AUTONOMY AND ROBOTICS TECHNICAL REPORT

VSY Innovation Team

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Contents

1.0 Definitions

The following definitions are used throughout this document and are provided for clarity and documentation.

Term	Definition
VSY	Seaspan Vancouver Shipyard
ART	Autonomy and Robotics Technologies
UVV	Unmanned Underwater Vehicles
AUV	Autonomous Underwater Vehicles
CPPS	Cyber-Physical Production Systems
AM	Additive Manufacturing
AR	Augmented Reality
PLM	Product Lifecycle Management
GMAW	Gas Metal Arc Welding
WAAM	Wire Arc Additive Manufacturing
ROV	Remotely Operated Vehicles
VDC	Vancouver Dry Docks
NFRF	New Frontiers in Research Transformation
CFI	Canada Foundation for Innovation
JELF	John R. Evans Leaders Fund
DOF	Degrees of Freedom
LiDAR	Light Detection and Ranging sensors
KPI	Key Performance Indicators
CSR	Confined Space Robotics Inc.
CMP	Co-bot Mobility Platform
GTAW	Gun Tungsten Arc Welding

2.0 Purpose

This document outlines potential technologies for the development of **Autonomy and Robotics Technology (ART)** within Seaspan. The aim is to present ART solutions for specific applications. It highlights current gaps, data sources, feasibility analyses, and describes the core features and functions of proposed ART technologies.

3.0 Autonomy and Robotics Overview

The marine science and technology industry has experienced rapid growth over the past two decades. There is increasing interest in ocean exploration and the development of technological products for maritime and offshore applications, particularly in marine robotics [1]. Current efforts focus on utilizing advanced technologies such as remotely operated vehicles and autonomous robots to enhance our understanding of the ocean, as well as to support maritime and naval operations. Key applications include ship monitoring, emergency operation support, and offshore inspections [1].

3.1.0 Autonomy versus Robotics

The terms "autonomy" and "robotics" are often used interchangeably, though they refer to distinct concepts.

Robotics is a field within engineering and computer science that focuses on creating intelligent machines to assist humans with various tasks [2]. Robotics encompasses a wide range of devices, from simple remote-controlled toys to complex robots used in manufacturing that perform repetitive tasks [2].

Autonomy refers to the ability to operate independently without external guidance. In technology, this means applications can perform tasks without direct human intervention [3]. The term "autonomous" is commonly associated with artificial intelligence, robotics, and agents such as bots [4].

When combined, autonomy and robotics result in machines that function like humans without requiring constant human control. Examples of autonomous robots include cleaning robots like Roomba, food delivery robots from Uber Eats, and self-driving vehicles like Waymo's [4]. These robots are equipped with sensors and systems that help them detect obstacles, navigate, and operate safely, as illustrated in Figure 1 below.

FIGURE 1: SENSORS ON A WAYMO FUNCTIONING IN SAN FRANCISCO [5].

Co-bots, or collaborative robots [6], are designed to work alongside humans in various tasks. They are equipped with sensors that continuously assess their environment and automatically switch to safety mode if a human disrupts their operations [6]. Depending on the application, these robots can be **semi-autonomous** or fully operated by humans. In Section 7.0, we will propose co-bots specifically for welding and painting tasks.

3.2.0 Robotics in Maritime Manufacturing

Robotics in maritime manufacturing plays a significant role in reducing safety concerns, enhancing production processes, increasing precision and reducing human labor [@]. The integration of robotics and automation technologies has led to greater efficiency and innovation in shipbuilding and offshore platform construction. Below are key areas where robotics are transforming manufacturing processes in the maritime industry:

1. **Automated Shipbuilding and Assembly:** Robotic systems are widely used in shipyards for assembly and construction tasks. These systems perform repetitive tasks with high precision, improving productivity and reducing human error.
    a. **Welding Robots:** Automated welding systems are increasingly used in shipbuilding for precision in joining large metal plates and structures. These robots ensure high-quality welds that meet safety and structural integrity standards, which are essential for maritime vessels.
    b. **Robotic Arms for Assembly:** Robotic arms are used to lift and position heavy components, such as ship sections, beams, and machinery, accurately within the production line. These robotic arms enable faster assembly and ensure precise alignment during the manufacturing process.

2. **Robotic Inspection and Quality Control:** Quality control is a critical aspect of maritime manufacturing, and robotics are increasingly used for inspecting and ensuring the quality of manufactured parts and ships.
    a. **Vision Systems and Sensors:** Robots equipped with vision systems and sensors are used to inspect ship components for defects such as cracks, corrosion, or imperfections in welding. These systems provide consistent, reliable quality checks that are crucial for ensuring the safety and durability of maritime vessels.
    b. **Non-Destructive Testing (NDT):** Robotics equipped with ultrasonic and other NDT methods are used to inspect materials for internal defects without causing damage. This allows manufacturers to identify potential issues early in the production process.

3. **Automation in Subsea Platform Manufacturing:** In addition to shipbuilding, robotics also play a significant role in the manufacturing of offshore platforms and subsea systems.
    a. **Automated Welding and Cutting:** Robotic systems are employed for welding and cutting operations on subsea platforms, where human access is limited. These systems perform tasks such as cutting metal structures, welding pipes, and assembling large subsea modules, enhancing productivity, and reducing costs.
    b. **Robotic Assistance in Component Testing:** Robotics are used to test various components and systems in offshore platforms before they are deployed, ensuring they meet the strict standards for operation in harsh marine environments.

The integration of robotics in maritime manufacturing has led to improved safety, efficiency, and precision in shipbuilding and offshore platform construction. As technology continues to advance, we can expect even more sophisticated manufacturing solutions that contribute to improving safety, reducing costs and more efficient operations in the maritime industry.

3.3.0 In Water Robotics in Maritime Industry

The application of in-water robotics within the maritime industry has seen significant growth, particularly in areas such as maintenance and inspection. These robotic systems, often in the form of **autonomous underwater vehicles (AUVs)** and **remotely operated vehicles (ROVs)**, play a crucial role in enhancing the efficiency and safety of maritime operations. Below are key areas where in-water robotics are applied in the maritime sector:

1. **Underwater Inspection and Monitoring:** In-water robots, particularly ROVs, are essential tools for inspecting submerged maritime structures like ship hulls, offshore platforms, and subsea pipelines. These robots are equipped with high-

definition cameras, sonar, and other sensors to detect structural damage, corrosion, biofouling, and leaks.

   a. **Hull Inspection:** ROVs and AUVs are used to inspect ship hulls for signs of damage, deterioration, or the presence of invasive species that could affect the vessel's performance and safety. These inspections are conducted without the need for human divers, improving safety and reducing downtime.
   b. **Subsea Infrastructure:** ROVs are critical for maintaining and inspecting underwater infrastructure like pipelines, cables, and underwater rigs. These robots can operate at great depths, often in hazardous environments, ensuring that critical maritime infrastructure remains operational.

2. **Marine Environmental Monitoring**: In-water robotics are increasingly used for environmental monitoring in oceans and seas. These robots help to collect data on water quality, temperature, salinity, and other environmental parameters.
   a. **Pollution Detection:** AUVs are deployed to monitor marine pollution levels, including oil spills and plastic debris. They can traverse large distances autonomously, collecting data and providing real-time information on pollution events, which is crucial for environmental protection and response efforts.
   b. **Marine Wildlife Monitoring:** In-water robots equipped with sensors can also be used for non-invasive monitoring of marine wildlife populations. They collect data on biodiversity, allowing researchers to study ecosystems without disturbing fragile marine habitats.

3. **Autonomous Navigation and Exploration:** AUVs, equipped with sophisticated navigation systems and sensors, can autonomously explore underwater environments for scientific research, resource exploration, or even military applications.
   a. **Seafloor Mapping and Resource Exploration:** AUVs are used for seafloor mapping, helping to locate natural resources such as oil, gas, and minerals. They can map the seabed with high resolution, providing data that is vital for offshore resource exploration.
   b. **Autonomous Navigation:** These robots navigate autonomously using GPS, sonar, and other advanced sensors. This autonomy is particularly useful for deep-sea exploration, where human presence is impractical or impossible due to pressure and environmental conditions.

In-water robotics are transforming the maritime industry by providing safer, more efficient, and cost-effective solutions for underwater inspection, monitoring, and maintenance. With the ability to operate in extreme conditions, these robots are indispensable for ensuring the safety, sustainability, and productivity of maritime operations, from routine vessel maintenance to environmental monitoring.

3.4.0 Current State of the Art within ART

While advancements in robotic applications within the maritime and naval industries have progressed, the ocean remains a challenging environment with several constraints. Key issues include high pressure and low temperatures in polar regions, bandwidth limitations in acoustic communication devices, and restricted power supply systems for long-range missions [1]. Additionally, autonomous applications require effective navigation, motion control, and mission control systems [1]. Despite these challenges, there have been successful implementations of robotic applications.

3.4.1. Current State of the Art within Shipbuilding

The shipbuilding industry, though historically labor-intensive, is gradually integrating advanced technologies. Despite its complexity and project-based nature, recent innovations are transforming shipbuilding into a more efficient and digitally driven sector. Below are the key advancements that define the current state of the art in shipbuilding:

1. **Integration of Cyber-Physical Production Systems (CPPS):** The adoption of cyber-physical production systems (CPPS) marks a significant step in modern shipbuilding. These systems enable real-time communication and collaboration between manufacturing components, allowing for intelligent decision-making during the production process. This capability supports the flexible production of high-quality, customized vessels with efficiency levels approaching mass production.

2. **Digital Continuity Across the Product Lifecycle:** Digital continuity is a central feature of I4.0 in shipbuilding, facilitating the integration of design and manufacturing processes. Real-time, decentralized design systems collect and optimize manufacturing information, enabling seamless alignment of design and production. This holistic approach ensures that the entire lifecycle of a ship, from initial design to construction and maintenance, benefits from improved coordination and efficiency.

3. **Additive Manufacturing (AM) and Augmented Reality (AR):** Emerging technologies such as additive manufacturing (AM) and augmented reality (AR) are becoming pivotal in shipbuilding. AM is being utilized for producing specialized components and for on-demand manufacturing of spare parts, significantly reducing inventory and production lead times. AR, on the other hand, is enhancing

ship maintenance and assembly by providing workers with real-time, immersive visualizations of complex tasks, improving accuracy and reducing errors.

4. **Intelligent Automation and Early-Stage Optimization:** While automation in shipyards is less advanced compared to industries like automotive and mechanical engineering, it is predominantly applied in the initial stages of production where intermediate products share similarities. Automation technologies, including robotics, are increasingly utilized for welding, cutting, and other repetitive tasks, streamlining operations and reducing manual labor.

5. **Challenges in Complex, Project-Based Manufacturing:** Despite these advancements, the shipbuilding industry faces unique challenges. Shipbuilding projects are highly individualized, involving millions of distinct components that vary significantly as production progresses. The distributed nature of manufacturing, where components are produced at different locations, adds further complexity. These factors often limit the extent of automation in later stages of production and demand specialized expertise and strategic coordination.

6. **Product Lifecycle Management (PLM) and Strategic Integration:** The integration of Product Lifecycle Management (PLM) systems is helping shipbuilders address the complexities of managing product information across the lifecycle. PLM systems support the adoption of I4.0 solutions, enabling smarter decision-making and resource optimization. PLM tools are essential for the transition to digital continuity, ensuring that design, manufacturing, and maintenance processes are interconnected and efficient.

7. **The Shift Towards Smart Manufacturing:** Smart manufacturing technologies are becoming a necessity for shipbuilders to remain competitive. These include automation solutions, intelligent visualization tools, and interconnected systems that enhance collaboration across the construction value chain. However, compared to sectors such as automotive, shipbuilding lags in adopting these innovations due to the industry's high costs, complexity, and reliance on traditional methods.

The current state of the art in shipbuilding reflects a gradual yet significant shift toward digital transformation and smart manufacturing. While challenges remain, especially in achieving full automation and digital integration, the adoption of technologies such as

CPPS, AM, AR, and PLM are paving the way for a more efficient, sustainable, and competitive shipbuilding industry.

3.4.2 Current State of the Art within In-Water Robotic Applications

Most of these applications focus on **Unmanned Underwater Vehicles (UUVs)** and **Autonomous Underwater Vehicles (AUVs)**. Notable projects that have emerged and continue to evolve within the industry include various use cases, such as seafloor mapping, 3D inspections of offshore infrastructure, dam inspections, and deep-water archaeology [1]. However, it is important to recognize that technology often has limited operational depth, and many applications struggle in areas with significant 3D relief [1].

Improving safety is a critical focus in maritime technology. For instance, when divers operate in harsh underwater conditions on naval ship hulls, the **CADDY**—a specialized autonomous underwater vehicle—was developed to enhance diver safety and support [7]. The CADDY serves three core functions: monitoring diver safety, acting as an extended arm for underwater tasks, and performing simple operations like illuminating areas or capturing images [7]. Before a mission, both the diver and the CADDY are briefed on the plan. The CADDY then guides the diver along a predetermined path, ensuring proper distance and responsiveness to pre-trained hand signals for communication [7]. Detailed functions and objectives of the CADDY are depicted in Figure 2.

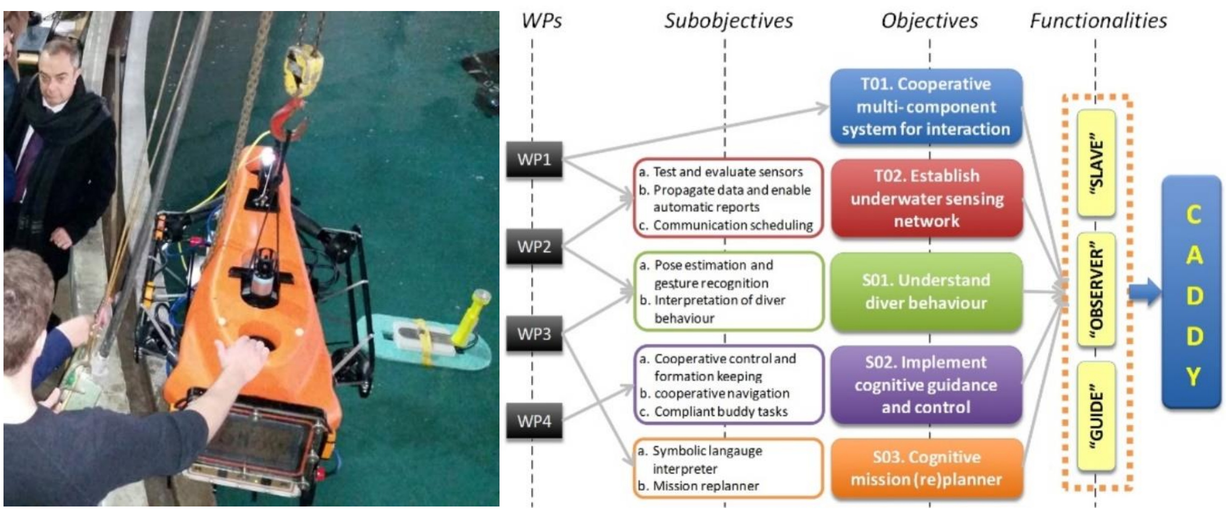

FIGURE 2: CADDY'S FUNCTIONS, OBJECTIVES AND VISUAL [7].

Underwater exploration and mapping are crucial for gathering navigation data and visualizing the ocean floor. The Morph Project was initiated to address challenges in mapping underwater environments that current technology struggles to handle [1]. This project innovated underwater robotics by developing a system of multiple mobile robot nodes equipped with complementary sensors. These nodes communicate via flexible links, facilitating information flow without the constraints of physical connections [8].

This adaptive capability allows the robots to reconfigure based on their environment, which enhances the number of simultaneous viewpoints and enables high-resolution data collection [1]. Figure 3 illustrates how these links can adapt to different environments. Potential applications of the Morph Project include pipeline and harbor monitoring, as well as studies of cold-water coral reefs and ecosystems in underwater canyons [8].

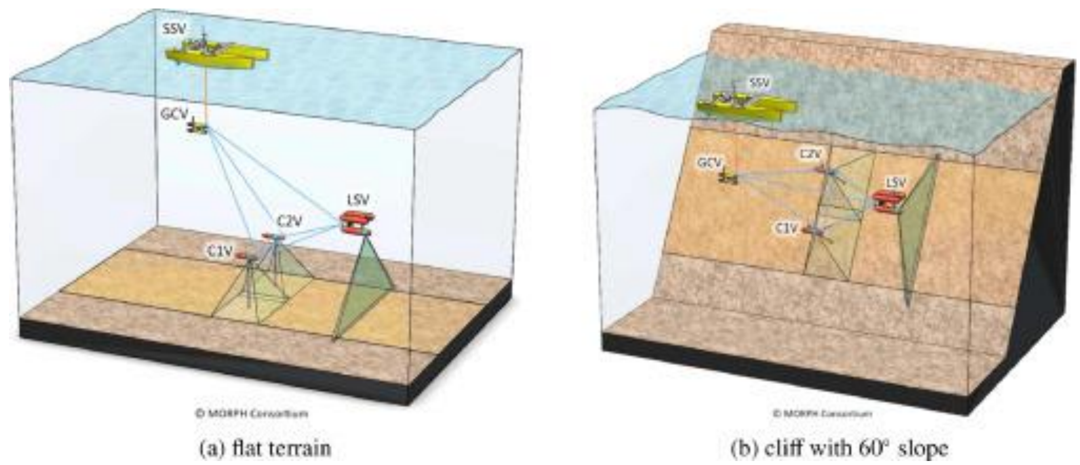

FIGURE 3: HOW THE ROBOT WORKS IN DIFFERENT ENVIRONMENTS [8]

Completing repetitive underwater missions presents an opportunity to enhance efficiency. The PANDORA project focuses on an Autonomous Underwater Vehicle (AUV) designed for executing repetitive tasks within a water tank [1]. PANDORA can detect task execution failures, respond appropriately, and operate robustly under various conditions. It has a runtime of up to three hours without intervention, even in water tanks that experience perturbation currents, blocked valves, and panel occlusions [1].

The PANDORA system operates in five phases: dive, transit, approach, docking, and intervention [9]. During the dive phase, the vehicle is deployed from a support boat and transitions into the transit phase, where it engages in cooperative navigation with the surface AUV until it reaches the designated acoustic coverage area [9]. In the approach phase, the vehicle locates the AUV-friendly intervention panel to dock. Once attached, it performs manipulation tasks such as opening or closing valves and unplugging or plugging connectors [9].

FIGURE 4: PANDORA IN ACTION WITHIN A WATER TANK [9]

A key 3D simulation tool utilized in both the PANDORA and Morph projects is UWSim [9]. This software is essential for validating and establishing benchmarking mechanisms within the simulator, allowing for easy comparison of control and vision algorithms [9]. UWSim features a Graphical User Interface (GUI) that facilitates the necessary human-robot interaction required to complete tasks [9].

Current advancements are focused on creating a software development environment that offers extensive simulation capabilities. This integrated software, based on the ROS framework, aims to enable any AUV to function as a Morph node by simply adding a unified interface [9].

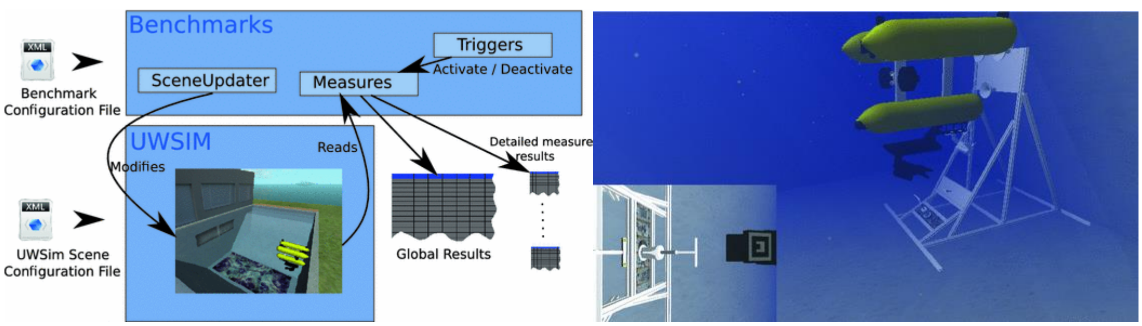

FIGURE 5: IMPLEMENTATION OF UWSIM WITHIN PANDORA [9]

In conclusion, Autonomy and Robotics Technology (ART) within the industry has been actively advancing over the past two decades. Many projects have resulted in viable products that are now being sold or implemented in various studies to promote further innovation.

3.4.2 Current State of the Art within Manufacturing Robotic Applications

Manufacturing robots have become integral to the modernization of production processes across various industries, including shipbuilding and maritime construction. Robotic systems are increasingly utilized to enhance efficiency, accuracy, and safety while reducing costs and dependency on manual labor. Below is an overview of the current state of the art in manufacturing robots for maritime applications:

1. **Diverse Robotic Welding Techniques:** Manufacturing robots in the maritime industry employ a variety of welding techniques to address the unique challenges posed by marine structures:

- **Gas Metal Arc Welding (GMAW):** The dominant technique in robotic welding, appreciated for its ability to deliver consistent quality and high productivity, particularly with carbon steel.
- **Laser Welding and Hybrid Techniques:** These methods are being explored for their precision and ability to weld complex materials and configurations.
- **Wire Arc Additive Manufacturing (WAAM):** This technique has gained traction for its potential in creating complex components and supporting on-demand part production.

2. **Material Versatility and Advancements:** Robotic systems in maritime manufacturing are primarily used with carbon steel, given its prevalence in ship construction. However, there is a growing focus on expanding material compatibility to include high-strength alloys, aluminum, nickel-aluminum bronze, and other specialized materials. This expansion reflects the industry's evolving needs for lighter, stronger, and more corrosion-resistant materials.

3. **Technological Innovations in Robotic Systems:** Several cutting-edge developments have shaped the capabilities of manufacturing robots in the maritime sector:

- **6-Axis Robotic Arms:** These systems offer enhanced flexibility and precision, allowing robots to navigate complex geometries and confined spaces typical of marine structures.
- **Vision-Assisted and Sensor-Enabled Systems:** Technologies like laser vision systems and sensors enable real-time monitoring and adaptive control, improving weld accuracy and reducing defects.
- **Portable and Mobile Robotic Platforms:** These systems are specifically designed for large-scale and confined environments, such as double-hulled ship structures, facilitating operations in challenging maritime settings.

Some key advantages of using manufacturing robots include safety and accessibility. enhanced productivity and improved quality and consistency. On the other hand, several challenges hinder the widespread adoption of manufacturing robots in the maritime sector. The complexity of marine structures, environmental constraints, material and process diversity and integration and control are all factors that hold the industry back. Although, ongoing research is addressing these challenges by optimizing welding parameters, developing intelligent control systems, and exploring advanced materials for maritime applications. Collaborative mobile robots, vision-assisted finishing systems, and noise-filtering algorithms for laser systems represent some of the cutting-edge innovations being explored.

The current state of the art in manufacturing robots for the maritime industry underscores a transformative shift toward automation, driven by technological advancements in robotic welding and process control. While challenges persist, particularly in adapting to the complexities of shipbuilding, the integration of intelligent, flexible, and adaptive robotic systems holds the promise of revolutionizing maritime manufacturing, enhancing efficiency, safety, and competitiveness.

4.0 Benefits to Seaspan

There are three area's that can enable a more effective and efficient use of ART:

1. Improving Operational Safety
2. Improving Efficiency of Scaling Capabilities & Managing Workload Increases
3. Improving Repeatability Time of tasks

4.1.0 Improving Operational Safety

The marine industry includes various activities, such as shipbuilding, maintenance, cargo handling, and offshore operations. Each of these areas poses unique risks, including exposure to heavy machinery, hazardous materials, and difficult environmental conditions. By investing in automation and robotics, operational safety can be significantly improved. These technologies can take over high-risk tasks in hazardous environments, enabling real-time monitoring of operations and environmental conditions, thus enhancing safety for personnel.

4.2.0 Improving Efficiency of Scaling Capabilities & Managing Workload Increases

Recent investments in the marine industry have led to a surge in demand for labor, resulting in an increased number of jobs and tasks. While this growth presents exciting opportunities, it also creates challenges. The heightened demand results in a workforce gap, leading to increased responsibilities for existing employees, which can negatively affect job satisfaction and productivity. Embracing technological advancements, particularly through automation and robotic solutions, can help alleviate the burden on current staff and address these challenges, facilitating significant growth and development.

4.3.0 Improving Repeatability Time of Tasks

In the marine industry, numerous repetitive tasks are essential for the manufacturing, testing, and maintenance of ships. To improve the repeatability and efficiency of these processes, it is vital to reduce the time spent on each task. Autonomy and Robotics Technology (ART) can significantly shorten the duration required for repetitive tasks while maintaining high precision. This ensures consistency in operations and enables employees to concentrate on more complex, value-added activities.

5.0 Current and Future ART Integration at Seaspan

Canada's marine industries are a significant source of economic growth, job creation, and innovation [10]. In British Columbia, the new B.C. Maritime Industries Strategy has invested up to $25 million in modernized infrastructure [11]. This growth brings increased demand for labor and resources. To effectively manage this workload, the integration of ART at Seaspan will enhance task efficiency and support the growing demand.

5.1.0 Current ART Integration

Robotic applications being introduced at Seaspan target specific operational gaps within the company, particularly in welding processes, to enhance capacity and meet rising demand. Piping systems are crucial for transferring fluids between equipment systems in a ship [12]. **Spool welding** involves joining sections of pipe to form the complex piping systems on ships, requires precision and speed to meet tight production schedules. Each system consists of pipe spools, which are manufactured by combining various piping materials [12]. Timely manufacturing of these spools is essential for determining profitability, as delays can significantly impact building costs [12]. Seaspan welds their own pipe spools to prevent delivery delays. Similarly, **panel welding**—used in the construction of large sections of a ship's hull—demands high-quality welds that are both strong and aesthetically uniform.

A current example is the use of two pipe welding robots in shipyards in Victoria and North Vancouver. Sourced from Novarc Technologies, these Spool Welding Robots (SWR) facilitate pipe fabrication [13]. Workers operating the robot do not need programming knowledge, enabling them to perform welding tasks from root to cap automatically, without interrupting the arc [13]. This human-operated robot consistently produces high-quality welds, as shown in Figure 6 below.

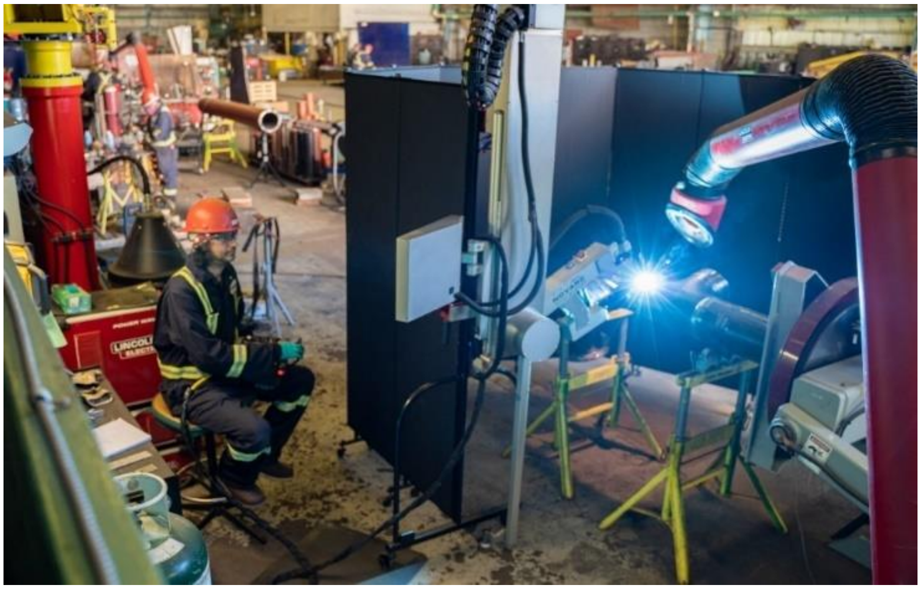

FIGURE 6: HUMAN OPERATING WELDING ROBOT WITHIN THE VANCOUVER SHIPYARDS [13].

There is a first-generation pipe spool welding robot at VDC and a third-generation robot at VSL, sourced from Novarc. Technologies, a local company in B.C. [13]. The MIG Spool Welding Robot (SWR) we currently use is specifically designed for pipe, small pressure vessel, and other roll welding applications and is visually represented within Figure 7 below [13]. After implementing this robot, the time required to produce a pipe joint decreased by 230 minutes [13].

FIGURE 7: MIG SWR FROM NOVARC. TECHNOLOGIES [12].

Co-bots, as described in Section 3.0, are collaborative robots designed to work alongside human operators. For instance, a co-bot used for welding, particularly in panel assembly, enhances productivity by facilitating a smoother and faster workflow to meet production demands [14]. Most co-bots require minimal programming knowledge, making them accessible for workers, as they are intended to assist rather than operate autonomously [13]. The welding co-bot shown in Figure 10 below is controlled via a teach pendant, allowing the operator to easily instruct the robot on its tasks [14]. This user-friendly interface fosters collaboration and efficiency in the workplace.

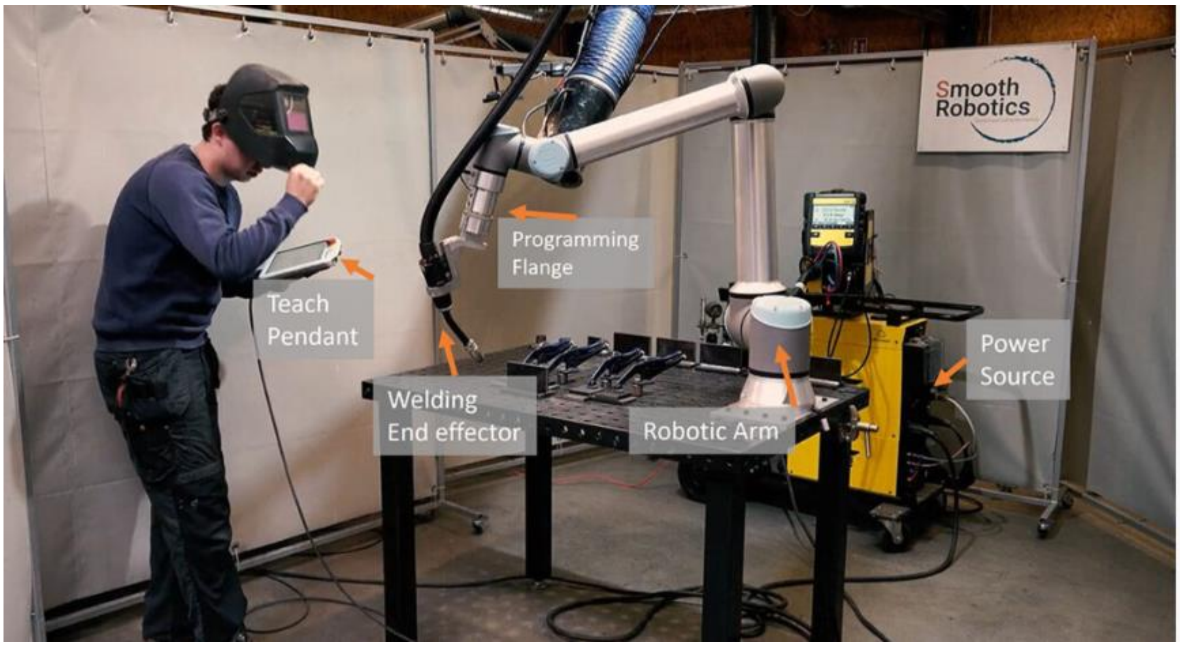

FIGURE 8: WELDING CO-BOT [14].

5.2.0 Future Art Integration

The Seaspan Chair in Robotics for Marine Vessels at **University of British Columbia (UBC)** aims to position the UBC as a global leader in marine robotics innovation, with a specific focus on advancing AUV’s, vessel hull inspection, and coordinated robotic swarms for marine operations [15]. Over the next five years, the initiative will foster cutting-edge research, establish state-of-the-art facilities, and secure major funding to accelerate the development and deployment of marine robotics technologies. The goal is to enhance the speed at which innovations transition from research to practical, real-world applications in the marine industry, particularly in Canada’s West Coast marine ecosystem.

A key component of the plan is the development of a Marine Engineering Laboratory at UBC, equipped with water tanks, AUVs, surface drones, and data acquisition systems [15]. This facility will serve as a testing ground for marine robotics, enabling the optimization of technologies for underwater hull inspection and other marine tasks. The lab will be funded in part by a successful **John R. Evans Leaders Fund (JELF)** application, which will provide [redacted] for the infrastructure [15]. Additionally, funding for aerial robotics will allow for integrated imaging and sensing capabilities above water, complementing the underwater systems [15]. This facility will also become a hub for industry collaboration, particularly with Seaspan, to ensure the practical application of research outcomes.

In addition to developing infrastructure, the Chair plans to pursue major funding initiatives, including the **New Frontiers in Research Transformation (NFRF)** and **Canada Foundation for Innovation (CFI)** Innovation Fund grants [15]. These funding opportunities will support large-scale interdisciplinary research teams, combining expertise in robotics, artificial intelligence, and control systems. By 2026, the NFRF grant, worth approximately [redacted], will enable the creation of transformative research initiatives, while the CFI grant in 2027 will further enhance research infrastructure for marine robotics [15].

To connect academic research with industry needs, the Chair will also create internship opportunities for UBC students to work with Seaspan and other industry partners. These internships will provide valuable hands-on experience, bridging the gap between theoretical knowledge and real-world applications in marine robotics. Furthermore, collaboration with other Seaspan Chairs at UBC, as well as key UBC researchers in robotics, control systems, and machine learning, will drive interdisciplinary solutions to complex challenges in marine robotics, such as swarm coordination, hull inspection, and acoustic tracking [15].

By the end of the [redacted] period, UBC is expected to be a world-class hub for marine robotics, with fully established research facilities, secure funding, and a robust network of collaborations that will drive the development of new technologies and innovations for the marine industry [15]. The Chair's work will significantly contribute to transforming marine operations through advanced robotic systems, positioning UBC as a leader in this emerging field.

6.0 Robotic Form Factors

This is where the introduction of hull cleaning robots becomes valuable. These machines can crawl along or remain close to the ship's hull, both above and underwater, performing necessary cleaning tasks without the need for human divers. Currently, hull cleaning operations for Seaspan Ships are contracted out to **Vancouver Dry Dock Corporation (VDC)**, which lifts the hull out of the water for inspection and maintenance before submerging it again.

Ship crawlers are designed to tackle challenging tasks in hard-to-reach areas, and several designs have been explored for this purpose. Some models feature **underwater thrusters**, which combine a propeller with an electric motor for enhanced propulsion and precise control in underwater environments [16]. These systems enable crawlers to navigate effectively in complex settings, significantly improving operational capabilities [16]. The designs often include **crawler belts** as a locomotion system, enhancing the robot's mobility and allowing it to overcome obstacles [16].

The crawler belt system provides propulsion power and facilitates efficient steering, enabling precise maneuvering in challenging environments [17]. **Degrees of Freedom (DOF)** refers to the maximum number of independent values that can vary within a data sample [17]. In the robotic crawler illustrated in the figure below, the robotic arm has two degrees of freedom. The first DOF allows the arm to rotate within a vertical plane to reach nearby objects, while the second serves as a gripper mechanism made up of two mirrored four-bar **kinematic chains** [17]. A kinematic chain consists of rigid bodies connected by joints, providing constrained motion and serving as the mathematical model for mechanical systems [17]. Each chain consists of two **rockers**—links that do not revolve—and a **coupler** that connects the two rockers [17]. This design enables the robot to navigate effectively along surfaces, ensuring stability and traction even in challenging conditions. The skeleton of this mechanism is shown in Figure 9 below.

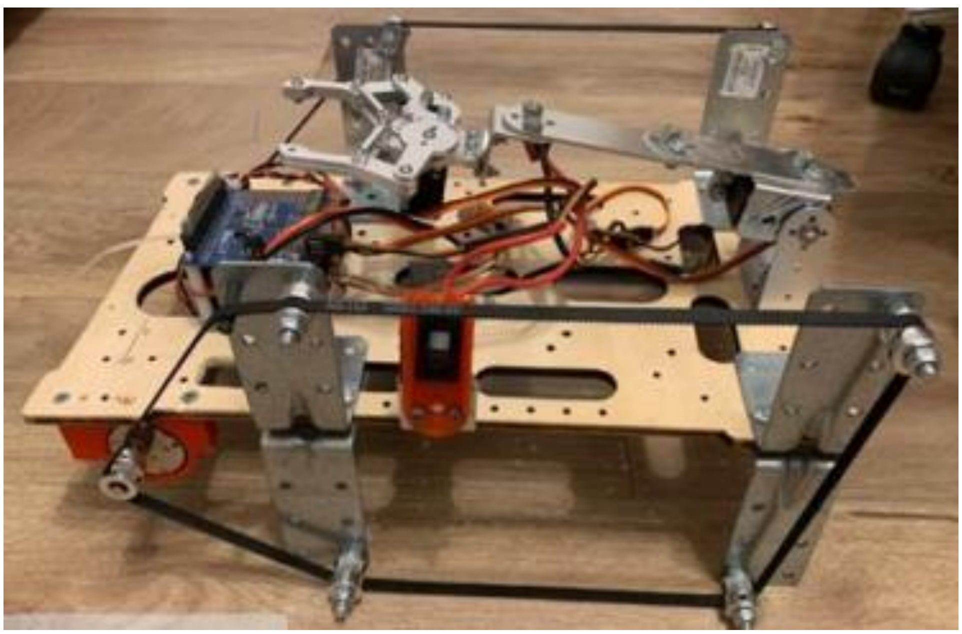

FIGURE 9: CRAWLER BELT SKELETON [17].

Another adaptation for ship crawling robots is the incorporation of magnetic force, which provides consistent adhesion. This feature allows the belt to maintain flexibility, enabling it to automatically adjust to minor changes in the wall surface, as illustrated in Figure 10 below [18]. This enhancement improves the robot's ability to navigate and adhere securely to various surfaces, further increasing its operational effectiveness in challenging environments.

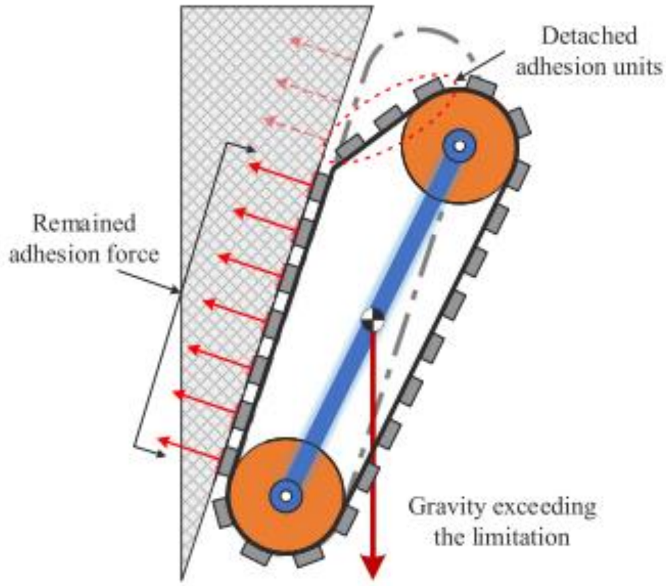

FIGURE 10: MAGNETIC CRAWLING MECHANISM [18].

Other ship crawling examples with different kinematic structures include the **ARMROV** which uses six **thrusters**, with four dedicated to vertical movement and two for horizontal [19]. It also obtains two **manipulator arms** which is a programmable multifunctional device that is responsible for moving parts, objects, or tools through different motions to complete tasks [20]. These arms help the robot clean both the port and starboard sides simultaneously, allowing for efficient cleaning of the ship's hull as shown in Figure 11 below. The kinematic system moves in a controlled manner, with thrusters providing force in different directions.

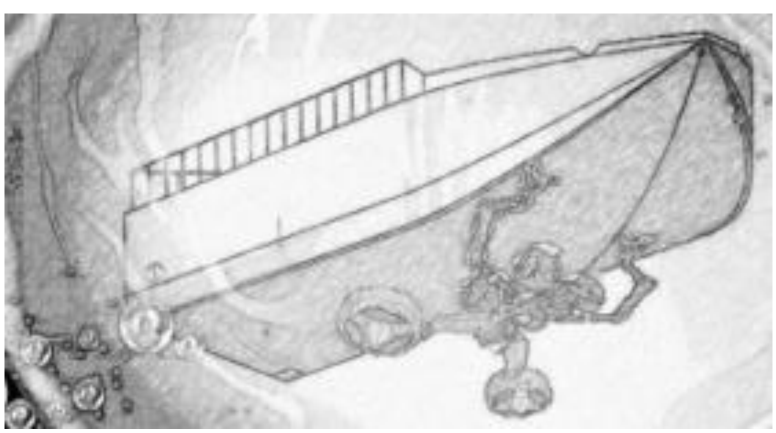

FIGURE 81: DESIGN CONCEPT FOR ARMROV [19].

This allows it to be highly maneuverable but lacks in maintaining a fixed center of gravity and buoyancy during cleaning operations. In terms of adhesion, the robot is enhanced by a combination of thrusters, and an inflatable lift bag [19]. In addition to the thrusters, adding a magnetic force to the robot to further stabilize itself when needed. Taking inspiration from the **Magnetic Hull Cleaning Robot**, which uses a magnetic four-wheel system. This makes this version of a ship hull cleaning robot a reliable mechanism for staying attached to the hull, especially on smooth or slightly curved surfaces [21].

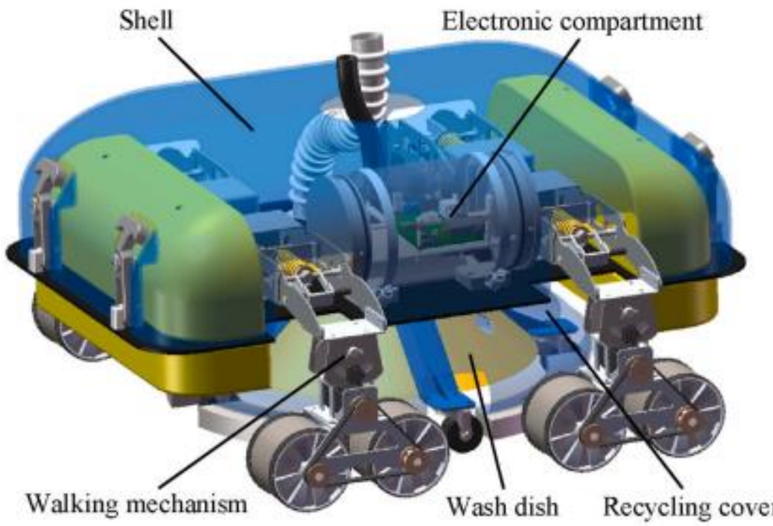

FIGURE 9: STRUCTURE OF MAGNETIC HULL CLEANING ROBOT [21].

To add stronger adhesion, alterations such as adding a **magnetic gripper** or **on/off magnets** to the body of the robot to increase adhesion. Although the ARMROV has great mobility due to the inflatable lift bag and the combination of thrusters, it lacks stability as it depends on the precise balance of its center of gravity and buoyancy, meaning it must be carefully designed [19].

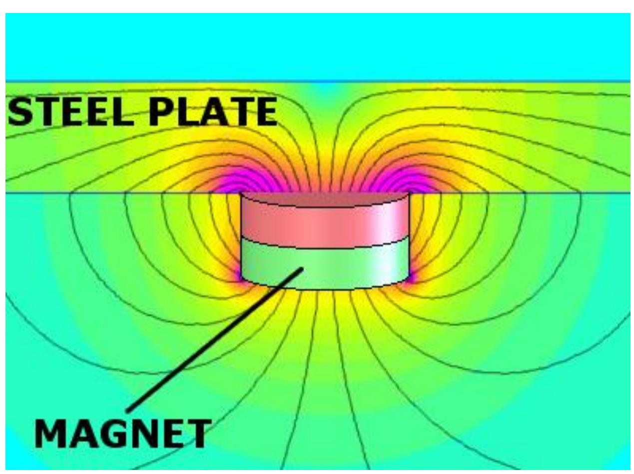

FIGURE 10: EXAMPLE OF AN ON/OFF MAGNET AND THE MAGNETIC FORCE [22].

Another robotics application within the paint shop will streamline repetitive tasks, enhancing overall operational efficiency. The implementation of a co-bot designed for surface preparation tasks, including blasting, removing oxidation, and repainting, aims to enhance worker safety, operational efficiency, and environmental sustainability. Key objectives of this robot include improving quality and consistency in production and reducing material and energy waste. The introduction of co-bots will also promote worker retention by providing safer, less physically demanding roles. Throughout the project's implementation, adherence to industry standards for safety and environmental impact would be prioritized, with progress assessed **via Key Performance Indicators (KPIs)** focusing on scope, timeline, budget, quality, and resource utilization. This is important as to create a specialized robot, a robotic company would provide their base model and then add an **actuator** as shown in the figure below to ensure the robot can conduct the task as described.

FIGURE 11: COMPONENT THAT ENABLES ROBOTIC MOVEMENT OR AN ACTUATOR [23].

Human-operated drones can significantly reduce safety risks for quality inspectors by providing real-time aerial overviews of critical areas that need inspection [23]. Although several companies manufacture drones for industrial inspection, customizations would be required to adapt them to our specific needs, especially for navigation and mapping data. For instance, data from Holo-ship, formatted in x, y, z coordinates, can be used as training data to map the ship’s structure, enabling the drone to navigate with a clear understanding of the vessel’s layout.

Additionally, drones would need specialized training to detect key issues that inspectors look for, such as corrosion, dents, and other structural defects. This would involve incorporating image recognition and machine learning algorithms into the drone’s operating system to ensure it can autonomously identify and flag these potential problem areas during inspections.

As an example, when equipped with advanced sensors and imaging systems, drones can remotely monitor power lines, capturing detailed visuals and detecting issues like wear, corrosion, or damage [24]. They can also generate accurate 3D representations using **Light Detection and Ranging (LiDAR)** sensors, which help identify small-scale deformations [24]. However, operating drones in harsh weather conditions presents challenges, such as maintaining a clear line of sight for accurate positioning, determining appropriate landing zones, and ensuring navigation stability in various wind conditions [24]. Some drone prototypes have addressed these challenges by incorporating **probes**—air pressure sensors used to stabilize altitude [24]. As shown in Figure 11 below, the outer cage of the drone is equipped with these probes to help maintain stability during operation.

FIGURE 12: DRONE WITH PROBES [24].

6.1 Use Cases

Examples of robotic applications and their specific use cases based off what was described in section 6.0 within Table 1 below.

TABLE 1: ROBOT USE CASES

Use case	Description	Benefit to Seaspan (Section 4.1.0 - 4.3.0)	Users
Drone Inspection Robot	An unmanned vehicle that is human operated and can detect, analyze, and gather data on core components that are generally inspected visually by humans.	Improving Operational Safety and Repeatability of Tasks (4.2.0-4.3.0)	Quality Inspection Engineers, Maintenance Engineers.
Ship Hull Cleaning Robot	An autonomous vehicle that self-drives along the hull of the ship and cleans. Specifically targeted for biofouling.	Improving Operational Safety and Repeatability of Tasks (4.2.0-4.3.0)	Seaspan product to use and sell.
Pipe Welding Robot	A co-bot that specifically targets pipe welding spools.	Improving Efficiency of Scaling Capabilities & Managing Workload Increases (4.1.0)	Welders, Engineers.
Panel Welding Co-bot	A co-bot that specifically targets panel welding.	Improving Efficiency of Scaling Capabilities & Managing Workload Increases (4.1.0)	Welders, Engineers.
Paint Shop Robot	A co-bot that specifically targets blast painting.	Improving Repeatability of Tasks (4.3.0)	Paint Shop Engineers.

7.0 Robotic Solutions

This section offers a high level technical and business analysis of the proposed robotic designs, with the goal of guiding further research and development efforts. Three proposals involve integrating existing robotic models with specialized features, requiring collaboration with external companies to optimize internal processes. One proposal involves designing and building a robot in-house, which could also be marketed as a commercial product. The technical analysis of each design may include:

- Design Overview: A brief description of the robotic system and its specialized features.
- Benefit to Seaspan: The expected impact on company operations or processes.
- Drawings/Sketches: Visual representations of the design.

The business analysis may include:

- Potential Partners: Relevant companies for collaboration, including quotes and service offerings.
- Timeline: Key milestones from research and design through to implementation.
- Cost and Time Scale: Estimations for total project duration and financial investment.

7.1.0 Welding Robots

Welding robots are revolutionizing the shipbuilding industry by improving efficiency, consistency, and safety in the manufacturing of ships and marine vessels. At shipyards, particularly in tasks like spool and panel welding, robotic systems are becoming essential tools for enhancing productivity and quality. Advanced collaborative robots (co-bots), can automate these processes, significantly reducing manual labor, minimizing human error, and ensuring high-quality results. These robotic systems also help meet the growing demand for quicker turnaround times in the shipbuilding industry, all while improving worker safety by handling hazardous tasks in challenging environments. With advancements in welding technology, robots are transforming the way shipyards operate, paving the way for smarter, safer, and more efficient ship production.

7.1.1 Two Pipe Welding Systems

Building on the success of the **MIG Spool Welding Robot (SWR)** at VSL and VDC provided by **Novarc. Technologies,** we propose acquiring the **TIG SWR** from the same company to further enhance our pipe welding efficiency. The TIG SWR allows operators to achieve high-quality welds at speeds 2-3 times faster than the MIG SWR [25]. Utilizing the **Gas Tungsten Arc Welding (GTAW)** process, it provides superior arc and weld puddle control, making it particularly suitable for clean welds on thin materials where appearance is critical for maintaining high-quality standards [25].

FIGURE 13: EXAMPLE OF WELD FROM TIG SYSTEMS.

The robotic welding system offers significant advantages, including up to [redacted] cost savings by reducing welding expenses. It delivers higher deposition rates of up to 4 lbs/hour, far exceeding traditional TIG systems. With up to 300% faster travel speeds, projects are completed more quickly, while maintaining the highest quality welds that meet or exceed industry standards. The system also minimizes spatter, ensuring a cleaner work environment and less post-weld cleanup. Its patented TIPTIG feeding system ensures exceptional weld quality through an innovative design. Further investigation into implementing a TIG system at Seaspan is ongoing.

7.2.0 Drone Inspection Robot

The drone co-bot designed for ship inspection is an advanced autonomous system equipped with high-resolution cameras, ultrasonic sensors, and environmental monitoring tools to assess the quality of a ship's structure. This co-bot works in tandem with human operators to conduct detailed inspections of the ship's hull, decks, and internal compartments, identifying signs of wear, corrosion, and other potential structural issues [24]. By flying under remote control, the drone can access hard-to-reach areas, such as the upper decks or beneath overhangs, where human inspectors might face difficulty. The drone is capable of real-time data transmission, allowing inspectors to monitor the ship’s condition from a safe distance while providing instant feedback on any anomalies. Additionally, the drone’s AI-driven software can process inspection data to detect patterns of deterioration over time, offering predictive maintenance insights that help in reducing operational downtime and extending the lifespan of the vessel. With a drone’s lightweight design, durability in harsh maritime conditions, and seamless integration with other maintenance systems, the co-bot represents a significant leap forward in ship quality assurance and maintenance efficiency.

Flyability is a drone company that offers their Elios 3 UT drone specifically to perform contact inspections, which is ideal for close visual inspections and UT measurements in confined, hard to reach places [27]. This drone can perform ultrasonic thickness measurements on vessels and by combining with LiDAR, it can provide localization of all measurements and display them in a 3D model [27]. An example of a software output and 3D model captured by Elios is shown in the figure below. Elios is known to be able to get into hard-to-reach places and is remote controlled.

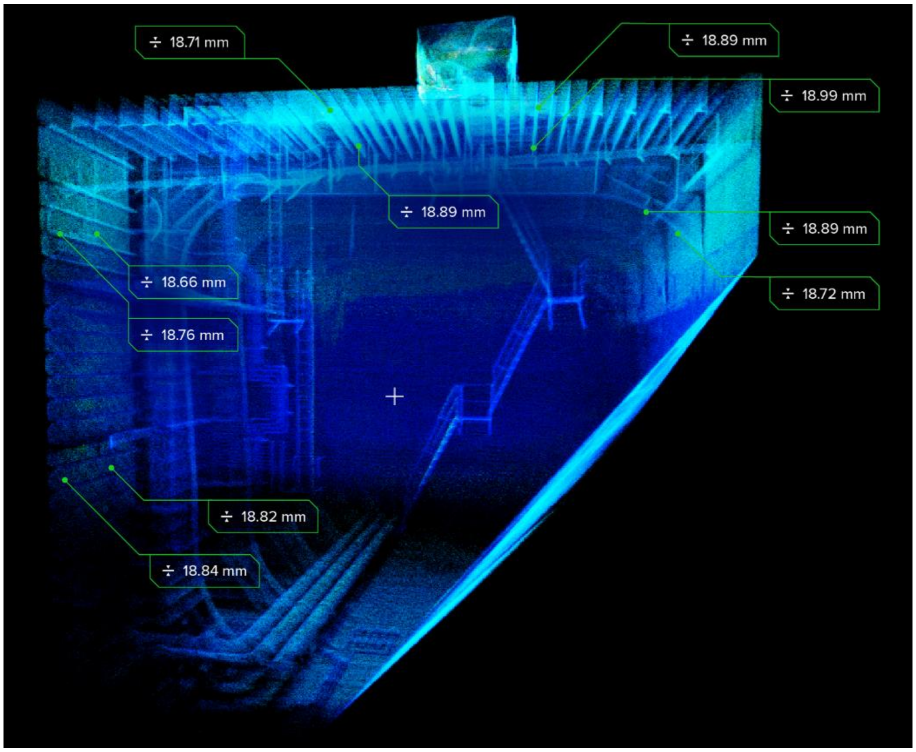

FIGURE 20: ELIOS CAPTURE AND 3D MODEL OUTPUT [27].

While flyability has a base model that they can specialize in for Seaspan's needs, another company called **Drones Maritime** specifically focuses on drones for purposes within the maritime industry [28]. Using thermal cameras, these drones can measure the temperature of each pixel they capture, alerting to possible breakdowns [28]. A similar feature of this drone is that using ultrasound it can measure thickness in inaccessible or elevated areas [28]. An example of the drone provided by Drone Maritime is in the figure below.

FIGURE 21: DRONE MARITIME'S PRODUCT [28].

In addition to this, the underwater image quality Drone Maritime's product can carry out is high-resolution photography and video. The underwater drones move in all directions once submerged as it obtains 6 motors as shown in Figure 22 below, allowing them to reach up to a depth of 300m [28]. Further investigation is being done to implement a drone at Seaspan.

FIGURE 22: DRONE WITH 6 MOTORS [28].

7.3.0 Paint Shop Robot

Confined Space Robotics Inc. (CSR), based in Edmonton, Alberta, is a leader in designing and integrating advanced robotic systems for industrial applications. The company specializes in providing automation solutions for challenging environments, focusing on enhancing safety, efficiency, environmental stewardship, and productivity [29]. CSR develops both semi-autonomous and fully automated robotic systems, including collaborative robots (co-bots) for human interaction and solutions for material handling and maintenance [29].

Confined Space Robotics (CSR) has developed a few robotic applications for this use case. The **CSR Renew-Tech** platform is a custom-built software solution that enables seamless control and path planning for robotic systems, ensuring precise task execution, such as material application and removal, along with real-time diagnostics and user-friendly interfaces for operators. The **Co-bot Mobility Platform (CMP)** features a mobile base integrated with a co-bot arm, designed to work with a variety of co-bot-related tools. Key **co-bot end effectors** have been designed to semi-automate specific tasks: the **Needle Scaler** for surface preparation, the **Laser Ablation** tool for substrate treatment, the **Grinder** for weld surface preparation and coating repairs, the **Grit-Blasting** nozzle for removing coatings, contaminants, and oxidation from large areas, and the **Spray-Coating** gun for applying protective coatings on steel substrates [29]. These components work together to streamline various processes within shipbuilding and maintenance, offering a high degree of automation and precision.

The project for developing robotic systems will progress through several key phases. The **Design Phase** involves creating detailed engineering designs for each system, encompassing custom software, user interfaces, and integration strategies [29]. In the **Procurement Phase,** necessary materials and components will be sourced [29]. The **Fabrication & Assembly Phase** focuses on assembling and configuring robotic systems, integrating both custom hardware and software [29]. Following this, the **Optimization Cycles Phase** will entail testing, refining, and optimizing each system to ensure they meet required performance and safety standards. The **Documentation Phase** will produce comprehensive user and maintenance manuals, while the **Training Phase** will provide extensive training for shipyard personnel on the safe and effective use of each robotic system [29]. The timeline proposes a September 2025 finish date.

The figure below is the estimated total cost of the project, with a payment plan of [redacted] upfront and the rest given throughout the project duration. The company is proposing a team of 4 people including a project director, a lead robotics engineer, lead software engineer and a site coordinator. Currently, we are within the negotiation stage for the proposed contract from CSR.

Description	Estimated Cost (CAD) Unit Price	Qty	Sub Total
Engineering & Development	[redacted]	1	[redacted]
N. Vancouver Facility + Studio Lease	[redacted]	1	[redacted]
Personnel Travel (est 1 person, 3 days inc travel, every 2 weeks, on avg)	[redacted]	1	[redacted]
Cobot Mobility Platform	[redacted]	4	[redacted]
Needle Scaler End Effector	[redacted]	1	[redacted]
Laser Ablation End Effector	[redacted]	1	[redacted]
Grinder End Effector	[redacted]	1	[redacted]
Grit-Blaster End Effector	[redacted]	1	[redacted]
Spray-Coating End Effector	[redacted]	1	[redacted]
	Total (excluding taxes, shipping, etc.)		[redacted]

FIGURE 23: COST BREAKDOWN OF PROPOSED PAINT SHOP ROBOT [29].

7.4.0 Ship Crawler Robot

Ship hull cleaning is a critical maintenance task that directly impacts vessel performance, fuel efficiency, and environmental compliance [16]. Traditional methods of hull cleaning involve divers, manual labor, or large-scale underwater cleaning systems, all of which present challenges in terms of cost, safety, and environmental impact. Ship crawling robots offer an innovative solution to this problem by automating the cleaning process, reducing the need for human intervention, improving efficiency, and lowering long-term operational costs [16].

These robots typically operate on the hull's surface, using advanced sensors, cameras, and cleaning mechanisms (such as brushes and high-pressure water jets) to remove biofouling, algae, barnacles, and other marine growths that accumulate over time [16]. The model proposed will be fully autonomous, reducing the need for dry-docking and manual labor. Many modern ship crawling robots are equipped with AI and machine learning algorithms that allow them to navigate complex hull surfaces with high precision, minimizing the need for manual intervention and reducing human error. As a comparison, the ship crawler can be depicted as a Roomba for the hull of a ship.

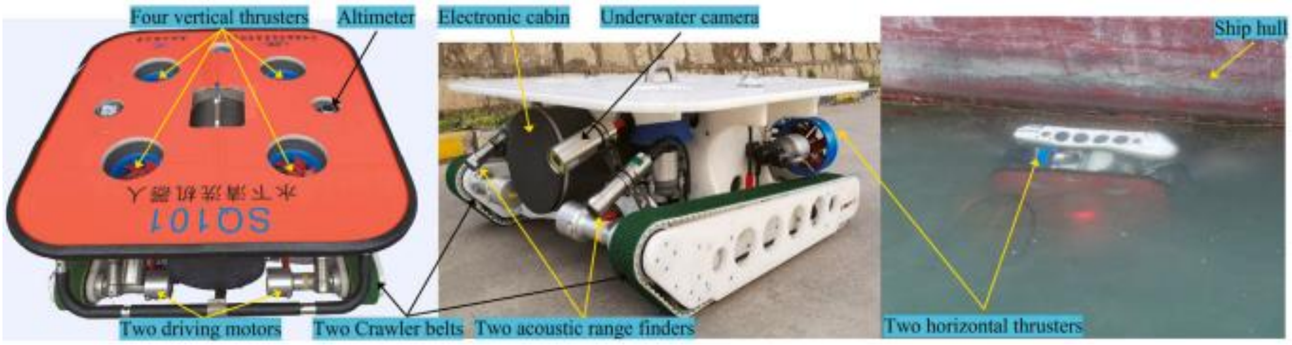

FIGURE 24: VISUAL REPRESENTATION OF A PROTOTYPE SHIP CRAWLER [16].

Other benefits that the ship crawler provides are regular cleaning to help prevent the spread of invasive species, reduces drag, helps improve fuel efficiency, reduces carbon emissions, and reduces the need for manual labor which increases safety. Ultimately, the robot will lower operational costs and minimize vessel downtime.

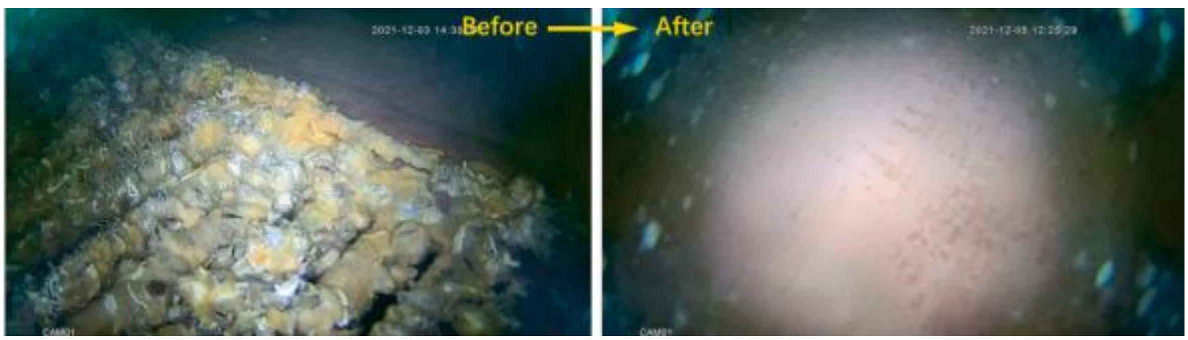

FIGURE 25: RESULTS OF PROTOTYPE'S CLEANING [16].

The kinematic structure of the underwater cleaning robot is integral to its ability to move and adhere to the ship's hull while performing cleaning tasks. The robot's kinematics are governed by the interaction of its thrusters, crawler belts, and sensors, which enable precise movement in three modes: **cruising**, **adhering**, and **climbing** [16]. This design will be equipped with six thrusters. Four being vertical to provide adhesion force to maintain contact with the hull, helping the robot move when attached vertically [16]. The other two will enable the robot to move horizontally, maneuvering along the hull's surface and providing stability when moving in confined spaces. The robot obtains two crawler belts which are to be powered by **brushless DC motors**, allowing the robot to "crawl" along the surface by creating frictional forces [16]. The belts are responsible for linear motion and rotation along the hull. They can also be used to adjust the robot's position relative to the surface to maintain a constant cleaning path [16]. The encoders attached to the crawler belts measure the velocity of each belt allowing for precise control of the robot's speed and position [16]. Taking influence from another robotic design that obtains magnetic wheels as their kinematic structure to encourage more adhesivity, adding on/off magnets is a good way to increase this adhesion as well.

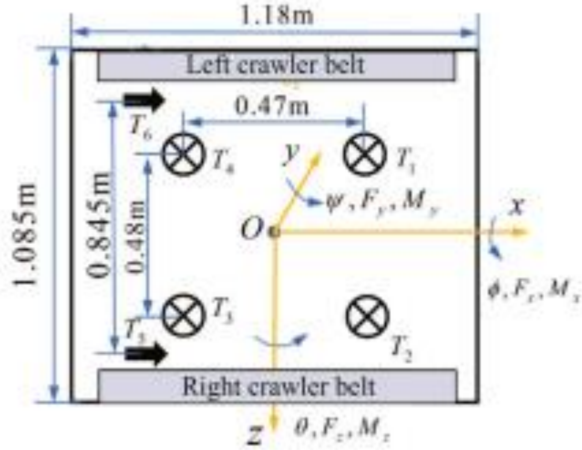

FIGURE 26: EXAMPLE DIMENSIONS OF SHIP CRAWLER [16].

The robot’s kinematic structure allows it to operate in three distinct control modes:

1. **Cruising Mode**: The robot uses the two horizontal thrusters to move toward the hull while maintaining a **desired depth**, **yaw angle** (ψ) and **pitch angle** (θ) close to zero, with the yaw angle being adjusted to steer toward the hull and prevent collisions. The yaw is controlled by a **PID controller** which adjusts the thruster’s output to guide the robot toward the desired heading.
2. **Adhering Mode**: Once the robot is close to the hull, the vertical thrusters will provide the force to adhere to the hull’s surface. The robot shifts from a cruising state to adhering by setting the pitch angle (θ) to 90 degrees, ensuring that the robot is firmly attached to the hull before transitioning to climbing mode. In this mode, the robot maintains a steady position on the hull, preventing slippage during cleaning operations.
3. **Climbing Mode**: The robot moves vertically up or down along the hull surface. The vertical thrusters generate the necessary upward or downward forces to move the robot while the crawler belts provide the motion along the surface. The robot's position is adjusted by controlling the pitch angle to maintain vertical orientation

while climbing. This ensures that the robot can perform cleaning tasks without losing contact with the hull surface.

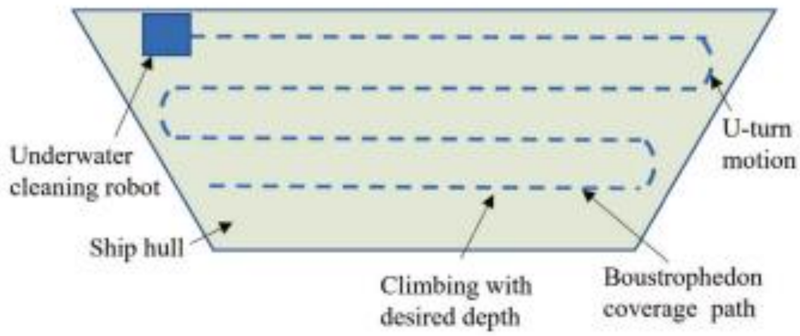

FIGURE 27: BOUSTROPHEDON CLIMBING PATH [16].

In regards, to controls and sensors, they are crucial to providing a role in the kinematic structure by providing sensor**. Inertial measurement units (IMU's)** are used to measure the robot's angular velocity and orientation, helping the system adjust the roll, pitch, and yaw angles to maintain stability. **Acoustic range finders** measure the distance between the robot and hull, ensuring the robot remains at the correct distance during cleaning, while the altimeter measures depth and height relative to the hull. **Encoders** on the crawler belts allow for precise control of the robot's velocity and movement, ensuring accurate coverage of the hull without omitting areas.

Kinematic equations are useful for modeling kinematic behavior of the robot as is uses a combination of forces and moments generated by the crawler belts, thrusters, and feedback from the sensors. Some of these equations are:

1. **Linear velocity and angular velocity**: The robot in the horizontal and vertical directions depend on the forces generated by the thrusters and the motion of the crawler belts.

2. **Rotation**: Primarily driven by the differential velocities of the two crawler belts, which create a turning moment. The relationship between the velocities of the crawler belts and the robot's rotation angle is key to controlling its motion along curved or angled surfaces of the hull.

3. **Positioning**: This on the hull is controlled by adjusting the velocities of the thrusters and belts to achieve the desired trajectory along the hull, following a boustrophedon cleaning pattern.

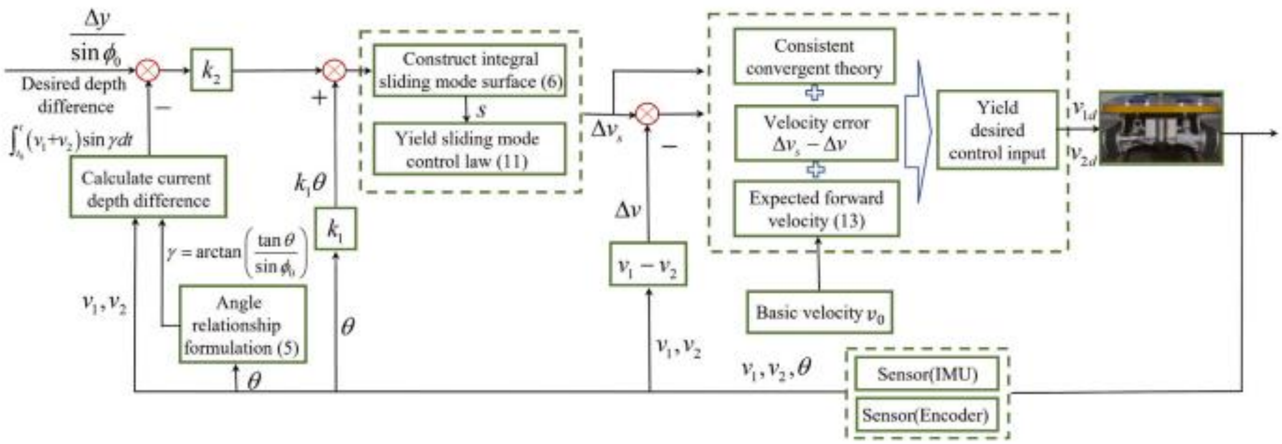

FIGURE 28: DIAGRAM OF AN EXAMPLE CONTROL SYSTEM.

While the initial investment in research, development, and production of the robot is substantial, it proposes to be a product that the company can develop and then sell. Below are the projected costs associated with developing the ship hull cleaning robot:

1. **Research and Development (R&D):** Robotics systems and autonomous vehicle design require significant upfront investment in research, development, and system integration. A typical cost for developing a robotic system in the industrial sector, such as underwater robotics, can range from $[redacted] to $[redacted] depending on the complexity and scale of the system [30]. The inclusion of autonomous navigation and AI systems adds additional layers of complexity, often increasing the overall cost due to the specialized software development and testing required. This is a crucial cost factor for the hull cleaning robot.

2. **Hardware Manufacturing:** In terms of hull cleaning systems, large-scale maritime industry solutions, including autonomous cleaning robots, are designed with an emphasis on durability and efficiency. Industry reports suggest that specialized robotic cleaning systems designed for ships cost anywhere from $[redacted], depending on the level of automation, sensor sophistication, and cleaning mechanisms used [31]. This aligns with the estimated costs for a robotic hull cleaning system, especially when integrating sensors, AI algorithms, and high-pressure cleaning mechanisms.

3. **Material Costs:** The cost of materials for building robotic systems, especially those operating in harsh marine environments, tends to be high due to the need for corrosion-resistant materials, watertight seals, and advanced power systems.

Materials for these robots can account for 20-30% of the overall system cost [32]. This includes durable metals like titanium, specialized polymers, and the power storage systems needed for extended autonomous operation. When designing a robot that must adhere to the hull, ensuring the robot is lightweight and corrosion-resistant while still strong enough to carry out the cleaning functions will significantly impact material choices and, consequently, costs.

4. **Software Integration:** The integration of machine learning and AI for autonomous navigation and operation, especially in complex environments such as ship hulls, further increases the development cost. The implementation of AI algorithms, including real-time navigation and hull detection, requires highly skilled software engineers and machine learning specialists, with salary costs in this area generally ranging from [redacted] annually [33]. Software development for such autonomous systems typically adds significant cost, as robust testing and iteration are required to ensure reliability and safety.

5. **Additional Costs:** Additional costs will be associated with the long-term maintenance and potential updates for the robot's software and hardware systems. These operational costs are often underestimated, but ongoing support and iterative improvements are necessary for maintaining competitive performance in the maritime industry. As seen in similar industries, maintaining robotic systems can add 10-15% of the initial development cost annually for software updates and hardware maintenance [34].

Therefore, the total estimated development costs for the prototype and initial commercial production phase would range from [redacted] The robot's operational savings make it a highly viable investment for ship operators. Key benefits that contribute to the **Return on Investment (ROI)** include:

1. **Fuel Savings:** Regular hull cleaning can reduce drag and fuel consumption by **5-10%**, which translates into significant long-term savings, especially for large fleets. Industry research suggests that regular hull cleaning can lead to a fuel efficiency improvement of up to 7%, depending on the vessel type and environmental conditions [35]. Ships with biofouling can experience up to a **30% increase in fuel consumption** over time, making regular cleaning a critical factor in maintaining operational efficiency [36].

2. **Reduced Operational Downtime:** By eliminating the need for dry-docking for cleaning purposes, ships will experience fewer periods of inactivity. This leads to

increased productivity and faster turnaround times. The maritime industry has long faced challenges with dry-docking, as it often leads to extended downtime, costing operators significant amounts in lost revenue. One study estimates that the cost of dry-docking for routine maintenance can range from [redacted] depending on the vessel size [37]. Therefore, eliminating this process through autonomous cleaning can offer considerable financial benefits.

3. **Labor Cost Reduction:** The robot will replace manual cleaning and diving operations, significantly reducing the need for human labor and the associated costs. Labor-intensive methods, such as diving and manual scraping, incur high operational costs due to safety concerns, training, and time spent performing these tasks. Automating the process through robotics reduces not only the cost of labor but also improves safety, reducing potential risks and liability [38].

4. **Environmental Compliance:** Meeting regulatory standards for biofouling and invasive species is crucial for avoiding fines and penalties. The **International Maritime Organization (IMO)** and other regulatory bodies have set strict guidelines regarding biofouling management, requiring ships to maintain clean hulls to prevent the spread of invasive species [39]. Non-compliance with these regulations can result in fines and vessel detentions, which further increases operating costs. By ensuring continuous hull cleaning, the robot will help operators stay compliant, reducing the risk of these costly penalties.

5. Given the combination of **direct cost savings** (fuel, labor, and downtime reductions) and **indirect benefits** (improved environmental sustainability and compliance), it is estimated that the robot would pay for itself after **2-3 years** of operation. In terms of selling the robot as a company product, there is significant research and development already invested in robotic systems designed for hull cleaning and other marine applications, showing the market feasibility for such innovations [40][41]. The investment in autonomous robotics for hull cleaning represents not only a technological advancement but also a sustainable solution that will drive cost savings and operational efficiency across the maritime industry.

There are very few companies that make them specifically for hull cleaning. One of our competitors is a robotics company called **Vertidrive**, which makes the Vertidrive V700 which is a magnetic ship crawler as shown below [42].

FIGURE 14: VISUAL REPRESENTATION OF THE VERTIDRIVE V700 [42].

The primary customers for this product will be large shipping companies, vessel owners/operators, and possibly companies involved in offshore platforms and oil rigs. In addition to this, a ship crawler improves safety, minimizes dry-docking, reduces fuel consumption and lowers operational downtime—all significant benefits for customers. Given these high-value features, the product can be priced as a premium offering.

8.0 Report Summary N/A

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