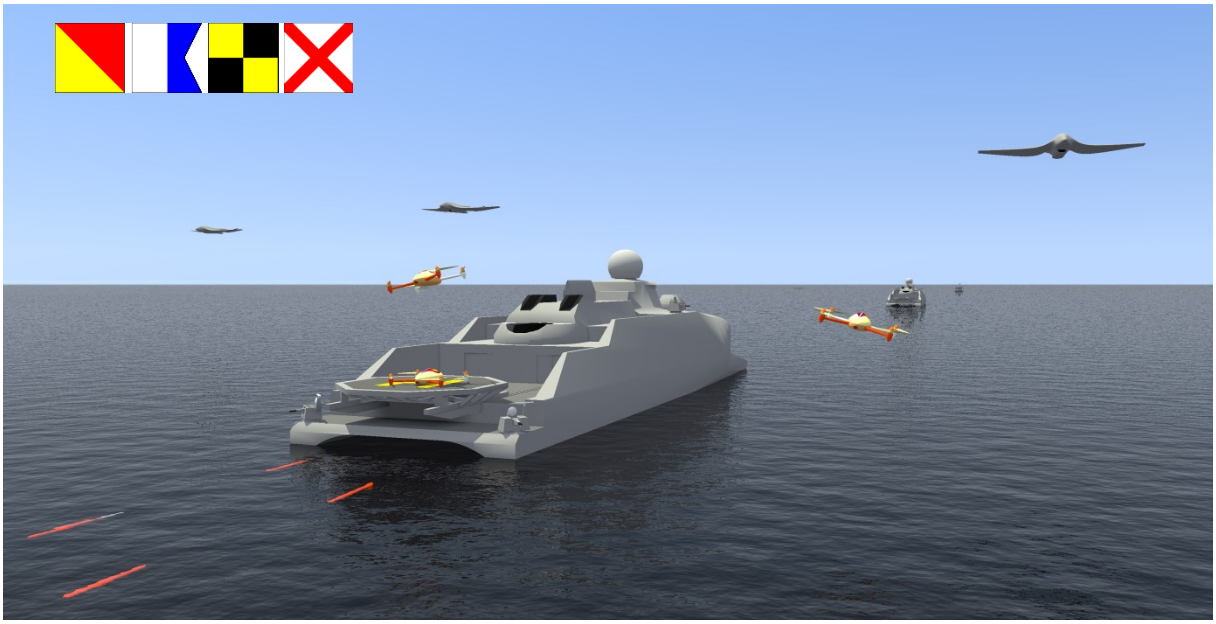
Unmanned autonomous (aerial) vehicles for maritime applications

State of the art, challenges & opportunities for autonomous systems in the Dutch Maritime & Offshore industry



Project data

Project number:	*MIIP 007 -2018*
Executed for:	*Netherlands Maritime Land and Ministry of Economic Affairs*
Executed by:	*Maritime Knowledge Centre, NLDA, TNO and TU Delft*
Project title:	*Unmanned autonomous (aerial) vehicles for maritime applications*
Project leader:	*Maritime Knowledge Centre*
Project duration:	*01-03-2018 until 31-12-2018*
Publication date:	*14-02-2019*
Status:	*Final report*

Maritiem Kennis Centrum
Ministerie van Defensie
TNO innovation for life
TU Delft

Table of contents

1. Introduction

1.1 Background

Developments regarding unmanned (autonomous) systems are expanding at an enormous pace. Progress is made in the maritime industries with autonomous/remotely operated underwater vehicles for the inspections of underwater infrastructure. Recently, an Israeli unmanned remote-controlled marine vehicle was built in the Netherlands, which received the 2017 KNVTS Ship of the Year award. In inland shipping there is genuine interest for autonomous and/or remote controlled systems. However, the developments seem to be rather fragmented and the potential of unmanned autonomous (aerial) vehicles is yet to be fully utilized.

Over the last few years TNO has gained a lot of experience with (unmanned) autonomous systems in road transport, shipping and underwater operations using autonomous systems. In road transport the first concepts have been tested and are already applied.

Furthermore, TU Delft has developed various drones for civil applications, and the Royal Netherlands Navy is now in the process of developing her own in-house autonomous systems. In North Western Europe several initiatives are being taken to launch unmanned shipping at increased levels of autonomy. Several EU projects were started and also in The Netherlands the EU project Novimar studying the concept of inland vessel trains (platooning) was recently started.

1.2 Aim of the project

Developments in the Dutch Maritime industries should be shifted into a higher gear in order to stay in the lead in international maritime developments. At present, a coherent overview of (business) opportunities of unmanned autonomous vehicles (including aerial) is missing for the various maritime sectors such as, short sea shipping, offshore oil and gas, fisheries, wind at sea, dredging, port services, inland shipping and navy. It is very likely that solutions for certain market segments could in turn benefit other market segments. Such an inventory should present current developments, state of the art and possibilities of these systems. This should accelerate the developments of these unmanned autonomous systems for the various sectors in the Dutch maritime industry.

The objective is to provide insight in the technical and economic feasibility of unmanned autonomous (aerial) vehicles for the various maritime sectors.

A follow up project is foreseen where a consortium of maritime companies and knowledge institutes will co-operate in developing successful unmanned (aerial) vehicle concepts, at increased levels of autonomy for the maritime sector. This could lead to a robust practical applicability with demonstrators at sea.

1.3 Approach

In order to get a solid overview of developments with regard to unmanned autonomous vehicles, interviews with several stakeholders were carried out.

A standard interview format was developed during the project, which was used in the interviews with maritime companies, knowledge institutes and unmanned autonomous service providers (see Addendum 1).

Special attention was given to the potential of possible business cases for maritime service providers and users, as some unmanned autonomous vehicle developments seem to be driven by a technology push rather than a market pull.

Therefore, interviews were primarily scheduled with shipping companies, offshore construction companies, dredging companies and the Royal Netherlands Navy as users of these systems.

Furthermore, interviews were held with several unmanned autonomous systems suppliers, shipyards and system integrators, in order to check the willingness and readiness of the maritime technology and system providers to implement these innovative and novel solutions in real practice.

Finally, the state of the art with regard to unmanned autonomous technology was researched with the help of Netherlands knowledge institutes (i.e. NLDA, TNO and TU Delft) and innovative development companies.

This report gives an overview of the current status of unmanned autonomous applications and developments in the Dutch Maritime industries. Furthermore, suggestions are given to proceed in promising directions for useful, safe and robust applications of unmanned autonomous systems in the maritime and offshore sector.

1.4 Levels of Autonomy

It is important to define what autonomy is about: In this report 10 levels of autonomy are defined. At the lowest level: level 1, the computer offers no assistance at all and the operator does all the work. At the highest level: level 10, the computer makes all the decisions and neglects the operator (Parasuraman, Sheridan, & Wickens, 2000).

Over the past decades, we have seen an increase in levels of autonomy of various systems, but rarely systems operate at autonomy level 8, 9 or 10. Nevertheless, this is currently possible from a technological perspective and gradually the discussion has started up on desirability and consequences of systems operating at the highest level of autonomy.

Notably, an autonomous system is not necessarily an unmanned system. A car can drive autonomous with people on board, as can a ship. Remotely operated systems can be controlled at different levels of autonomy.

In order to be clear and precise when discussing 'autonomous systems' the following scale for autonomy levels will be used.

Level	Description
10	The computer operates autonomous and neglects the operator
9	The computer only informs the operator when the computer decides to do so
8	The computer only informs the operator when the operator asks
7	The computer automatically executes and informs the operator afterwards
6	The computer allows the operator limited veto time before executing automatically
5	The computer proposes an alternative and executes if the operator agrees
4	The computer proposes an alternative
3	The computer limits the number of choices
2	The computer gives a complete set of decision alternatives and action alternatives
1	The computer offers no assistance: the operator performs everything

Table 1: Levels of autonomy

2. Market questions and needs

2.1 Underwater autonomous systems

2.1.1 State of the art

The Maritime & Offshore industry is imagining a future where underwater operations are safe, sustainable, efficient, yet still cost-effective. This horizon is difficult to reach with current capabilities, especially when looking at the inspection, repair and maintenance (IRM) of offshore infrastructures and the extension of operations into more hazardous ocean environments, such as the arctic and deep sea. A related industry need is to obtain better quality and georeferenced marine data. Besides oceanographical and geological data, the collection of ecological data becomes increasingly important to ensure sustainable maritime operations.

Meanwhile, developments in the field of autonomous systems are advancing rapidly. On the roads and in air autonomous solutions are already being used extensively, both for research and commercial applications. In the maritime domain, Autonomous Surface Vessels (ASVs) and Autonomous Underwater Vehicles (AUVs) are used increasingly for long and costly data gathering operations such as hydrographic surveys, hazard surveys, pipe route inspections and finding wrecks. Further growth from emerging markets like deep sea mining, aquaculture and offshore renewables may however shift the focus of future developments. AUVs are currently not yet commercially applied for repair and maintenance operations, because the level of autonomy is yet insufficient for these kinds of operations.

2.1.2 Desk study

In the following sections, some of the key technological aspects of Autonomous Underwater Vehicles are discussed, serving as an introduction to the topic. The scope of this desk study is limited to Autonomous Underwater Vehicles (AUVs) and thus excludes Remotely Operated Vehicles (ROVs). Also, manipulators are left out of the scope because these tools are not yet commercially of-the-shelf (COTS) available for autonomous systems.

2.1.2.1 Manoeuverability & navigation

Compared to tethered Remotely Operated Vehicles (ROVs), wireless AUVs allow for better manoeuvrability and can operate up to a standoff distance of multiple kilometres depending on the AUV type and the payload required during operation. This range limit is mainly caused by communication limitations, leading to increased autonomy requirements. The extended manoeuvrability extends their applicability to operations below ice and into the deep sea and results in safer operations that do not require the support vessel in the operational area.

Regarding the navigation of AUVs, most concepts are torpedo-shaped [e.g. oceanscan lauv, figure 1, and figure 4] for optimal navigation over straight trajectories, matching their main application being seabed mapping. However, alternative hovering [e.g. Saab seaeye, figure 4] or swimming concepts [e.g. Eelume, figure 4] exist that provide better manoeuvrability near subsea infrastructure, which is required for nearby inspection. After deployment, AUVs follow a pre-programmed course and navigate using (a combination of) the following techniques:

- GPS positioning at the surface
- Inertial Navigation System (INS), using dead reckoning based on depth sensors, inertial sensors, Acoustic Doppler Current Profilers (ADCP) and Doppler Velocity Loggers (DVL)
- Acoustic ranging using acoustic beacons with known positions
- Sonar Simulations Localization and Area Mapping (SLAM) based on distinct objects and or bathymetric features

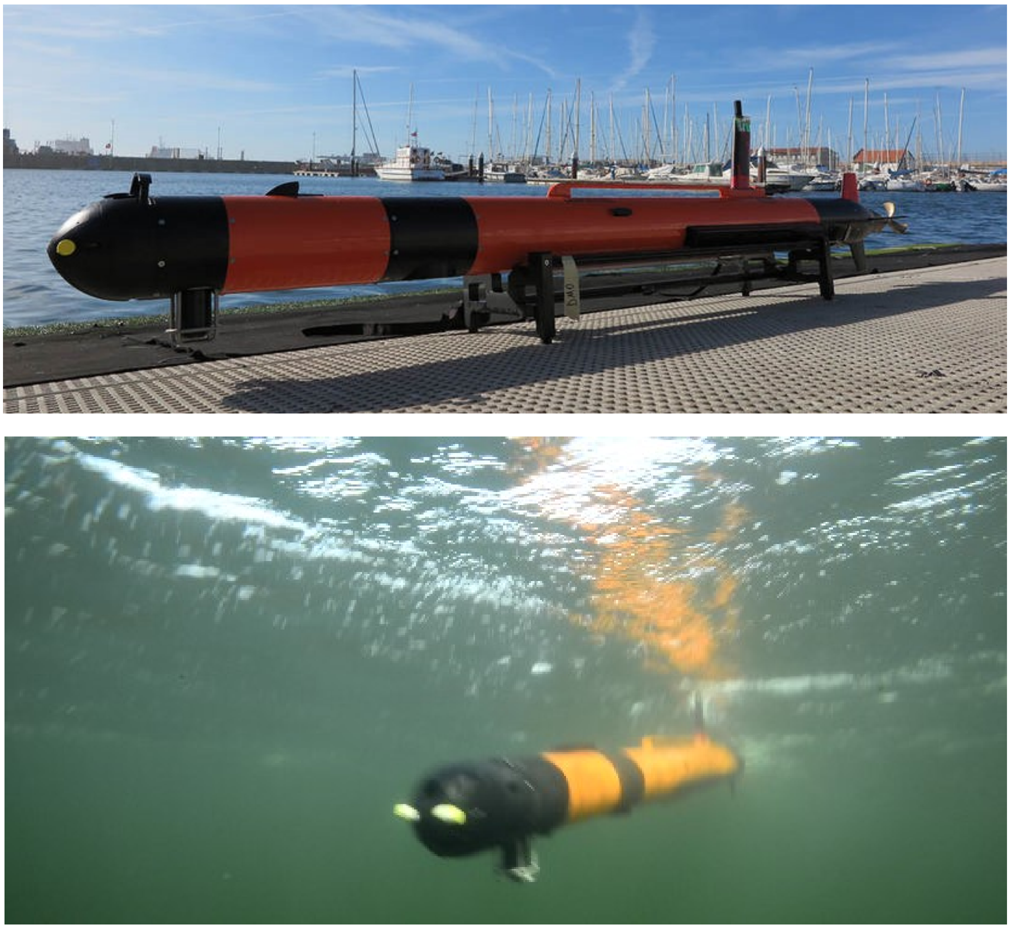


Figure 1: AUV owned by TNO shown on dock and operating underwater. For more information on the TNO AUVs see appendix 3

2.1.2.2 Sensing

AUVs can be equipped with a wide range of sensors for acoustic and optical imaging. Also, AUVs can be equipped with biological (e.g. chlorophyll), chemical (e.g. salinity) and physical (e.g. temperature, & pressure) sensors to collect data across the water column as a function of time by flying around and sampling at different locations. Besides data acquisition, the collected data can be used by the system to enhance its situational awareness. This enhanced situational awareness can be used to (i) make better decisions when intervention is needed (give sufficient platform autonomy) and to (ii) enhance the navigation accuracy.

With regard to the accuracy of seabed imaging sensors, AUVs have the advantage over surface vehicles that they are able of flying relatively close to the sea floor (<5 m altitude in area of low relief), making it possible to collect data at much higher resolution than surface based sonars. It should be noted however that for areas with significant bathymetric features AUVs need to fly higher to avoid collision.

2.1.2.4 Deployment and recovery

Although autonomous, most AUV concepts are deployed from a support vessel. Exceptions are (i) glider (Figure 4) systems that are designed to operate fully autonomously for periods up to multiple months without operator interaction, able of providing excellent spatial coverage and (ii) resident systems that can reside and recharge in a docking station (Figure 2) when inactive. An example is the Eelume system (figure 4)).

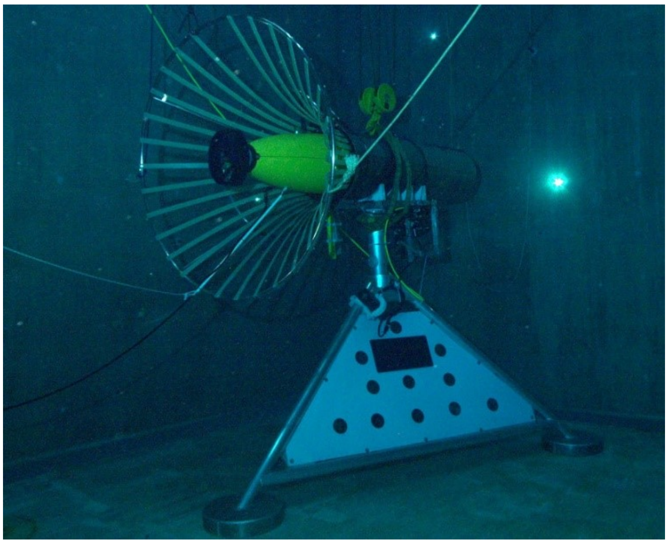


Figure 2: AUV docking station (MBARI, 2017)

2.1.2.4 Autonomy

The primary autonomous capability of AUVs involves navigation (path planning) and collision avoidance. There is however a trend towards increased vehicle intelligence (decision making capability), enabling platforms to e.g. asses the quality of collected data, interpret (classify) sensor data, optimize the mission in situ (given a high-level mission objective) and even co-operate together (interoperability) with other platforms. For operations where the level of autonomy is high enough, no direct human control is needed during operation. For operational scenarios involving a support ship, this means that the vessel and crew can be used for other tasks, increasing the amount of data that can be collected for a given amount of ship-time.

2.1.2.5 Acoustic communication and networking

A major driver for enhancing the autonomous capabilities of AUVs is that, while submerged, only a very limited amount of data can be communicated within an underwater network and network delays can be very high. This is because AUVs rely on acoustics for communication over significant distances.

Innovative acoustic communication methods, networking protocols and data compression, help to make optimal use of the limited available acoustic communication bandwidth. The complexity of the acoustic communication channel will, however, retain its limitations and sufficient autonomous capabilities are needed to cope with situations without a communication link.

An alternative innovation that enables larger amounts of data communication is wireless docking, where AUVs are data mules that set up a short-range high-speed wireless data link with a gateway node using, for example, optical communication.

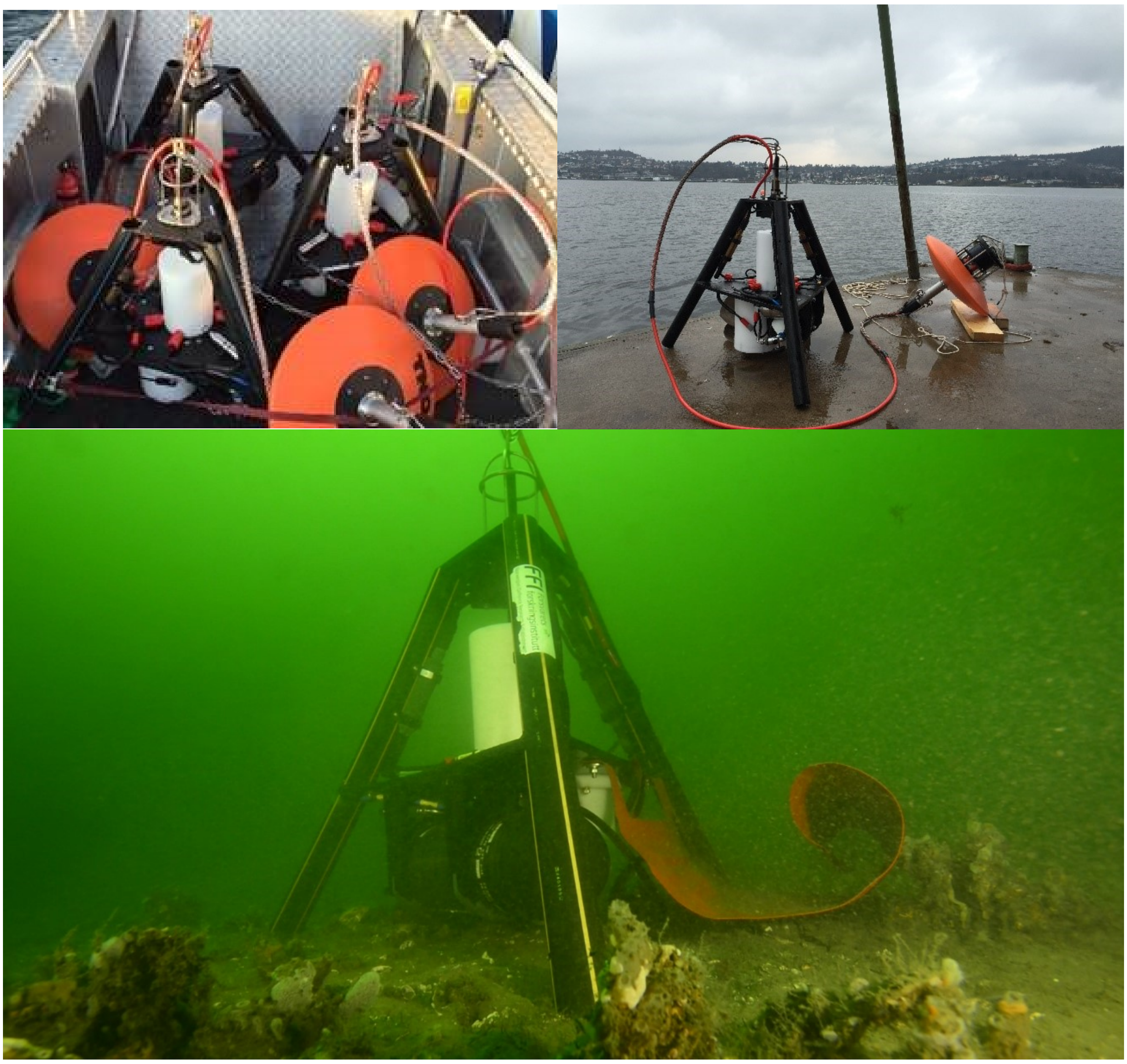


Figure 2: TNO acoustic network nodes. Top left: various nodes ready for deployment, top right: modem and base station shown on dock, bottom: base station situated on sea floor.

2.1.2.6 Other aspects

Other important aspects of AUV technology are:

- **Endurance:** As AUVs are battery powered, their battery life is limited. This requires intelligent use of power and payload
- **Robustness:** reliability in harsh environments (e.g. net entanglements & other obstacles, high currents, corrosion, leakage, high pressure, biofouling, limited visibility)
- **Miniaturisation:** Due to the challenging underwater environments, robust AUVs are costly. There is however a trend towards the developments of cheaper AUVs with reduced payload that may open up a new range of applications.
- **Legislation:** Currently there is very little legislation regarding the use of AUVs. However, legislation may arise when AUVs become a more commonly used asset in maritime operations. Specific topics that could become a part of legislation would involve the impact on marine life and the obligation to retrieve lost AUVs.

2.1.3 Survey

A survey was carried out with various maritime companies to better understand their current use, vision and current experience with unmanned underwater vehicles.

It was found that current use of AUVs is limited to hydrographical surveying tasks, where some companies own underwater vehicles and others allow for subcontractors to use these systems. While different challenges where mentioned by the different companies, the main need for innovation where related to robust underwater communication, navigation, sensing and deployment & recovery. There was no direct need mentioned for further research on legalisation, power usage & cooperative autonomy. However, some of the innovative solution discussed during the interviews did require a higher level of single platform autonomy than currently available on COTS systems.

It was concluded that although Dutch maritime industry is carefully following developments in the fields of autonomous systems, they are not yet making the transition from conventional methods. Reasons given are (i) high investment costs, (ii) non-proven technology, (iii) already available assets suitable of performing maritime operations.

2.1.4 Recommendations

Companies are now looking into the feasibility of unmanned vehicles for maritime operations and technology is advancing quickly. Where most commercially used AUVs act as low-level autonomy data mules to explore the oceans, more and more customized and specialized solutions become available. It is expected that developments in the field of autonomous (underwater) robotics will change the way maritime operations will be carried out in the future, but that further research is needed to increase the performance of unmanned systems in order to compete with current operational optimized solutions.

TNO recommends Dutch industry to take a proactive role in the integration of autonomous systems in their operations to strengthen their position in the offshore market. As the Netherlands does not have a large equipment manufacturing industry for underwater autonomous systems, it is recommended to cooperate with international partners to make use of the state of art technology. The EU provides field lab opportunities to cooperate with maritime robotics providers, such as e.g.: https://www.eumarinerobots.eu/

More information on the research focus of TNO and their vision on innovation regarding unmanned (autonomous) systems can be found in addendum 3.

Figure 3: Collection of images showing the wide variety of AUV size and types. From left to right, from top to bottom: liquid robotics wave glider, Kongsberg sea glider, Saab Sabertooth hybrid ROV/AUV, Kongsberg Eelume AUV, oceanscan-mst man portable Light-AUV (LAUV) owned by TNO, Kongsberg (Liquid Robotics, 2019; SAAB, 2018; Eelume, 2015; OceanScan, 2018; Druglimo-Nygaard, 2014).

2.2 Surface operations

2.2.1 State of the Art

There are many initiatives with regard to unmanned autonomous surface vessels around the globe. Most initiatives deal with small and medium size systems, where small is defined as portable and medium size as trailer-able or transportable via containers. Large scale unmanned autonomous or remotely controlled surface vessels at level 5 to 6 are not in operation so far. In Norway the Yara Birkeland is an autonomous container ship that is under construction and due to be launched in 2019. Following trials with a small crew on board, it is supposed to operate autonomously at level 5 to 6 by 2020. The Yara Birkeland project is planned to be the first fully logistics concept from industrial site operations, port operations and vessel operations in the world. More on the Yara Birkeland is found under the subparagraph Large Systems.

Next to entire unmanned autonomous surface vessels of various sizes, several maritime companies are developing autonomous subsystems, which eventually will support the development of an entire ship concept (e.g. mooring systems, docking systems, engine room systems, etc.)

In the Netherlands several companies are active in providing solutions for small and medium size unmanned and/or autonomous surface vessels at different autonomy levels. For large size vessels some initiatives are underway, but fully large size unmanned autonomous (level 9 and higher) surface vessels are not likely to be used in The Netherlands in the coming years.

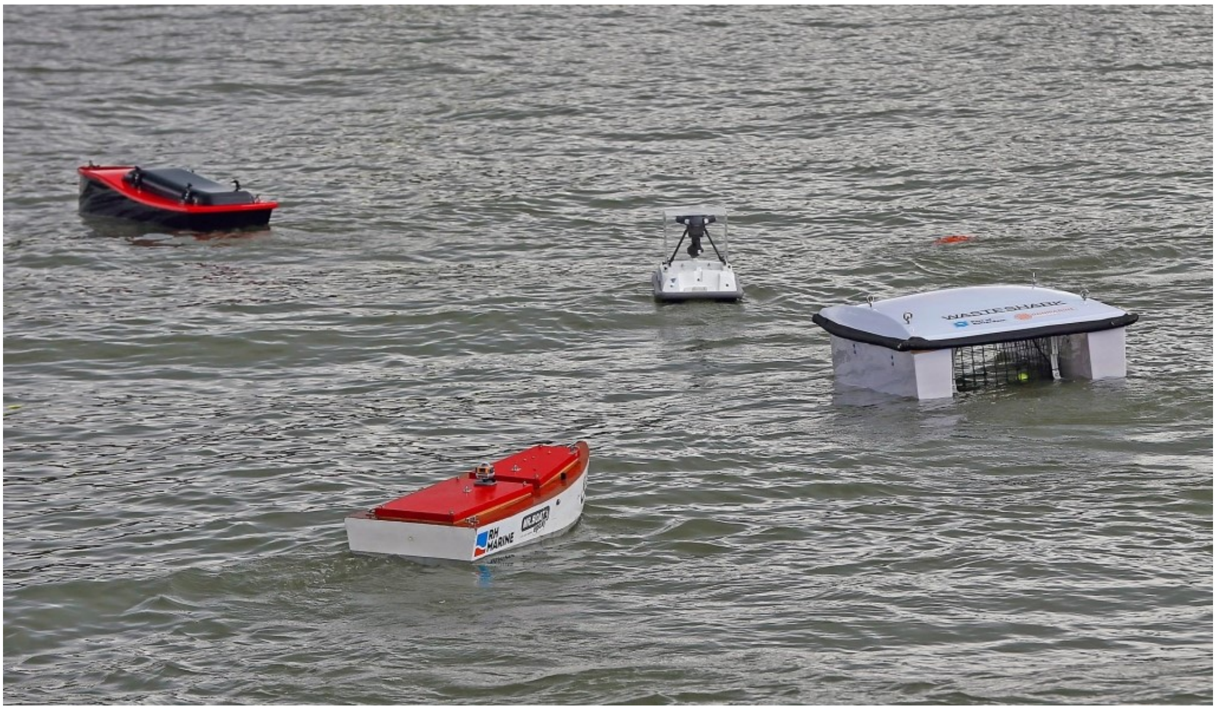


Figure 4: Some examples of small unmanned (autonomous) surface systems (RDM Centre of Expertise, 2016)

2.2.1.1 Manoeuvrability and Navigation

The manoeuvrability of small size (portable) unmanned surface vessels (USV) is outstanding for operations in confined port areas such as, quays, but also in large maritime constructions, like locks or between floaters. The size of the USV and the fact that no person is required allows for very small and manoeuvrable vessels. However, the platform stability and the stabilisation of sensors on the platform poses a challenge for small size USVs.

For medium and large size USVs no major differences in manoeuvrability with normal medium and large size vessels are encountered regarding stability and stabilisation of sensors on board. The absence of people on board for USVs allows for more extreme ship motions since there is no personnel that can suffer from seasickness or other degradation in performance. This can be an important driver for further development of USVs. Especially catamarans with reduced payload and low resistance seem to be fit for these tasks, although their behaviour in waves is not always optimal.

The remote-controlled navigation of small size USVs can be executed visually (directly or via camera’s), but also manually or autonomously with the aid of GPS (and their differential systems) and/or AIS via digital charts and/or pre planned way points.

The risk is that navigation aids are jammed or spoofed. This introduces a large risk for operation and safety. We’ve seen examples of that and for the NL Navy this is an important concern.

For medium and large size USVs the visually remote-controlled navigation is not a real option since the operation will be probably not be carried out in close proximity of the person ashore responsible for the operation. This increases the necessity for improved navigation security. Also, communication between USV and surrounding vessels becomes more important.

After deployment, USVs, like AUVs, can also follow a pre-programmed course and navigate using (i) acoustic beacons with known positions and Long Base Line (LBL) localisation[ref] or (ii) a combination of Ultra Short Base Line (USBL) acoustic communication, GPS positioning and Inertial Navigation System (INS) (using dead reckoning based on depth sensors, inertial sensors, Acoustic Doppler Current Profilers (ADCP) and Doppler Velocity loggers (DVL).

2.2.1.3 Sensing

USVs can be equipped with a wide range of sensors for acoustic, radar, lidar and camera imaging and water sampling. A floating platform can use both the water (sonar, acoustics, optical) as well as the air (radio, radar, lidar, IR and visual) for sensing and is therefore the most optimal platform for multi sensor integrated applications.

With regard to optical sensors Unmanned Aerial Vehicles (UAVs) have the advantage over USVs that they have a larger operating speed and can therefore cover larger areas in a shorter amount of time.

With regard to the accuracy of seabed imaging sensors, AUVs have the advantage over USVs that they are able of flying relatively close to the sea floor, making it possible to collect data at much higher resolution.

2.2.1.4 Deployment and recovery

Even when autonomous, most USV concepts are deployed from a support vessel or from a shore-based station due to the risks and the capital costs of the assets. Exceptions might be the small size USVs that will be designed to operate fully autonomously for several weeks or months without operator interaction, able of providing excellent spatial coverage and local resident systems that reside and recharge in a docking station when inactive (see e.g. Eelume).

2.2.1.5 Autonomy and operational concept

The primary autonomous capability of USVs involves navigation (path planning) and collision avoidance. There is however a trend towards increased vehicle intelligence (decision making capability), enabling platforms to e.g. asses the quality of collected data, interpret (classify) sensor data, plan the mission (given a high-level mission objective) and even co-operate together (interoperability). For operations where the USVs have a sufficiently high level of autonomy, no direct human control is needed during operation. For operational scenarios involving a support ship, this means that the vessel and crew can be used for other tasks, increasing the amount of data that can be collected for a given amount of ship-time (Yoerger et al., 2007a, b). The USVs also need to know which ship is the support ship with certainty.

2.2.1.6 Communication and networking

Communication with USVs will most probably be executed via line of sight radio connections or satellite communication. More important is that communication is secure and certain. Otherwise there is a risk of USVs being hijacked.

2.2.1.7 Other issues

The lack of legislation for unmanned autonomous surface vessels is an important issue. Especially since there are usually many other vessels in the area that might not be unmanned and/or autonomous. Questions like “who is responsible for what”, what are the rules in case of collision (avoidance), the execution of port operations (pilots, tugs, linesmen, etc.) when ships are unmanned, and how should safe distances be maintained under different operational scenarios (e.g. boarding the pilot, navigation in confined waters, mooring operations etc.)

2.2.2 Desk Research and interviews

This paragraph provides an overview of developments in the field of small size unmanned surface vessels. Although we found quite some developments, we're not certain that all developments are covered.

2.2.2.1 Small size systems

Aquatic Drones

Next to medium size surface vessels several small unmanned remotely and/or autonomous vessels are currently developed in the Netherlands. Aquatic Drones has developed a small catamaran for autonomous inspection and monitoring of waterways, ports and sea. According to founder and CEO Maarten Ruyssenaars Aquatic Drones are smart and clean ships equipped with sensors. Autonomous (unmanned) measurements can be carried out as bathymetry, water quality, fish counts, hull inspections, quay inspections, detecting oil spills, sampling and monitoring of bridges and locks. The data is automatically analysed and interpreted, enabling the end user to execute more effective and efficient management and maintenance. This at a much lower cost and environmental footprint and an increase of quality and sustainability of waterways, natural areas, coastal areas and ports (Smash!, n.d.).

Aquasmart XL

Figure 5: AquaSmart XL (AquaSmartXL, 2018)

Wasteshark Ranmarine

Figure 6: Watershark (Nguyen, 2016)

Maritime Robotics

Maritime Robotics is a Norwegian company that has developed several unmanned autonomous surface vessels and produces small and medium sized (portable) systems. Moreover, they have participated in a Dutch pilot of RWS, NL Navy and NL coastguard.

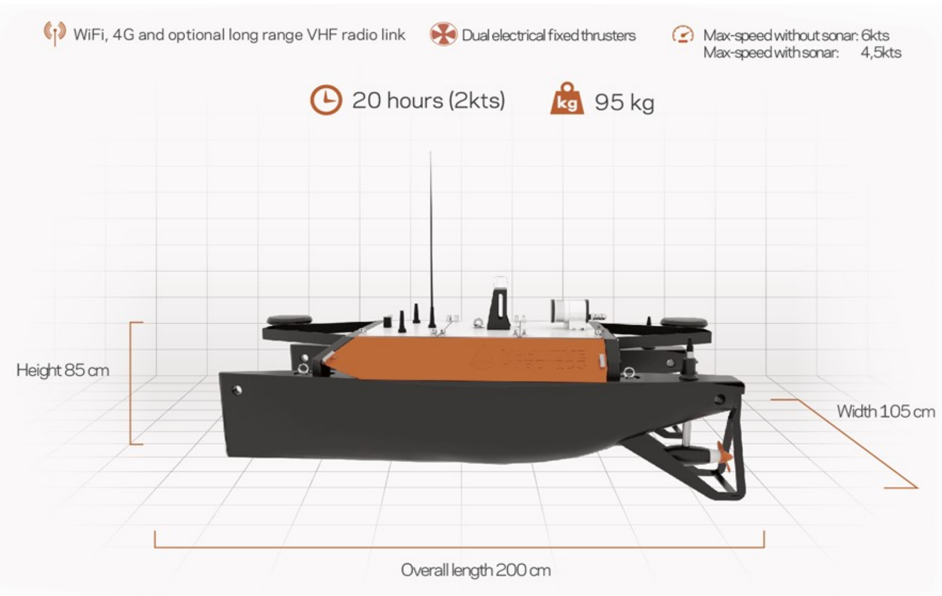


Figure 8: Otter (Maritime Robotics, n.d.)

Liquid Robotics

Wave Glider

- Water Speed: 1kt to 3kts
- Endurance: Up to 1 year (may vary based on operating conditions and location)
- Operating Water Depth: > 15m
- Station Keeping: 30m radius (CEP90)
- Payload: 7 modular bays
- Tow Capability: Up to 500kg mass
- Average Continuous Power: 5W – 20W
- Max Solar Collection: 180W
- Battery Storage: 0.9kWh – 6.8kWh
- Communications: Satellite, Cell, Wi-Fi

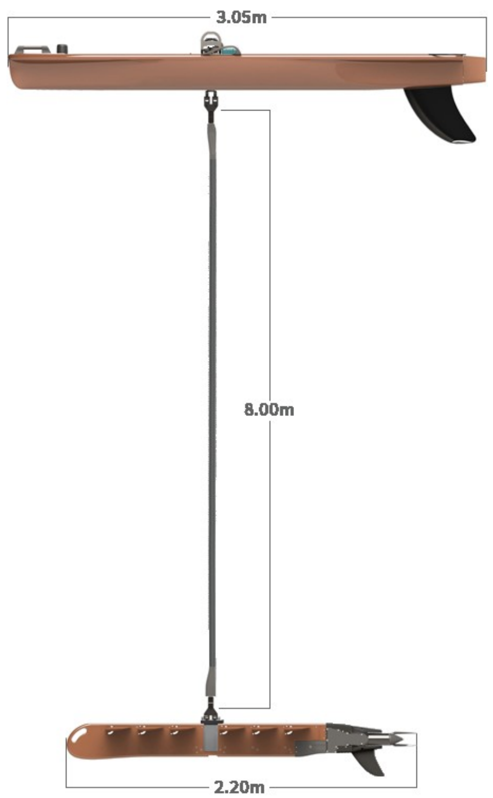


Figure 9: Wave Gilder (Liquid Robotics, 2019)

2.2.2.2 Medium size systems

Seagull- 301(USV)

Unmanned autonomous surface vessels are in an early development stage. Unmanned vessels are already in use in several international navies like the US Navy and the Israeli Defence Force (IDF). For IDF an Unmanned Surface Vessel named Seagull-301 was built in the Netherlands and was awarded with the Netherlands KNVTS Ship of the Year price 2017. This vessel with a length of 12 meters and a payload of 2500 kg is an example of the current state of the art for medium size unmanned surface vessels (USV) and was developed by L-3 Klein Associates and SeaRobotics and built by De Haas Maassluis and Ginton Naval Architects BV.

Figure 10: Seagull USV (KNVTS, 2017)

ASV global

ASV global is a British company that has developed around 100 unmanned autonomous surface vessels and participated in 2016 in a Dutch pilot of Deltares, RWS, NL Navy and NL coastguard. According to ASV global their unmanned autonomous surface vessels offer the ability to hold a persistent presence in a specified area without the added risk or cost associated with a manned vessel. This presents huge potential to coastal surveillance and security applications in a time where saving costs, creating efficiencies and improving safety are vital (ASV Global, n.d.).

The controller offered by ASV offers the operator a range of modes:

- Remote mode: direct remote control: not autonomous at all (level 1)
- Automatic mode: assisted remote control: holding heading, course over the ground and speed (level 5).
- Mission mode: enabling operator to plan a range of complex missions in detail (level 5).
- Autonomous aided control: Mission plan changes and on-board navigational decision making to avoid collisions and achieve mission goals. The operator can override if required (level 6)
- External mode: this mode can be applied to any mode above.

So, the highest level of autonomy offered is currently level 6.

An unmanned autonomous service vessel that was tested in The Netherlands in 2016 was the BAE P950 rib converted by ASV Global.

Figure 11: BAE P950

Maritime Robotics

Maritime Robotics is a Norwegian company that has developed several unmanned autonomous surface vessels and produces both small and medium sized systems. Moreover, they have participated in a Dutch pilot of RWS, NL Navy and NL coastguard in 2016.

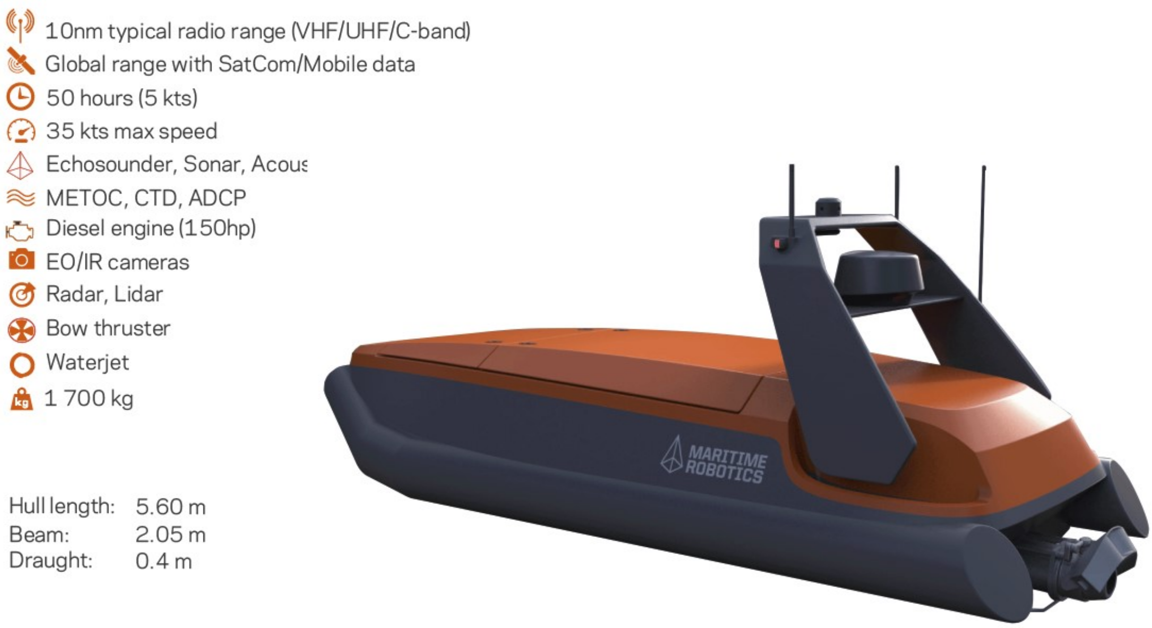


Figure 72: Mariner USV (Maritime Robotics, 2018)

2.2.2.3 Large size systems (>15 metres)

Sea hunter

Sea Hunter is an autonomous unmanned surface vehicle (USV) launched in 2016 as part of the DARPA Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) program. She was christened 7 April 2016 in Portland, Oregon. She was built by Vigor Industrial. The vessel continues the line of experimental "Sea" ships, including the Sea Shadow, Sea Fighter, and Sea Slice. Sea Hunter is classified as a Class III USV and designated the Medium Displacement Unmanned Surface Vehicle (MDUSV) (Vincent, 2016)

Figure 13: Sea hunter (DARPA, 2018)

The initially unarmed prototype, built at a cost of twenty million dollars, is a 132-foot (40 meter)-long trimaran (a central hull with two outriggers). She is an unmanned self-piloting craft with twin screws, powered by two diesel engines with a top speed of 27 knots. Her weight is 135 tons, including 40 tons of fuel, adequate for a 70-day cruise. Cruising range is "transoceanic," 10,000 nautical miles at 12 knots [7] fully fuelled with 53,000 litres of diesel, enough to "go from San Diego to Guam and back to Pearl Harbor on a tank of gas." Sea Hunter has a full load displacement of 145 tons and is intended to be operational through Sea State 5, waves up to 2.0m high and winds up to 21 knots, and survivable through Sea State 7, seas up to 6m high. The trimaran hull provides increased stability without requiring a weighted keel, giving her a higher capacity for linear trajectories and better operations in shallow waters, though the greater width decreases manoeuvrability.

A removable operator control station is installed during the testing period "for safety and backup" until it can be determined to reliably operate on her own. So currently it operates at approximately autonomy level 6 . Operationally, computers will drive and control the ship, with a human always observing and taking charge if necessary in a concept called Sparse Supervisory Control, meaning a person is in control, but not "joy sticking" the vessel around. It can patrol without human guidance, using optical guidance and radar to avoid hitting obstacles or other watercraft. The ship has a host of non-standard features because of her lack of crew, including an internal layout that offers enough room for maintenance to be performed but not for any people to be permanently present.

She is expected to undergo two years of testing before being placed in service with the U.S. Navy. If tests are successful, such craft may be armed and used for anti-submarine and counter-mine duties, operating at a small fraction of the cost of operating a destroyer,[10] $15,000-$20,000 per day compared to $700,000 per day; it could operate with Littoral Combat Ships, becoming an extension of the LCS ASW module. Deputy US Defence Secretary Robert Work said that if weapons are added to the ship, a human would always remotely make the decision to use lethal force. (Weapon use is normally regarded at a maximum autonomy level 5)

Zulu

Figure 14: Zulu (Schuttevaer, 2017)

The Belgian entrepreneur Antoon van Coillie of Blue Line Logistics awarded the Dutch shipyard Groeneveldt Marine Construction in Hendrik Ido Ambacht the project for the building the first series of unmanned inland vessels named Zulu 3 and 4. The technology used for these vessels consists of a combination of sensors, radars, GPS and collision avoidance-technology that will be provided by several Scandinavian companies (Blue Line Logistics, 2018; (Schuttevear, 2018).

Kotug RT Borkum remote controlled

Figure 15: RT Borkum

At the 2018 International Tug, Salvage and OSV Convention and Exhibition (ITS) in Marseille the RT Borkum was remotely controlled over a distance of almost 1200 kilometres in the Rotterdam port area. The tugboat captain used a secure internet connection and camera images to safely navigate the vessel in the Rotterdam port area Maashaven.

Kotug reports that they are convinced that remotely controlled vessels are the first step towards fully unmanned autonomous surface vessels. At present, several simple tasks can already be executed remotely. Real time technology can assure a captain at a remote location the ability to operate the vessel safely. Combined with drone technology for transfer of the towing cable, unmanned shipping will come within reach both technically and commercially.

Since unmanned sailing does not yet comply with the current rules and regulations, Kotug would like to see the rules adjusted in order that tug boats can execute their tasks fully autonomous in the future. For the remote-controlled RT Borkum Kotug co-operates with Alphatron, KPN, M2M Blue, OnBoard, Rotortug and Veth (Schuttevaer, 2018).

MV Yara Birkeland

Yara Birkeland will be 80 metres long, with a beam of 14.8 metres and a depth of 12 metres. It will have a draught of 6 metres and will be propelled by electric motors driving two azimuth pods and two tunnel thrusters. Batteries rated at 7.0-9.0 MWh will power the electric motors, giving it an energy optimal speed of 6 knots (11 km/h) and a maximum speed of 10 knots. It will have a capacity of 120 TEU. The Norwegian Government gave a grant of approx. 14 million Euros towards the construction of the ship, about a third of the total cost, in September 2017 (Konsberg, 2017).

Figure 16: Yara Birkeland

Yara Birkeland is named after its owners Yara International and its founder, Norwegian scientist Kristian Birkeland. It will be designed by Marin Teknikk, with navigation equipment by Kongsberg Maritime. It will enter service in 2019, initially operating as a manned ship. Yara Birkeland will sail on two routes, between Herøya and Brevik (7 nautical miles) and between Herøya and Larvik (30 nautical miles), carrying chemicals and fertiliser. Remote operation will start sometime in 2019 and by 2020 it will be fully autonomous. The autonomy level is not mentioned but is probably level 5 to 6.

Finferries Falco

Figure 17: Car Ferry Falco (The Engineer, 2018)

Rolls-Royce (RR) and Finnish state-owned ferry operator Finferries have successfully demonstrated a fully autonomous ferry in the archipelago south of the city of Turku, Finland. During the demonstration, the Falco, with eighty invited VIP guests aboard, conducted the voyage under fully autonomous control. The vessel detected objects utilising sensor fusion and artificial intelligence and conducted collision avoidance. It also demonstrated automatic berthing with a recently developed autonomous navigation system. All this was achieved without any human intervention from the crew (SWZ MARITIME, 2018).

This ship seems to be the first vessel that sails autonomously at the highest levels (level 9).

November 29, 2018 Norwegian Ferry Folgefonn visited three ports autonomously. The tests were conducted in the presence of the Norwegian Maritime Authority (NMA). The operator selected the next berth, and then authorised the controller to take control of the vessel. According to the website, the ship was able to leave the dock, manoeuvre through the harbour entrance, and dock alongside the terminal. Also this trial was tested at the highest level of autonomy.

So current state-of-the art in shipping is that it is possible to let a large ship sail autonomously over a restricted time and distance, including manoeuvring and docking operations and decisions, equivalent to the early auto-pilots used in airplanes.

Joint Industry Project – Autonomous shipping

In the Netherlands a joint industry project has been set up to investigate the potential of unmanned and autonomous shipping. This project involves a full-scale test using a fast crew supplier. These tests are currently planned to take place on the North Sea.

More info on JIP: https://maritimetechnology.nl/projecten/jip-autonomous-shipping/

Figure 18: SEAZIP (SEAZIP, 2019)

2.2.2.4 Unmanned Autonomous Subsystems

Autonomous Shipping is high up on the agenda: 36 percent of ship-owner executives believe it to be the future of merchant shipping. 90 percent of those in support believe that the use of unmanned ships will be routine in as little as 20 years. "We have seen an enormous shift in public opinion here", says VDR managing director Johns. The two-decade horizon is not a far-fetched prospect, considering the average service life of a ship, he adds (SMM, 2017).

When it comes to fully autonomous ships, they follow the lead of the automobile and airplane when it comes to first moving toward advanced cruise-control/autopilot, using these technologies as stepping stones for autonomous systems.

For example, ABB just released their Marine Pilot Control:

Stepping stone to autonomous shipping The ABB Ability™ Marine Pilot Control is a pioneering technology that is already available today and that will act as a stepping stone into the future of autonomous shipping. Autonomous shipping requires a DP system that can replace traditional solutions designed for disconnected operation (ABB Ability, 2018).

There are some smaller companies that are leaning into level 2/3 autonomous large surface vessels.

EcoPilot re-optimizes the route plan throughout the voyage to make sure that the ship arrives on the specified time, whilst minimizing fuel consumption. An unforeseen change in the time schedule is easily handled by an automatic re-optimization of the remaining route (QTAGG, 2018)

There are also some robots that crawl along the outside of the ship using magnets for cleaning of hard-to-reach surfaces.

2.2.3 Conclusions and recommendations Surface systems

Small unmanned, remote controlled and/or autonomous surface systems are already in use for several tasks like visual (quay) inspections, cleaning and monitoring operations. These systems will continue to develop rapidly in the coming years and do not pose a serious threat to other maritime users in port areas or for near shore operations. The stability of the platform and its sensors in waves and harsh weather conditions poses an important challenge to the usability of these systems. At present, these systems are brought into the market by a strong technology push. Maritime clients operate as smart buyers of these systems and/or use these systems via service providers for specific tasks (inspections etc.) Although governmental clearance is required for operation of these systems, this is not likely to become a serious problem.

Medium and large size autonomous systems can pose a threat to other shipping in the vicinity and cannot be operated without proper clearance of the authorities. In case of collisions and damage, questions regarding responsibility and liability will soon emerge. A legal framework is required for medium and large surface vessels in order to operate properly. In line with truck transport surface vessel trains are probably one of the first solutions that will be developed in the shipping. Also, the operation of autonomous surface vessels in totally dedicated (isolated) areas is an interesting option to consider. This scenario is comparable to autonomous vehicles at large container terminals or (target) practice areas for defence operations.

2.3 Aerial operations

2.3.1 State of the Art

Over the last decade the cost of drones has decreased considerably while the capability has increased considerably. This has led to them being explored and used in many different industries and by consumers themselves. Figure 19 shows the growth of the number of drone registrations in the US since they began registering drones. Most of these drones perform many of their flight functions with an autonomy level below 4, however some safety settings increase autonomy to level 6, such as in auto-landing situations when the battery gets too low.

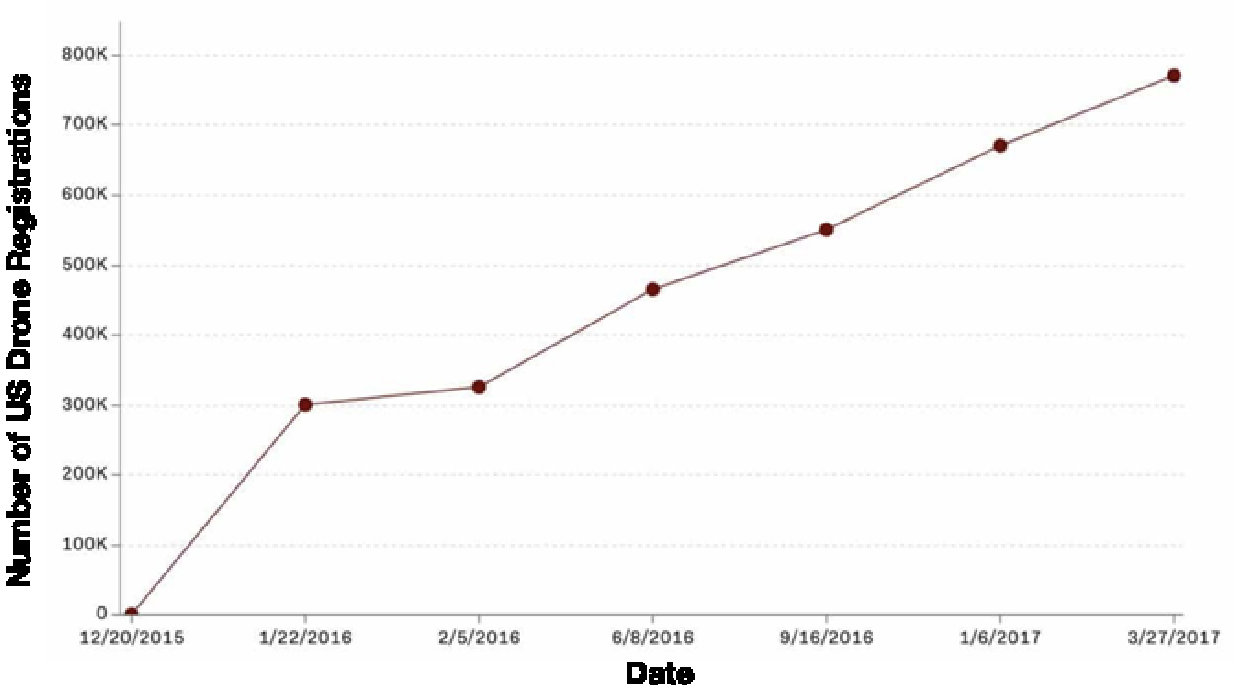


Figure 19: Growth in the number of US Drone Registrations (Chavers, 2018)

This growth in the capability and utility of drones has begun to be explored by the maritime domain as people in the domain continue to look to use tools to improve their operations. This section will explore the current situation of autonomous vehicles as they are used in the maritime domain.

2.3.1.1 Technical and Regulatory Start of the Art

As drones continue to proliferate, they are decreasing in cost and increasing in performance, yet the main limitations continue to be flight time (e.g. battery life), robustness, and precision. This section will discuss the technical state of the art of Unmanned Aerial Vehicles (UAVs). Due to the fact that, the consumer market is leading the way in drone technology development, much of the technical focus will explore those consumer type drones.

2.3.1.2 Flight Time/Range

While many high-end drones are being produced, it is still quite rare to see a flight time of over 30 minutes on a battery powered small UAV as is shown in Table 2. Most of the small drones are powered by lithium ion batteries and are quite small (in part to reduce cost), and thus have short lifetimes.

Product	Flight time	Control range
Blade Chroma Quadcopter Drone	30min	2500m
Sim Too Pro	30min	1000m
DJI Phatom 4	28min	3500m
DJI Mavic Pro	27min	7000m
DJI Inspire 2	27min	7000m
Parrot Bebop 2	25min	3200m
DJI Phantom 3 Standard	25min	1500m
DJI Phantom 3 Pro	23min	3000m
3DR Solo	22min	500m
Yuneec Q500+	22min	2000m

Table 2: Flight Time of Many Small Consumer Drones (Brown, 2019)

This is similar to the most popular commercial drones such as the DJI MG-1, pictured in figure 20 below, which has a flight time of 10-24 minutes.

Figure 20: DJI MG-1 Commercial Drone

While 30 minutes is a limiting factor for a number of maritime applications (such as beyond-line of sight information gathering), the trend in improvement of lithium-ion batteries paints a compelling picture for the future of drones having much longer battery life at the same or lower prices. Figure 21 shows the improvement in lithium ion battery performance over time, showing an improvement of about 5% per year in energy density and about 13% per year in battery cost. This drone operates with an autonomy level of less than 6.

A straight line can be drawn through a set of points, but other line types can also be drawn indicating a stand-still in energy density since 2005, and a slowing down of price reduction since 2005, with basically no price improvement over the last 5 years. This might indicate the lack of breakthroughs in this area over the last 8 to 10 years.

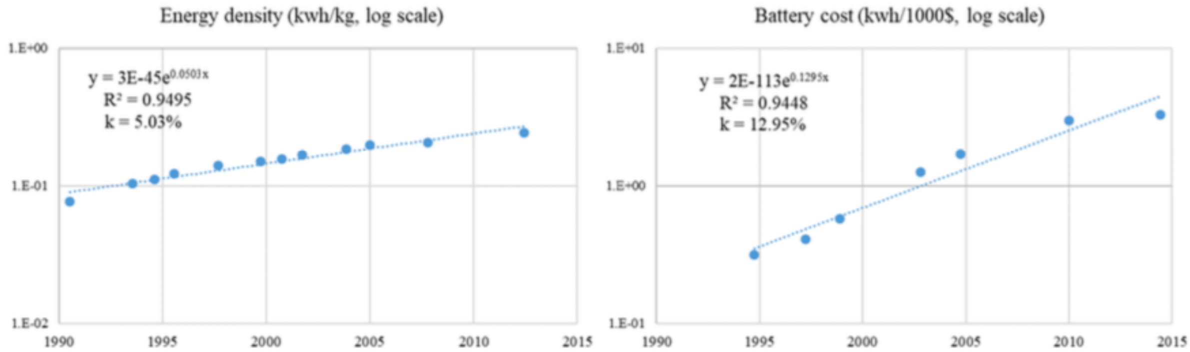


Figure 21: Historical Improvement of Lithium Ion Batteries

It is not feasible to get much more energy into a material than 1 eV per atom. Most solids have atomic weights of 30 GeV/c^2 which yields E/m = 3x10^-11 c^2. When you convert this into the more human Watt-hour/kg, you get 850 W-hr/kg. We're already at 200 W-hr/kg, which means that we can gain a factor of 4 before we hit this rough limit. With a growth rate of 5%, we hit this limit in 25 years and at 8% this is hit in 17 years. This is similar to the end of Moore's law.

Looking to the entire battery system the maximum energy is around 450 W-hr /kg (Fraunhofer, 2018).

Even with significant expected performance improvements in energy storage, it will continue to be a near term limiting factor and there are a number of potential solutions to this problem including tethering, alternative energy sources, and hybrid rotating-fixed wing drones.

Tethering

One solution to get around the problem of short flight times is adding a tether to continually provide power to the drone. This solution is attractive because it essentially eliminates any energy storage or consumption concerns for the vehicles, however it is less attractive when the use case requires flying far away from where it took off. Figure 22 shows an example of the Elistair Orion unmanned system, which can fly for up to 10 hours, but can only hover at around 80 meters. This drone operates with an autonomy level of less than 6.

Figure 22: Elistair Tethered UAS (Elistair , 2018).

Alternative Energy Sources

While lithium ion batteries are by far the most popular energy source for UAVs, there are other options including hydrogen fuel cells, such as those provided by Intelligent Energy, which can provide significantly higher energy density as shown in Figure 23. Using fuel cells can result in flight times of up to multiple hours (HES Energy Systems , 2018).

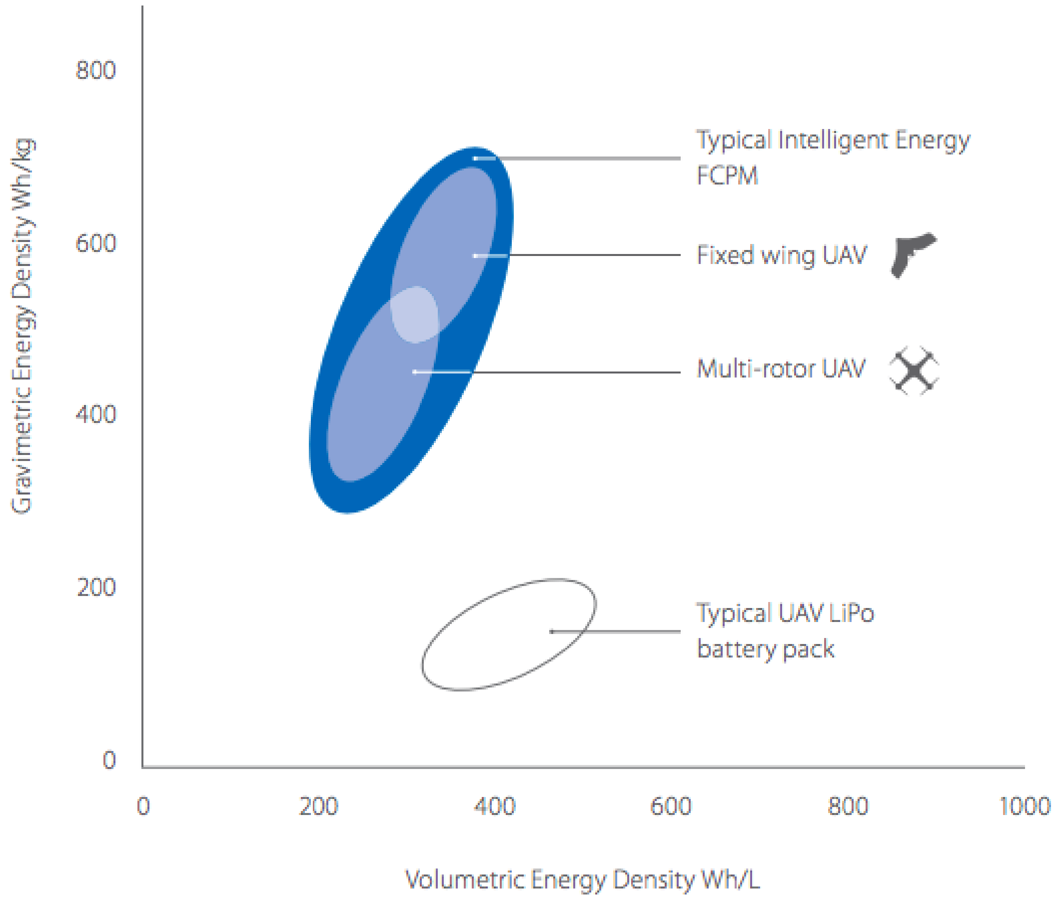


Figure 23: Comparison of UAV Fuel Cell Power Modules to Batteries (Intelligent Energy, 2018)

Hybrid Wing Designs

Most UAVs have chosen to use a design with multiple rotating wings (e.g. a quad copter), which allow for vertical take-off and landing, fine-tuned control, and the capability to hover, often at the expense of long flight times or distances that are often found in fixed wing designs (i.e. planes). Some designs have explored finding the 'best of both worlds' with a hybrid rotating-fixed wing design that allows for vertical take-off and landing, but also for long flight distances and times. Figure 24 shows an example of one such design created by the Micro-Air-Vehicle Lab at TU Delft. This drone operates with an autonomy level of less than 5.

Figure 24: Hybrid Rotating-Fixed Wing UAV Design (MAVLab, 2019)

2.3.1.3 Precision

Many of the small drones rely mainly on GPS for their precision in flight and landing, which provides about three-meter accuracy, which is often acceptable during straight line flight, but may not be acceptable for hovering applications or landing. In those such cases other solutions can be used to increase the precision, including using visual flight aiding with cameras as is shown and real-time kinematic algorithms and differential global positioning system (RTK GNSS GPS).

Visually aided navigation allows the use of electro-optical cameras to provide very precise landing and control of drones. This is often done through regular cameras and with advanced computer vision algorithms. These types of solutions should continue to improve rapidly as the performance of cameras and computer vision algorithms are common problems that will continue to improve independent of the rest of the developments in drones. Figure 25 shows a system that performs visually aided landing. This drone operates with an autonomy level of less than 6.

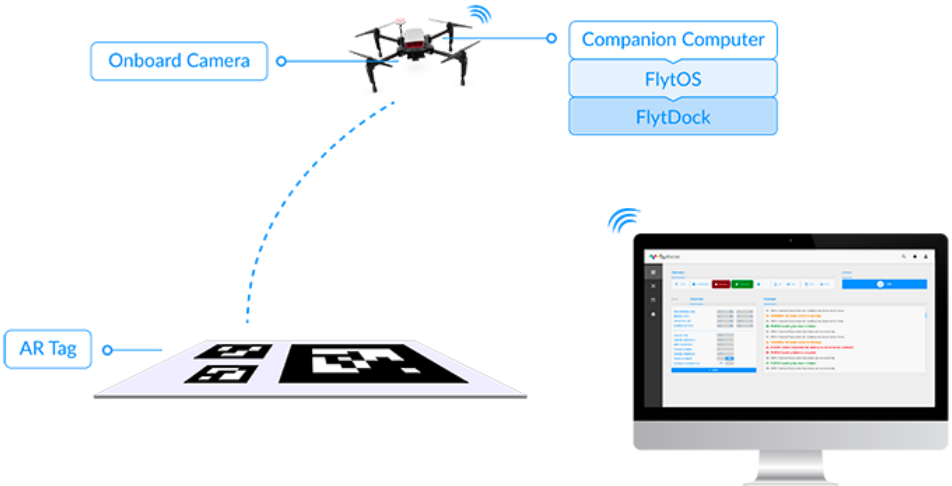


Figure 25: Visually Aided UAV Navigation (flytbase, 2018)

RTK GNSS GPS is technology that uses the same signals from the GPS satellites, but processes their waveforms rather than using just the information sent from the GPS satellites in order to achieve a higher accuracy. This solution will continue to improve with the update of the GPS system planned to begin in late 2018 (Wikipedia, 2018). Figure 26 shows the type of device that can be used to interpret the GPS signals more accurately.

Figure 26: RTK GNSS GPS (Emelyanova, 2016)

2.3.1.4 Robustness

Robustness of UAVs has also been an area of technical limitations that has received attention in recent years. Due to the technical requirements of precision and low weight (to keep help mitigate the flight time issue), many of the components of UAVs are fragile. During normal flight operations, it is relatively rare for these delicate components to be damaged, but they are easily damaged in an accident or during transportation. These issues are likely to be mitigated in coming years as increase in battery performance reduces the tight constraint on small and lightweight parts and as the designs of the drones continue to mature.

Use of drones in the maritime domain adds a couple other robustness constraints, including being able to operate in high winds, and the effect of working in the wet and salty conditions of the maritime environment. These maritime unique challenges deserve more exploration, as they are less of a concern in the consumer market and thus are less likely to be mitigated by developments of drones for non-maritime domains (this is unlike the case of the flight time issue, which is shared by drones in all domains).

One final robustness issue that may be unique to the maritime domain is a need for explosive resistant or non-sparking UAVs. These types of UAVs may be used in the oil and gas maritime industry where they will not be used today because of fears over starting a fire or causing an explosion.

2.3.1.5 Regulatory Challenges

With the rapid proliferation of drones, many governments have struggled to keep up with updating their policies and regulations to adapt to the new, potentially disruptive technology. This has resulted in a menagerie of different policies that range from being very restrictive to those being very open to drone use. Figure 27 shows the state of regulation for recreational use of drones in Europe color coded by their restrictiveness.

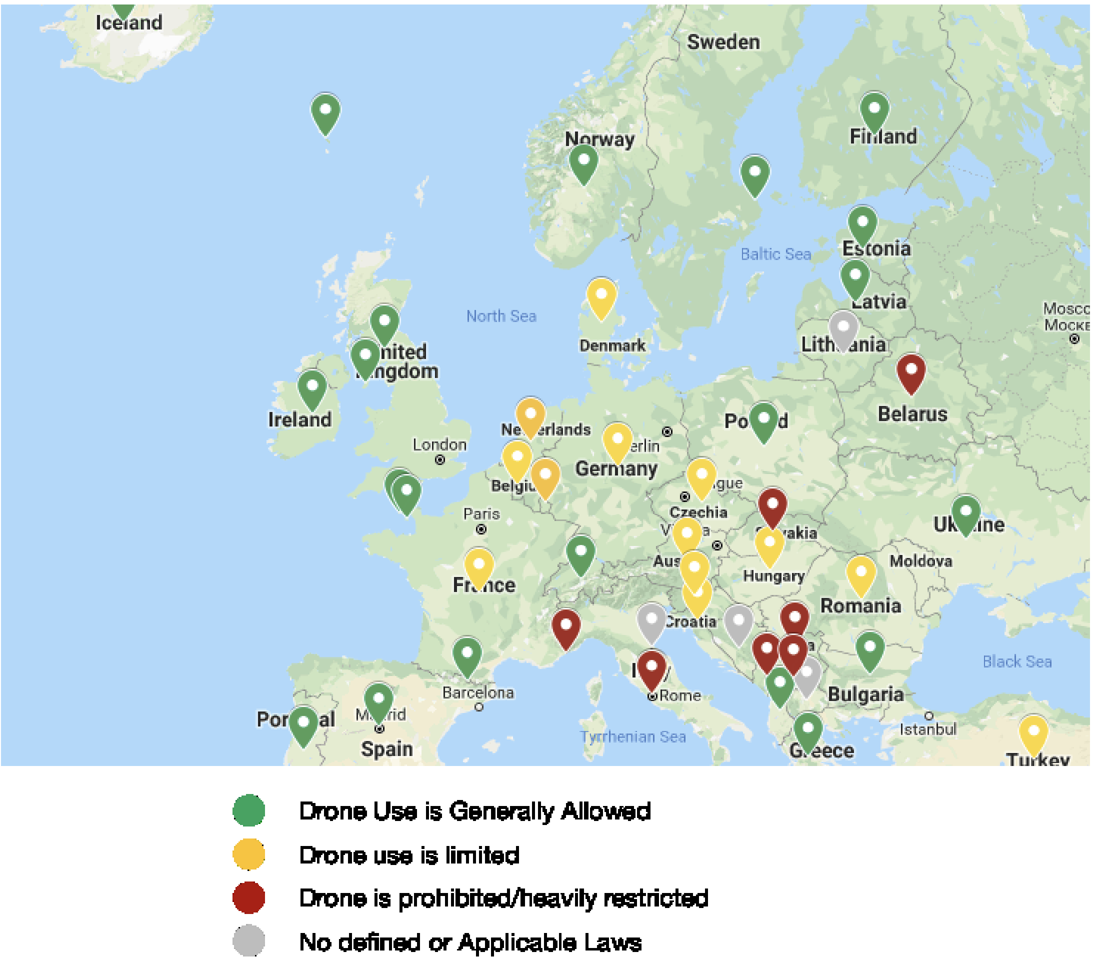


Figure 27: Drone Laws by Country (Simpson, 2017).

The impact of this for the use of drones in the maritime industry is that they are generally used while the vessels are at sea but have many more restrictions for use while in port. This particular issue of not being able to use drones in all ports was brought up in several of the maritime industry interviews as a need for future work.

2.3.2 Desk research and interviews

The industry survey consisted of several parts, first discussing the impact of autonomous aerial vehicles (AAVs) with large existing maritime companies, then discussing them with smaller existing maritime companies, then discussing it with new 'startups' focusing on AAVs that may have an impact on the maritime industry.

2.3.2.1 Discussions with large maritime players about their understanding of AAVs

Most large players in the maritime industry are not yet using AAVs for their operations, however there are a few that are using them for inspections, such as inspections for internal ballast tanks and even led to a large classification society releasing an R&D Roadmap and guidelines for drone surveys (Jallal, 2018). For this research we contacted several of these large companies through rapid, informal surveys at the SMM maritime trade show in Hamburg in September of 2018 (SMM, 2018).

One use of drones from large maritime players is in the defense sector, where traditional defense contractors are producing very large unmanned systems. One such example is the VSR 700 unmanned helicopter from Airbus which operates with an autonomy level of less than 3, is described in the quote below and is shown in Figure 28. These solutions are intended for use in information gathering missions that are over the horizon.

The helicopter drone VSR 700 is Airbus Helicopters idea of what the future of these systems might look like. Intended to be used in marine reconnaissance, the VSR 700 is still in its testing stage and should be ready for delivery in 2020. The direction this segment of military technology will take will not solely depend on economic and military interests (Ebbinghaus, MS&D: New Strategies to Guard Against Future Security Threats, 2018).

Figure 28: Airbus VSR 700 Helicopter Drone (npjprods, 2018)

Another use of drones by large maritime firms was in digital scanning and modelling of maritime assets. In particular they make use of smaller drones that are similar to consumer drones to scan whole sections of assets in an attempt to reduce time and cost. These drones operate with an autonomy level of less than 5. This is described in the two quotes below and is shown in figure 29.

The "Digital Twin" concept is an example: "The ability to reproduce ships digitally, and the use of drones fitted with high-tech cameras will reduce the effort involved in ship maintenance and mitigate safety risks," (Knut Ørbeck-Nilssen, CEO of DNV GL Maritime, SMM 2018 Keynote address)

For instance, the classification society DNV GL uses drones equipped with cameras to inspect structural elements in ships, tanks or offshore installations (Ebbinghaus, 2018).

Two specially trained DNV GL class surveyors and a drone equipped with a high definition camera work together to carry out the surveys. Even in dark, enclosed spaces, the area under inspection can be illuminated to capture high-resolution images. Drone surveys are carried out in real-time, with one surveyor operating the drone and the second remotely monitoring the recording on a tablet. It is possible to re-examine particular details on the recording, e.g. through enlarging a specific location on the screen (Galinski, 2019).

Figure 29: Drone for Maritime Surveys (DNV GL, 2019)

2.3.2.2 Discussions with new players in the maritime industry

There are a considerable number of new players who are working in the maritime industry with drones, and due to the relative youth of the technologies, it is these smaller players where most of the movement is taking place. In order to find them we connected with several startup organizations to find a large number of companies in one place.

The first place we discussed drones with was Yes!Delft, which houses a number of drone-related companies.

YES!Delft is the business incubator of the Technical University Delft, in The Netherlands. We believe in the impact tech companies can have, because they provide a crucial contribution to the innovation of our economy and society. Our programs turn promising ideas and teams into solid startups and grow them to successful companies. YES!Delft provides tech entrepreneurs with guidance and support in their startup journey. With 12+ years of experience we offer entrepreneurs access to mentors, experts, investors and corporate partners who share their know-how, network and experience. We currently have 200+ tech startups in our portfolio and are accepting new applications for our programs. (YES!Delft, https://www.yesdelft.com/)

After discussions with their start-up technology manager, several companies were identified to be working on drones that could be used in the maritime domain.

Delft Dynamics: https://www.delftdynamics.nl/

SeaState5: https://www.seastate5.com/eagle/

Atmos UAV: https://www.atmosuav.com/product/howitworks

Mainblades Inspections: http://mainblades.com/

Drones for Work: https://dronesforwork.nl/

Robotica in Maintenance Strategies: https://rims-bv.com/

The next place we looked was at the RoboValley, which is the commercialization arm of the robotics research that comes out of TU Delft and specifically out of the TU Delft Robotics Institute.

In RoboValley, more than 170 robotics researchers from a multitude of fields collaborate with other experts, entrepreneurs and decision-makers in both public and private sectors. As a result, a unique network is thriving, with TU Delft Robotics Institute at its heart. This allows RoboValley to take a leading role in the development of the next generation robotics. (RoboValley, n.d.)

As a broader approach, we used the Startup Delta ecosystem to find a total of 32 Drone companies in the Netherlands, which is shown in Figure 30.

We believe in the added value of strengthening, connecting and growing the thriving startup ecosystem of the Netherlands. We see the Netherlands as the best possible place for starting, growing and internationalizing business, and as a gateway to the rest of Europe (StartupDelta, 2019).

Figure 30: Map of Drone Companies in the Netherlands (StartupDelta, n.d.)

A sampling of the companies can be found below:

- Avular - https://www.avular.com/curiosity
- RanMarine - https://www.ranmarine.io/

- Aerovinci - http://www.aerovinci.com/
- SeaDrone - http://seadrone.nl/
- Tronics - https://www.tronics.com/en#intro

2.3.3 Academic Research Survey

One of the main groups working on drones in the maritime space is the Delft Robotics Institute, which is a group of 15 chairs from 6 faculties across TU Delft university working in a multidisciplinary fashion to create the future of robotics.

TU Delft Robotics Institute unites all Delft University of Technology's research in the field of robotics. Its main challenge is to get robots and humans to work together effectively in unstructured environments, and real settings. Within the institute both the 'hard' robot disciplines (mechatronics, embedded systems, control and Artificial Intelligence) and the 'soft' robot sciences (human-machine interaction, user interaction, architecture, ethics, security and design) have a prominent presence. By joining forces, and aligning research, education and valorization, TU Delft Robotics Institute takes a leading role in the creation of the next generation robots (TU Delft Robotics Institute , n.d.).

This group takes a wide view of the study of robotics, bringing in many different disciplines to tackles the challenges of the future of robotics in the air, on land, on sea, and under the sea. The following areas of knowledge contribution are brought to bear by the group (TU Delft Robotics Institute , n.d.).

Human context - Faculty of Technology, Policy and Management

Human values & ethics

Value sensitive design

Function decomposition

Involved Faculty:

Prof. Frances Brazier

Prof. Jeroen van den Hoven

Problem representation - Faculty of Aerospace Engineering

System approach

Safety

Swarm behaviour

Cybernetics

Involved Faculty

Prof. Eberhard Gill

Prof. Max Mulder

User centered design - Faculty of Industrial Design

Design for functionality

Design for usability

Design for reliability

Design for experience

Involved Faculty

Prof. Jo Geraedts

Prof. Richard Goossens

Intuitive interaction - Faculty of EWI

Man-machine interaction

Embedded systems

Shared autonomy

Involved Faculty

Prof. Catholijn Jonker

Prof. Koen Langendoen

Prof. Mark Neerincx

Safe interaction - Faculty of Mechanics, Materials and Maritime

Bio inspired design

Learning control

Computer vision

(bio)Mechatronics

Bio robotics

Involved Faculty

Prof. Robert Babuska

Prof. Frans van der Helm

Prof. Pieter Jonker

Prof. Just Herder

Prof. Martijn Wisse

Spatial presence - Faculty of Architecture and Built Environment

Spatial re-configurability

Interactive environments

Simulation tools

Involved Faculty

Prof. Kas Oosterhuis

Combining all of these talents, the main research themes are as follows (TU Delft Robotics Institute , n.d.):

interactive robots (robots for diagnostics and supported living)

swarm robots (collaborating satellites and UAVs for ship tracing, pollution and traffic monitoring)

robots that work (distributed interactive work support, i.e. for robot support in warehousing, greenhouses and food production)

One of the main researchers who is working specifically on autonomous vehicles in the Maritime Domain is Bart Remes and his Micro Air Vehicle Lab with Prof. Max Mulder, who was one of the interviewees for this study. His team has worked to further develop the hybrid wing UAV for use in the maritime domain. His main areas of research have been on integrating the drones within the existing systems, including finding ways to land on unstable, moving, turbulent ships in high winds. The full results of his interview can be found in the appendix of this study (MAVLab, n.d.).

2.3.4 Conclusions and recommendations Aerial systems

One of the main takeaways from this study on UAVs in the maritime industry is that the amount of investment and action involving UAVs in spaces outside of the maritime industry is much larger than that inside the maritime industry. Therefore it makes sense for the maritime industry to leverage the developments in the other domains and focus their resources on maritime specific problems. These maritime specific problems include:

- Making the drones more stable in high winds
- Making the drones more robust to wet and salty conditions
- Exploring ways for drones to land on moving, uneven, and unstable platforms
- Researching ways for continuity of drone regulations between ports in different locations

4. Conclusion and recommendations for follow-on projects

This has truly been a multi-disciplinary, multi-institution project with representatives from industry, academia, large companies, small companies, government and Defence, all involved in creating this study. After all the interviews, research, discussions and tests, there are three main takeaways for anyone who reads this document:

1. In order to understand and develop autonomy in maritime, it is absolutely critical to explore and work with autonomous technologies in other domains (i.e. ground, air, space)
2. The breakthroughs and cutting-edge solutions will not be developed by just one actor, but rather by people from many different types of organizations, such as universities, big business, government and start-ups, often times working all together.
3. The technology is moving much too quickly for even the largest of organizations to keep a handle on the developments in autonomy without partnering intelligently with other organizations to develop the technologies and implement the solutions

Given these three points, we found five areas where there exists a significant need for the maritime industry, but the knowledge and products are relatively underinvested in.

1. Modelling the stability of surface crafts (for both ASVs and for UAVs to land on)
2. Longer use-cycles for all autonomous vehicles (i.e. longer ranges, battery lives)
3. Secure and Resilient communication in difficult environments (i.e. underwater communication for UUVs or electromagnetically saturated environments for UAVs)
4. Traffic management of friendly and unknown autonomous vehicles
5. Legislation and standardisation to allow for clear use of all types of autonomous vehicles

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Addendum 1: Interview format for OALV project

Maritime Autonomy Questionnaire

Date:____________________
Company:____________________
Interviewer:____________________
Interviewee:____________________
E-mail:____________________

1. Which is your key **operational domain**?
(Offshore and Gas) (Offshore Renewables) (Dredging) (Defense) (Transport) (Recreational) (Other)

Further Comments:____

2. What is your preferred **business model** for autonomous systems?
(Service Provider) (Equipment Manufacturer) (Asset Owner) (Other)

Further Comments:____

3. What **current functions** do you carry out with autonomous systems?
____

4. What types of autonomous/unmanned **platforms** do you **currently** use?
(Airborne Drone) (Aut Surface Vessel) (Aut Underwater Vehicle) (Remotely operated vehicle) (Crawler) (Other)

Further Comments:____

5. Do you see **(future) opportunities** for autonomous systems?
____

6. What types of autonomous/unmanned **platforms** do you **anticipate** using in the future?
(Airborne Drone) (Aut Surface Vessel) (Aut Underwater Vehicle) (Remotely operated vehicle) (Crawler) (Other)

Further Comments:____

7. What are your perceived **requirements** of an autonomous systems?
A. Sensors: (Video) (Sonar) (Lidar) (Radar) (GPS or similar) (chemical) (Data transfer) (Other)
Further Comments:____
B. Actuators/physical manipulators: (required) (not required)
Further Comments:____
C. Level of Autonomy: (Level 1) (Level 2) (Level 3) (Level 4) (Level 5)
Further Comments (i.e. role of human):____
D. Required situational awareness: (telemetry)(data quality)(mission progress)(data access, e.g. video/sonar)
____
E. Operating Time: (<10 min) (<1 hour) (<3 hours) (<12 hours) (12+ hours)
Further Comments:____
F. Mass: (<1 kg) (<5 kg) (<10 kg) (<20 kg) (20+ kg)
Further Comments (i.e. man portable?):____
G. Cost: (<$1,000) (<$10,000) (<$100,000) (<$1,000,000) (<$10,000,000)
Further Comments (per unit, day, etc.):____
H. Position accuracy: (mm, cm, dm, m,…)
Further Comments (of platform and/or georeferencing data):__________________________________

8. What are the **main challenges**/obstacles to widespread adoption of autonomous maritime systems?
(Battery life) (Robustness) (Cost) (Deployment & Recovery) (Planning) (Sensors) (Data Analysis) (Legislation) (Training/education) (Safety) (Other)

Further Comments:____

Addendum 2: Major abbreviations in autonomous systems

AAV	Autonomous Aerial Vehicle
ACTUV	ASW Continuous Trail Unmanned Vessel
ADCP	Acoustic Doppler Current Profiler
ASV	Autonomous Surface Vessel
ASW	Anti-Submarine Warfare
AUV	Autonomous Underwater Vessel
COTS	Commercial off-the-shelf
DARPA	Defence Advanced Research Projects Agency
DVL	Doppler Velocity Logger
FCPM	Fuel Cell Power Module
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
INS	Inertial Navigation System
IRM	Inspection Repair and Maintenance
LAUV	Light Autonomous Underwater Vehicle
LCS	Littoral Combat Ship
LBL	Long Base Line
LIPO	Lithium Polymer Battery
MDUSV	Medium Displacement Unmanned Surface Vessel
ROV	Remotely Operated Vehicle
RTK	Real Time Kinematic
SLAM	Simultaneous Localization and Area Mapping
UAV	Unmanned Aerial Vehicle
UA(A)V	Unmanned Autonomous (Aerial) Vehicle
	Also OA(L)V in Dutch = Onbemande Autonome (Lucht) Vaartuigen
USBL	Ultra Short Base Line
UUV	Unmanned Underwater Vehicle

Addendum 3: Autonomous developments within TNO and TU Delft

TNO

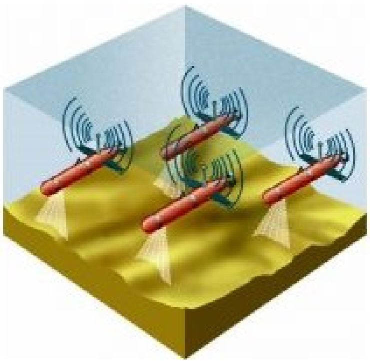
Over the last few years TNO has accumulated a significant experience with (unmanned) autonomous systems for road transport, shipping and underwater operations.

The maritime industry has an Increasing need for better predictability of operations, reducing CAPEX + OPEX and increased safety. The TNO Maritime & Offshore Operations group improves safety and increase value of Maritime Operations, making use of ICT, Human Factors sensor and automation knowledge.

In the field of autonomous shipping, TNO applies knowledge in national and international shared research projects together with industry and governments with a focus on maritime situational awareness, ICT, scenario database development, safety and regulations, and human factors. For these developments the TNO experts make use of knowledge from other industries like automotive. It started with Truck Platooning, in which convoys of two or more trucks drive safely and automatically with less than 10 metres of space between them. This technology has been developed to the point where it is being tested on public roads. One of the biggest challenges is devising a way to deal safely with as many unexpected scenarios as possible. This also counts for shipping. Now the gained experience is applied to the maritime industry. Together with partners TNO aims to demonstrate a semi-autonomous ship in 2019 and demonstrate a full autonomous ship in 2022.
See also: https://www.tno.nl/en/tno-insights/articles/the-best-helmsmen-work-on-shore/

With regard to use of Autonomous Underwater Vehicles (AUVs), a broad array of key technologies is studied within TNO, in order to increase the performance and usability of AUVs for defence and Maritime industry. The long term vision of TNO is that in the future the majority of underwater will be carried out by unmanned or autonomous systems, and that the role of the human will shift from being in direct control of the platform, towards asset manager of a large number of deployed robots doing the hard and dangerous work underwater in a cooperative architecture, as depicted in the figure below. Such a solution requires:

- **Robust underwater communication**: between platforms and operator
- **Single platform autonomy:** Decision making capabilities
- **Live sensor data processing & interpretation**
- **Cooperative autonomy:** interoperability between different platforms and adaptive mission planning
- **Robust underwater navigation and sensing**
- **Effective human machine teaming**
- **Effective mission planning**



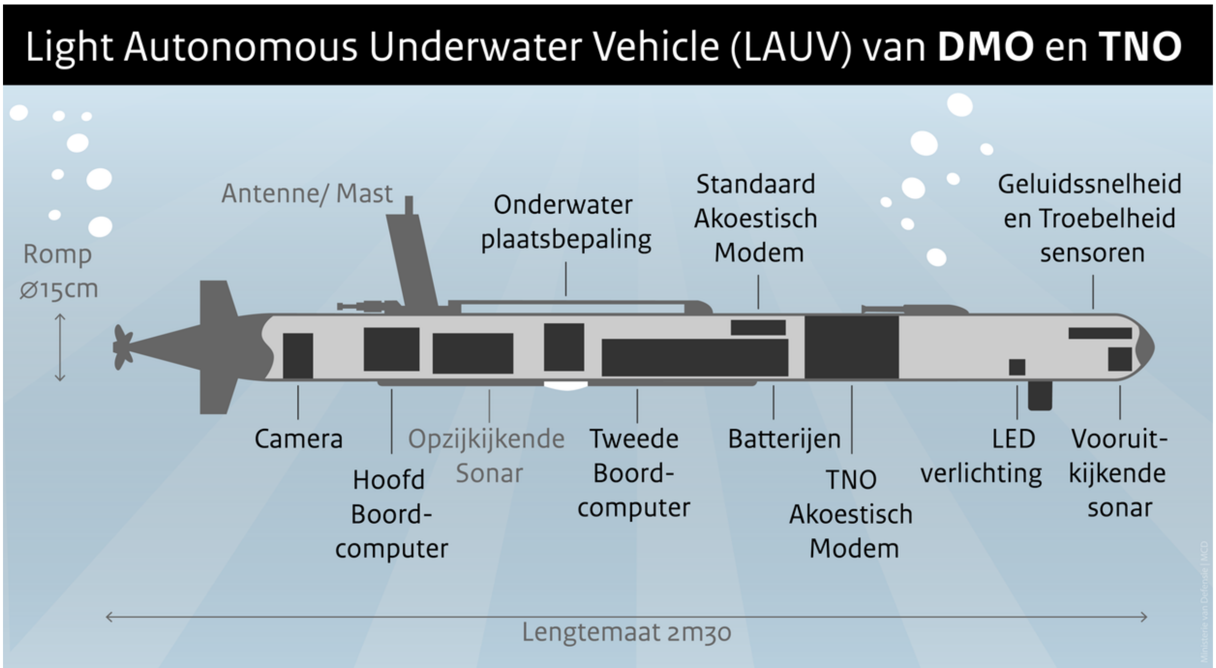
To achieve this goal, TNO aims at short cycle applied technology development & demonstration projects together with industry and defence to identify key issues or added value of the latest technological developments. In order to facilitate short cycle developments, TNO has invested in unique facilities and hardware to support both safe inhouse and realistic offshore experimentation, which is detailed further:

Anechoic basin: an 8*10*8 m inhouse anechoic water filled basin[1] that mimics open sea conditions, allowing for efficient controlled experimentation with the latest equipment before going offshore.

NILUS nodes and modem: autonomous bottom sensor nodes equipped with acoustic transmitter/receiver[2], to enable underwater acoustic networking and allows for a customized testing of communication and networking algorithms. This system has been developed in close cooperation with FFI.

[1] https://www.tno.nl/media/1318/leaflet_anechoic-basin2.pdf
[2] www.ffi.no/no/Publikasjoner/Documents/NILUS2012.pdf

3x LAUV: TNO has access to 3 AUVs (type ocean scan LAUV[3]). The AUVs are equipped with a software defined modem that allows for communication with the NILUS acoustic network. TNO owns one of the AUVs. The other two AUVs are owned by DMO.



[3] http://www.oceanscan-mst.com/

CORE: To support the maritime industry with their innovation initiatives especially in the field of shore support, to facilitate research in this area, and to improve the demonstration of new concepts, TNO created an innovative research environment, called CORE (Control Organization Research Environment). The environment easily allows shifts in levels of automation, through excessive information representation spaces; concepts for innovative information interaction are among the research goals.

More information on research carried out at TNO can be found here:

https://www.tno.nl/en/focus-areas/defence-safety-security/expertise-groups/acoustics-and-sonar/

https://www.tno.nl/en/tno-insights/articles/the-best-helmsmen-work-on-shore/

https://www.tno.nl/en/tno-insights/articles/how-do-underwater-vehicles-help-the-maritime-and-offshore-industry/

https://www.tno.nl/en/focus-areas/defence-safety-security/expertise-groups/acoustics-and-sonar/

https://magazines.defensie.nl/materieelgezien/2017/01/mg201701onderwaterdrones

https://www.hydro-international.com/content/article/underwater-communications-and-the-level-of-autonomy-of-auvs

TU Delft

TU Delft has long been a leader in research into maritime technologies as well as autonomous technologies and is well suited to be a leader in autonomous maritime technologies.

The university currently has many projects focusing on autonomy as it relates to the maritime environment

- NOVIMAR Project: https://novimar.eu/
- Autonomous Shipping for Smart Logistics: https://www.tudelft.nl/technology-transfer/development-innovation/research-exhibition-projects/autonomous-shipping/
- Autonomous small boats: https://www.tudelft.nl/en/3me/research/check-out-our-science/autonomous-boats/
- Integrated computer vision for autonomous marine operations: https://repository.tudelft.nl/islandora/object/uuid%3Aab0aaf98-6c44-497f-8f5c-d5af56847716
- Delft Robotics Institute: https://tudelftroboticsinstitute.nl/about-us

TU Delft also has a number of world class resources for conducting trials and research into maritime-based autonomous technologies.

- Towing Tank No.1: https://www.tudelft.nl/3me/afdelingen/maritime-and-transport-technology/research/ship-hydromechanics/facilities/towing-tank-no-1/
- Towing Tank No.2: https://www.tudelft.nl/en/3me/departments/maritime-and-transport-technology/research/ship-hydromechanics/facilities/towing-tank-no-2/
- Hexamove: https://www.tudelft.nl/3me/afdelingen/maritime-and-transport-technology/research/ship-hydromechanics/facilities/hexamove/
- Cavitation Tunnel: https://www.tudelft.nl/3me/afdelingen/maritime-and-transport-technology/research/ship-hydromechanics/facilities/hexamove/
- Cyber Zoo for testing aerial robotics: https://tudelftroboticsinstitute.nl/labs/cyber-zoo