallinen-on-suomessa-kehitetty-moottoroitu-ja-aseistettava-taistelusrffilauta-meri-turso-jolla-voisi-valvoa-venalaisten-sukellusveneita/6821d8ae-4ed4-4cf8-99a0-9ae7600d374a> (visited on 03/31/2025).
- [44] V. Kykkänen, "Näin Suomessa kehitetään nyt drooniteknologiaa sotaan: "siirrytään maratonista pikamatkoille"", fi, *mtvuutiset.fi*, 2025. [Online]. Available: <https://www.mtvuutiset.fi/artikkeli/nain-suomessa-kehitetaan-nyt-drooniteknologiaa-sotaan-siirrytaan-maratonista-pikamatkoille/9091648> (visited on 03/31/2025).
- [45] J. Rice-Jones and A. Pande, "Best single board computers in 2025", en, *XDA*, 2023. [Online]. Available: <https://www.xda-developers.com/best-single-board-computer/> (visited on 06/02/2025).
- [46] *ADAPTIV - Cloak of Invisibility*, en. [Online]. Available: <https://www.baesystems.com/en-us/product/adaptiv> (visited on 06/02/2025).

- [47] C. H. Popa *et al.*, “Distributed Maritime Operations and Unmanned Systems Tactical Employment”, en, Tech. Rep., 2018. [Online]. Available: https://calhoun.nps.edu/bitstream/handle/10945/59587/18Jun_SE_Capstone_Popa_et_al.pdf (visited on 06/02/2025).
- [48] H. Uçar, “RADAR CROSS SECTION REDUCTION”, en, *Journal of Naval Science and Engineering*, vol. 9, no. 2, pp. 72–87, 2013. [Online]. Available: https://www.researchgate.net/publication/305721036_Radar_Cross_Section_Reduction (visited on 06/02/2025).
- [49] C.-h. Hung and J. Chung, “Uncrewed surface vehicle unveiled - Taipei Times”, en, 2025. [Online]. Available: <https://www.taipeitimes.com/News/front/archives/2025/03/26/2003834074> (visited on 06/02/2025).
- [50] M. El-Hajj, “Enhancing Communication Networks in the New Era with Artificial Intelligence: Techniques, Applications, and Future Directions”, en, *Network*, vol. 5, no. 1, p. 1, 2025. DOI: 10.3390/network5010001. (visited on 06/02/2025).
- [51] P. Giordano, “Dynamic Messenger 23 Provides Lessons For Autonomous Vehicles in NATO Multi Domain Operations”, en, *NATO’s ACT*, 2023. [Online]. Available: <https://www.act.nato.int/article/dynmsg23-further-nato-mdo/> (visited on 06/02/2025).
- [52] M. Zetas *et al.*, “Empowering 6G maritime communications with distributed intelligence and over-the-air model sharing”, en, *Frontiers in Communications and Networks*, vol. 4, 2024. DOI: 10.3389/frcmn.2023.1280602. (visited on 06/06/2025).
- [53] *385th Unmanned Surface Vehicles Brigade (Ukraine)*, en. [Online]. Available: [https://en.wikipedia.org/w/index.php?title=385th_Unmanned_Surface_Vehicles_Brigade_\(Ukraine\)](https://en.wikipedia.org/w/index.php?title=385th_Unmanned_Surface_Vehicles_Brigade_(Ukraine)) (visited on 06/06/2025).

- [54] A. Fratsyvir, “Ukrainian drones destroy Russian radar, supply depots on Black Sea gas platforms, SBU says”, en, *The Kyiv Independent*, 2025. [Online]. Available: <https://kyivindependent.com/ukrainian-drones-destroy-russian-radar-and-supply-depots-on-black-sea-drilling-platforms/> (visited on 05/27/2025).
- [55] J. Waterhouse and K. Armstrong, “Russian ship hit in Novorossiysk, Black Sea drone attack, Ukraine sources say”, en, 2023. [Online]. Available: <https://www.bbc.com/news/world-europe-66402046> (visited on 04/17/2025).
- [56] H. Sutton, *Overview of maritime drones (usvs) of the russo-ukrainian war, 2022-24*, en, 2024. [Online]. Available: <http://www.hisutton.com/Russia-Ukraine-USVs-2024.html> (visited on 05/21/2025).
- [57] M. Bubalo and E. Goksedef, “Ukraine says it launched July attack on bridge to Crimea”, en, 2023. [Online]. Available: <https://www.bbc.com/news/world-europe-66397227> (visited on 04/15/2025).
- [58] S. Scarr *et al.*, “How Yemen’s Houthi rebels are carrying out attacks on Red Sea ships”, en, *Reuters*, 2024. [Online]. Available: <https://www.reuters.com/graphics/ISRAEL-PALESTINIANS/SHIPPING-ARMS/lgvdnngeyvo/> (visited on 04/20/2025).
- [59] E. Klutstein, *The new front against iran and its proxies: Underwater*, en, 2024. [Online]. Available: <https://www.misgavins.org/en/klutstein-the-new-front-against-iran-and-its-proxies-underwater/> (visited on 04/20/2025).
- [60] H. Sutton, *Houthi’s blowfish: Guide to explosive USV threat in Red Sea*, en, 2024. [Online]. Available: <http://www.hisutton.com/Yemen-Houthi-USV-Guide.html> (visited on 05/21/2025).

-
- [61] *BlueWhale (UUV)*, en. [Online]. Available: [https://en.wikipedia.org/w/index.php?title=BlueWhale_\(UUV\)](https://en.wikipedia.org/w/index.php?title=BlueWhale_(UUV)) (visited on 05/27/2025).
- [62] I. Hilton, "Taiwan Makes the Majority of the World's Computer Chips. Now It's Running Out of Electricity", en, *Wired*, [Online]. Available: <https://www.wired.com/story/taiwan-makes-the-majority-of-the-worlds-computer-chips-now-its-running-out-of-electricity/> (visited on 06/03/2025).
- [63] C. T. Moon, *Chinese Seize U.S. Navy Underwater Drone in South China Sea*, en. [Online]. Available: <https://www.defense.gov/News/News-Stories/Article/Article/1032823/> (visited on 06/03/2025).
- [64] M. Hernandez, "Maps: Tracking Tensions Between China and Taiwan", en, *The New York Times*, 2022. [Online]. Available: <https://www.nytimes.com/interactive/2022/world/asia/taiwan-china-maps.html> (visited on 05/21/2025).
- [65] *KATRAN "VENOM" - MAC - Military Armored Company HUB*, uk, 2024. [Online]. Available: <https://vpk-mac.com/katran-venom/> (visited on 04/14/2025).
- [66] C. M. Liu, *The Unresolved Legal Status of Maritime Drones: (War)ships or Weapons? - RSIS*, en, 2024. [Online]. Available: <https://rsis.edu.sg/rsis-publication/idss/ip24097> (visited on 06/09/2025).
- [67] *The Geneva Conventions and their Commentaries | ICRC*, en, 2024. [Online]. Available: <https://www.icrc.org/en/law-and-policy/geneva-conventions-and-their-commentaries> (visited on 06/11/2025).
- [68] *European Union AI Act: First regulation on artificial intelligence*, en, 2023. [Online]. Available: <https://www.europarl.europa.eu/topics/en/article/20230601ST093804> (visited on 06/09/2025).

-
- [69] *Trustworthiness for ai in defence*, en, 2025. [Online]. Available: <https://eda.europa.eu/docs/default-source/brochures/taid-white-paper-final-09052025.pdf> (visited on 06/09/2025).
- [70] T. Jones, *How Nations are Responding to Autonomous Weapons in War*, en, 2025. [Online]. Available: <https://autonomousweapons.org/global-perspectives-on-regulation/> (visited on 06/10/2025).
- [71] K. M. Sayler, *Defense Primer: U.S. Policy on Lethal Autonomous Weapon Systems*, en, legislation, 2025. [Online]. Available: <https://www.congress.gov/crs-product/IF11150> (visited on 06/10/2025).
- [72] NATO, *NATO's Digital Ocean Initiative gets a boost in Portugal*, en, 2024. [Online]. Available: https://www.nato.int/cps/en/natohq/news_228959.htm (visited on 05/21/2025).
- [73] *REPMUS 2025 CALLING NOTICE - Find a Tender*, en, 2025. [Online]. Available: <https://www.find-tender.service.gov.uk/Notice/007342-2025> (visited on 05/21/2025).