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van Cappelle, Laurien; Chen, Linying; Negenborn, Rudy

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# Survey on Short-Term Technology Developments and Readiness Levels for Autonomous Shipping

Laurien E. van Cappelle, Linying Chen(✉), and Rudy R. Negenborn

Department of Maritime and Transport Technology,
Delft University of Technology, Delft, The Netherlands
`{L.chen-2,R.R.Negenborn}@tudelft.nl`

**Abstract.** Recently, Autonomous Surface Vessels (ASVs) have attracted a lot of attention. Developing a fully autonomous vessel is challenging. Existing research provides a track from existing manned vessels to a remote-controlled vessel with reduced crews, an unmanned remote-controlled vessel, and at the end, a fully autonomous vessel. The first step is to equip existing vessels to realize autonomous sailing. In this paper, we focus on the technologies that make existing vessels "smarter". A categorization of technologies is provided based on the basic architecture of ASV: Navigation, Guidance, Control and Hardware. An overview of the technology developments in each category is presented. The Technology Readiness Level (TRL) is applied to indicate whether these technologies could become commercial in the short term.

**Keywords:** Autonomous surface vessel · Technology readiness level
Short-term technology development · Review

## 1 Introduction

Autonomous Surface Vessels (ASVs) have attracted a lot of attention. In [44], an overview of existing ASV projects has been provided. It shows the track from existing maned vessels to remote-controlled vessels with reduced crews, unmanned remote-controlled vessels, and at the end, fully autonomous vessels. Existing papers mostly focus on the last two steps, such as [27,44]. They usually assume the vessels are newly built. However, the number of merchant fleet in the world now is more than 90,000 [52]. Discarding existing vessels is unrealistic and leads to a great waste. Moreover, developing a newly built fully autonomous vessel is a challenging and calls for massive investment. In comparison, to equip existing vessel to realize autonomous sailing is more economical and practical.

In this paper, we focus on the first step, making existing vessels "smarter". The aim is to answer the question "how the vessel technology is going to change in the next 5 to 10 years". An overview of the technologies related to autonomous shipping is provided. We use the Technology Readiness Level (TRL) to indicate

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the maturity of the technologies, i.e., whether these technologies will become commercial in the short term.

This paper is organized as follows: Sect. 2 provides the categorization of ASV technologies and the indicator of technology maturity; an overview of the technology developments with corresponding TRL is presented in Sect. 3; Sect. 4 provides the concluding remarks of this paper.

## 2 ASV Technologies and Technology Readiness Level

In this section, we classify the technologies related to ASvs into different categories according to their functions. TRL is introduced as an indicator of technology maturity.

### 2.1 ASV Technologies

An ASV needs different parts to perform different functions. In [7,9,27,43], different categorizations of the subsystems of a typical ASV are provided. Generally, the basic subsystems that are needed for autonomous navigation include 4 parts, as shown in Fig. 1: Navigation, Guidance, Control, and Hardware.

The **Navigation** system of the vessel provides its own states and surrounding information for the decision makers. The **Sensor Fusion** is a software-based

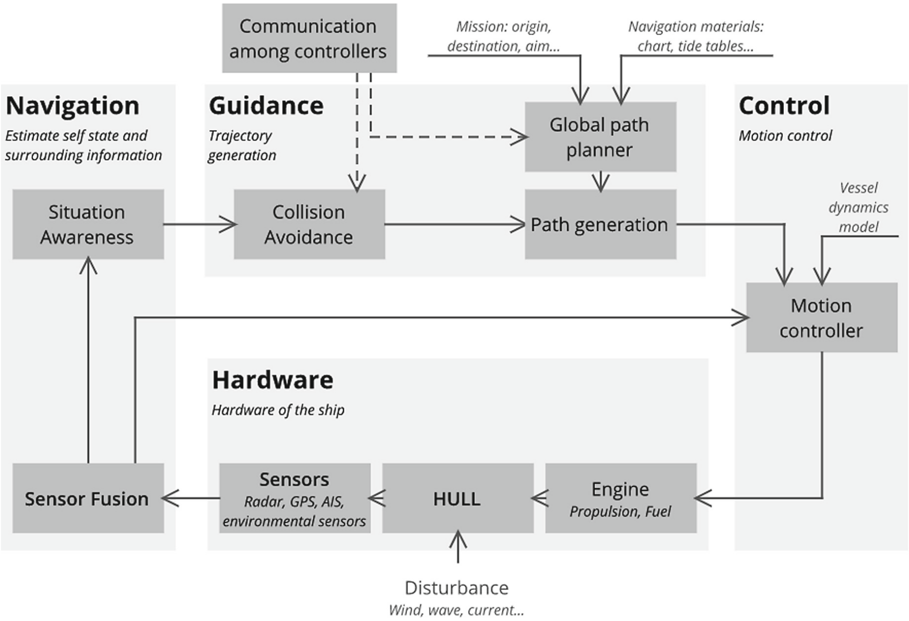

**Fig. 1.** Subsystems of a ASV [43]

system that combines the information from different sensors to create a visualization of the real world. To create a complete real-life representation of the surroundings is still challenging. Therefore, nowadays, the representation is used as a support system for the Officer On Watch (OOW). Another important function of the navigation subsystem is **Situation Awareness (SA)**. SA involves being aware of what is happening in the vicinity to understand how information, events, and one's own actions will impact goals and objectives, both immediately and in the near future [1]. One example of SA is recognizing objects with collision risks from the picture created by the Sensor Fusion. On current manned vessels, SA is usually done by OOW. Lacking or inadequate SA has been identified as one of the primary factors in accidents attributed to human error.

The **Guidance** system deals with the questions "when will the vessel arrive at which place through which path". The final result is an optimal collision-free path that a vessel should follow. The **Global path planner** uses optimization models and algorithms to make schedules and find the most efficient path for executing the schedules. With the information provided by the Navigation system, the **Collision Avoidance (CA)** block updates the global path to avoid obstacles if necessary. **Communication** among vessels and infrastructures can help to negotiate and cooperate with others and to make better decisions [10]. For existing vessel, communication is usually done by OOW using radio (Very High Frequency, VHF) and (mobile) phones.

With the path decided by the Guidance system, the task of **Motion Controller** is to process this information into commands to the actuators. For example, the path generator could state that the vessel should turn right to an angle of 30° compared to the current position and increase the speed with 1 knots to avoid another vessel. Then the software-based control system translates this input into actions, such as rudder angle and propeller speed.

The **Hardware** supports the software-based decision-making systems. The **Engine** usually refers to propellers and/or rudders. These are the actuators that follow the command and steer the vessel to the desired position. The **Hull** gives stability to the vessel and hold all the components. **Sensors** collect the information about the vessel and surroundings. Sensors used in existing vessels include (differential) Global Position System ((D)GPS), Automatic Radar Plotting Aid (ARPA), Visionary sensors, Internal navigation, environmental sensors and Automatic Identification System (AIS), etc.

## 2.2 Technology Readiness Levels

Technology Readiness Levels (TRLs) are used to assess the maturity level of a particular technology [34]. There are 9 technology readiness levels, see Fig. 2. TRL 1 is the least mature level of a technology and is equal to a report of a really basic idea, while TRL 9 is the highest, a successful mission operation of an actual system. For example, ARPA has been applied to vessels for decades. Therefore, it is at TRL 9. On the contrary, as an innovative concept, the Waterborne AGV [61] is at TRL 2. In this paper, TRLs are used to indicate which technologies will be applied in reality in the short term.

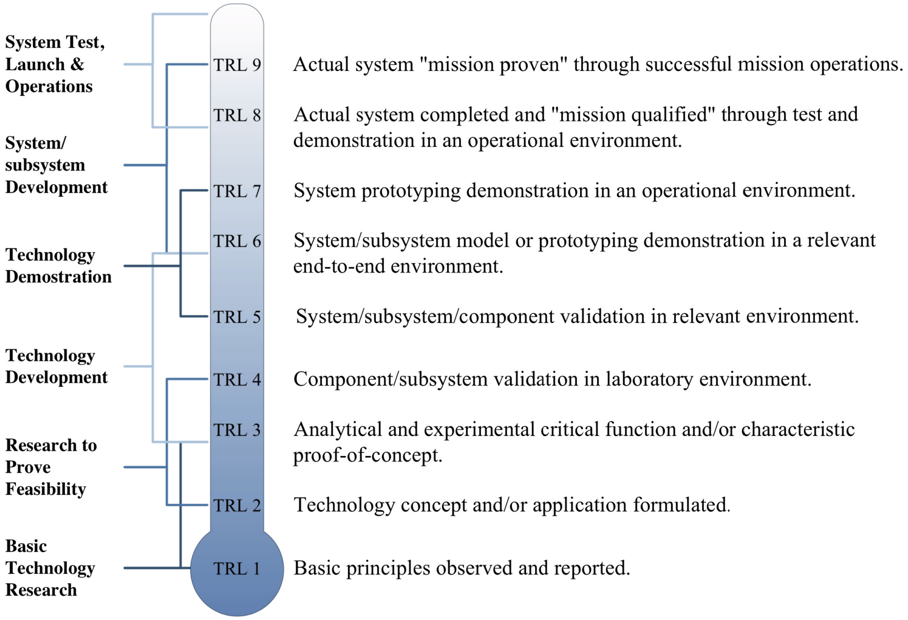

**Fig. 2.** Technology readiness levels [34]

## 3 Technology Developments

In this section, the technology developments towards autonomous sailing in the four subsystems and their TRLs are presented. A discussion on which developments could become commercial within 5 to 10 years is provided at the end.

For easier expression, each technology is labeled as 'D$s.n$', where $s$ indicates the subsystem that the technology belongs to (1 means Navigation, 2 means Guidance, 3 means Control, 4 means Hardware, 5 means others), $n$ is the ranking of the technology according to TRL. For example, D1.1 means the Navigation technology at the lowest TRL of the considered technologies.

### 3.1 Navigation

**Sensor Fusion.** Sensor fusion aims at using available information from different resources to create a representation of the real world. Table 1 gives the results of sensor fusion technologies that have been used or mentioned in existing research.

The sensor fusion technologies for cars are already at a high level. Tesla was already able to achieve a good sensor fusion by making use of ultrasonic, radar and visual cameras (D1.5) [48]. This was tested in an operational environment near a windfarm. A visual camera made a 2D image to fill in the missing information. This technology was implemented and tested on a golf cart. Wolken [55] created a sensor fusion by using a vessel-lidar system that is able to measure wind

**Table 1.** Developments in sensor fusion

| Label | Description | Sensors | | | | | Concept | | | | TRL | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Visual | Radar/ ARPA | Lidar | Ultrasonic | AIS | Principle | Simulation | Laboratory prototype | Prototype | | |
| D1.1 | State estimation | ✓ | ✓ | | | | | ✓ | | | 3 | [18] |
| D1.2 | Obstacle detection | | | ✓ | | ✓ | | | ✓ | | 4 | [3, 5] |
| D1.3 | Obstacle detection | ✓ | | ✓ | | | | | ✓ | | 7 | [59] |
| D1.4 | Wind measuring | | | ✓ | | | | | | ✓ | 7 | [55] |
| D1.5 | Sensor fusion | | ✓ | ✓ | ✓ | | | | ✓ | | 7 | [48] |

(D1.4). Youngam et al. [59] used lidar to measure distances to different objects (D1.3). Asvade et al. [5] compared different sensors and chose to combine Velodyne lidar with an Internal Navigation System (GPS/IMU) (D1.2). Hermann et al. [18] researched the usage of Kalman filtering in the state estimation of autonomous cars to make it more reliable (D1.1).

The sensors and sensor fusion technology for vehicles and for ASVs are similar. However, due to the differences in dimension and maneuverability, the measuring range, accuracy of sensors and the results of sensor fusion for ASVs are different from those for vehicles. In present, the most representative technology for ASVs is AIS, combining the information from a positioning system such as a GPS receiver, with other electronic navigation sensors, such as a gyrocompass or rate of turn indicator. AIS is intended to assist the OOW to supervise the state of the vessel, detect obstacles and allow maritime authorities to track and monitor vessel movements [3].

**Situation Awareness.** Understanding what is happening in the surrounding area is essential for the controllers taking actions. Maq et al. [28] proposed an obstacle detection method by making use of the Fuzzy C-Means (FCM) (D1.10). This method was able to create an artificial intelligence that classifies and identifies objects seen on the ARPA. In case of a real vessel, this method was able to recognize a vessel with an accuracy of 91.3%; for a noise, bank or channel target, the accuracy was between 82.6% and 91%. The system detects in real-time obstacles with a range up to 175m. Hermann et al. [18] tested a radar and visual based obstacle detection system successfully on an autonomous vehicle for speeds up to 30 m/s (D1.9). Yalcin et al. [58] proposed an obstacle and road detection for autonomous cars by only using lidar (D1.8). In the system developed by [20], HiCASS, the information from AIS, ARPA and Electronic Chart Display Information System (ECDIS) are combined to create an SA that can view up to 50 km (D1.7). Rødseth and Burmeister [39] stated that good obstacle detection and avoidance can reduce the number of accidents by providing a decision support for the OOW (D1.6) (Table 2).

**Table 2.** Developments in situation awareness

| Label | Description | Autonomy level | | | Concept | | | | TRL | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Supporting | Autonomous with supervision | Autonomous | Principle | Simulation | Laboratory prototype | Prototype | | |
| D1.6 | Situation awareness | ✓ | | | ✓ | | | | 1 | [39] |
| D1.7 | Multiple sensors for SA | | | ✓ | ✓ | | | | 3 | [20] |
| D1.8 | Lidar for SA | | | ✓ | | ✓ | | | 4 | [58] |
| D1.9 | Radar for SA | | | ✓ | | | ✓ | | 5 | [18] |
| D1.10 | ARPA for obstacle detection | ✓ | | | | | | ✓ | 7 | [28] |

According to these studies, human is the core of SA on existing vessels. SA technologies mostly play a supporting role for the OOW. More efforts should be made to apply them for fully autonomous vessels.

### 3.2 Guidance

**Global Path Planning.** The optimization of the global path can greatly improve the efficiency of transport. The development of Computational Logistics technology provides a great support for ship scheduling and path planning. [11,12] provided detailed review research on ship routing and scheduling. Typically, an optimization problem is formulated to find the most efficient scheduling for the transport of goods. Regarding path planning, based on [7,13,27,46], existing methods can be classified into three categories, Line-of-Sight (LOS), Potential field methods, Heuristic search algorithms and Evolutionary algorithms.

LOS is a successful guidance technique that is widely employed today, particularly in missile guidance technology [7] (D2.4). The idea behind LOS guidance is that if the vessel converges to a constant LOS heading angle directly between the vessel and target, it eventually converges to the target position. The disadvantage of LOS guidance is potential overshoot caused by reducing the cross-track error due to environmental disturbances [33].

Potential field methods (D2.3) take known obstacles into consideration by building a representation of the environment by potential gradients. Potential Field methods are first proposed by [23] for mobile robots. [57] implemented the potential field method for automatic ship navigation. It shows that the method is effective for ships involved in a complex traffic situation.

Heuristic search algorithms indicate those grid-searching techniques with associated heuristic cost functions (D2.2). A feasible, near-optimal path is found without performing an exhaustive search, as with uninformed (or blind) graph searching algorithms such as Breadth-first or Depth-first searches [7]. Among the group of heuristic search algorithms, A* and its extensions are commonly used to determine the path from an origin to a destination for land-based vehicles [42,53]. A comparison between A* and its extensions, i.e., A* with Post-smoothing, Theta*, and A* on Visibility Graphs, is shown in [9].

Evolutionary algorithms are increasingly employed in the design of path planners inspired by the behavior of biological systems (D2.1) [27]. [15] introduces a solution to the problem of planning for marine vehicles based on Ant Colony Optimization. However, when constraints such as obstacles, dynamic limits, and mission constraints must be satisfied, the method can be time-consuming.

The global path planning system is software-based, and the Computational Logistics technologies are relatively mature. Thus, the above-mentioned methods are all with high TRL levels (8–9).

**Collision Avoidance.** Ship collision is one major threat to navigation safety. Research on CA is dedicated to finding methods to detect collision dangers as early as possible and to find proper collision-free solutions. Table 3 provides several examples of current collision avoidance technologies. It also provide the autonomy level of the CA system using these technologies: does the OOW take actions (Supporting)? does the CA process need supervision of the OOW? is the CA process done autonomously?

The methods mentioned in existing research can be roughly divided into two types. One is the indicator-based. Some indicators have been defined to help to determine the collision risks and the actions should be taken, such as Distance at Closest Point of Approach (DCPA) and Time to the Closest Point of Approach (TCPA). Wang et al. [54] proposed a dynamic CA system that calculates the DCPA and TCPA (D2.8). Lazarowska et al. [25] proposed a concept where a new Decision Support System uses a Trajectory Base Algorithm (TBA) (D2.6). Tsou et al. A system proposed in [51] which based on AIS and ECDIS data shows a Predicted Area of Danger (PAD) for the vessel at that moment (D2.5). The OOW can choose actions to avoid the marked area.

The other one is rule-based. The rules of the road specify the types of maneuvers that should be taken in situations where there is a risk of collision. The most widely used is the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) set by the International Maritime Organization (IMO). Hyundai [20] developed the CA system named HiCASS. This system can analyze the locations of the objects and avoid them with respect to COLREGs (D2.12). The system was tested on a 13,800 TEU LNG carrier. The research of Hu et al. In [22], a CA system was proposed using an MPC method to predict the trajectories of (moving) obstacles. Then, own vessel avoids it with compliance with the rules (D2.10). Xu et al. [56] used the danger immune algorithm to find a set of operation instructions obeying the COLREGs (D2.9). Zhang et al. [60] designed a CA strategy where vessels work in cooperation to avoid collisions with respect to the COLREGs (D2.7).

There are methods combined the two type of approaches. For example, [19] used the DCPA and TCPA to detect a possible collision, and then generated new paths which compliance with the COLREGs (D2.11).

Table 3. Developments in collision avoidance

| Label | Description | COLREGs | CA indicator | Predictive? | Autonomy level | | | Concept | | | | TRL | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Supporting | Autonomous with supervision | Autonomous | Principle | Simulation | Laboratory prototype | Prototype | | |
| D2.5 | Plot PAD to create CA | ✓ | ✓ | | ✓ | | | | ✓ | | | 3 | [51] |
| D2.6 | TBA for CA | | ✓ | | | ✓ | | | ✓ | | | 3 | [25] |
| D2.7 | Distributed over vessels | ✓ | | ✓ | | | ✓ | | ✓ | | | 5 | [60] |
| D2.8 | Real-time DCPA and TCPA | | ✓ | | ✓ | | | | ✓ | | | 5 | [54] |
| D2.9 | Collision avoidance | ✓ | | | | ✓ | | | ✓ | | | 6 | [56] |
| D2.10 | Collision avoidance by MPC | ✓ | | ✓ | | | ✓ | | ✓ | | | 6 | [22] |
| D2.11 | Collision avoidance | ✓ | ✓ | | | | ✓ | | ✓ | | | 6 | [19] |
| D2.12 | Collision avoidance | ✓ | | | | ✓ | | | | | ✓ | 7 | [20] |

In the literature, many methods have been proposed for CA. However, there are challenges. Most CA methods rely on the prediction of trajectories of own ship or obstacles. However, due to the environmental disturbances and inaccurate ship motion models, the precision of predictions is not always sufficient.

**Communication.** Vessel-to-Vessel (V2V) and Vessel-to-Infrastructure (V2I) communication have many benefits [10]. Moreover, to make vessel control from the quayside possible, the communication methods and data stream capacity have to be improved [39].

The Internet is one of the options for V2V and V2I communication. To solve the problems of limited coverage and low access speed, SpaceX [6] tries to achieve worldwide internet connectivity with the launch of 800 low-orbit satellites in 2019 (D2.20). Google [64] plans to launch 180 satellites to provide the earth with a worldwide Internet connectivity (D2.19). Also, Facebook [49] is doing test-trails with solar-based drones to provide future worldwide internet (D2.17). Another way to achieve a better Internet connection is by making smarter use of the current availability's. The ESA [29] is now working on a two-way communication device between vessel and shore, which uses WiFi, 3G/4G, Very Small Aperture Terminal (VSAT) and INMARSAT (D2.18). Mu and Zhou [62] and Harada [31] proposed ad hoc networks between vessels to provide an Internet connection further of the coast. Ejaz et al. [14] proposed a meshing network between neighbouring vessels (D2.14), but in a more conceptual way. A switching device that chooses the cheapest and fastest option from the available sources at that moment can also achieve smarter use of the Internet resources. Mu et al. [32] proposed a device that switches between the different types of the Internet (D2.15): increases the data stream in case of WiFi connection and decreases it in the case of the satellite connection. Sumić et al. [47] thought to make a better use of terrestrial Internet sources would be more efficient (D2.13) (Table 4).

According to these developments, we can find many possible developments that can achieve better maritime communication, and they are likely to happen on a very short notice.

### 3.3 Motion Controller

For vessels, the motion control part is challenging, as the sailing is highly influenced by environmental disturbances, such as wind and water conditions.

GE marine solutions [16] designed a Vessel Control System (VSC) which is able to provide full remote supervisory control and monitoring of all ship systems (D3.5). In the Netherlands there is currently an inland vessel, called the MSC Saluté, sailing semi-autonomous (D3.4) [37]. It can follow an earlier recorded track by changing rudder angles. The MSC Saluté was able to follow the recorded track, but still needed some interventions of the captain when there are disturbances. Sørensen and Breivik [45] did a comparative research on four different control methods through simulations. Although all results seemed promising, the so-called $\mathcal{L}_1$ adaptive backstepping method with command governor achieved the best results (D3.3). Alfi et al. [2] make use of the well known

Table 4. Developments in communication

| Label | Description | | Technology | | | Concept | | | | TRL | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | New on-board? | Existing | Cooperation between vessels | New technology | Principle | Simulation | Laboratory prototype | Prototype | | |
| D2.13 | Use of terrestrial Internet | ✓ | ✓ | | | ✓ | | | | 2 | [47] |
| D2.14 | Multi-hop network | ✓ | | ✓ | | ✓ | | | | 3 | [14] |
| D2.15 | Switching between Internet sources | ✓ | ✓ | | | | ✓ | | | 6 | [32] |
| D2.16 | Mesh network among neighbouring vessels | ✓ | | ✓ | | | ✓ | | | 6 | [31, 62] |
| D2.17 | Worldwide Internet Facebook | | | | ✓ | | | | ✓ | 7 | [49] |
| D2.18 | ESA two way communication | ✓ | ✓ | | | | | | ✓ | 8 | [29] |
| D2.19 | Worldwide Internet Google | | | | ✓ | | | | ✓ | 9 | [64] |
| D2.20 | Worldwide Internet SpaceX | | | | ✓ | | | | ✓ | 9 | [6] |

$H\infty$ performance formula that is able to follow waypoints (D3.2). Zhu et al. [63] researched the possibility of capturing the highly nonlinear dynamics of a vessel in a simplified model (D3.1).

To conclude, the maneuverability of vessels is poor and the reaction time is extremely long. Moreover, the steering commands react differently in the different wind or water conditions. Therefore, accurate control of large cargo vessels could be possible, but there are still some big steps to make.

### 3.4 Hardware

**Engine.** One of the advantages of autonomous sailing is reducing emissions. The expectation is that cargo vessel will also become more environmentally friendly. The development of engines from cargo vessels is mainly based on the environmental friendliness of it. On short-term, this means the upcoming of hybrid or LNG powered vessel. Eventually, the engines could change into hydrogen or fully electric engines.

The Royal Academy of Engineering [40] carried out a multi-discipline study on different types of engines. On the short-term, they expect that diesel will still remain important propulsion method and LNG powered vessels will follow shortly (D4.4). As alternative propulsion methods, they introduced gas turbines and hybrid propulsion. The AMS [4] designed the newest LNG-electric driven inland tanker, called the Ecotanker III (D4.3). It already achieved a $CO_2$ reduction of 20% to 25%. AMS designed eight environmental friendly inland vessels in total, which are all currently in use. Guangzhou Vesselyard International Company Ltd. designed a full-electric cargo vessel and is now able to travel a distance of 80 km without charging (D4.2) [26]. Geertsma et al. [17] investigated the possibilities for future propulsion and concluded that hybrid propulsion would be a good alternative for the future (D4.1).

**Sensors.** SA relies on the information provided by the sensors. As the above section about SA already described the combination of sensors, this section focuses on individual sensors and supporting sensors as wind measuring sensors. Yalcin et al. [58] did a comparative research between radar, lidar, and ultrasound (D4.8). The results showed that lidar was the best option for obstacle recognition. Radar and ultrasound can also measure distance, but the obstacle identification is more difficult. The CoVadem-project [8] created a network where inland vessels can share their depth measurements (D4.7). When there are accurate depth measurements, vessel companies can optimize their routing and loading. Sakib [41] created a low-cost digital Inertial Measurement Unit (IMU) that provides the captain with a detailed hydrographic survey to make traveling safer for container vessels (D4.6). With the findings from Yalcin et al. [58], we can find that although the results of lidar imaging are really accurate, the technology is extremely expensive (D4.5).

## 3.5 Overall Developments

This section presents the developments of some technologies that needs the cooperation of the above-mentioned subsystems, in particular, the technologies related to maneuvering and maintenance (Table 5).

**Table 5.** Developments in vessel maneuvering

| Label | Description | Asisting devices? | Method | | Concept | | | | TRL | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Multi-shooting | ANN | Principle | Simulation | Laboratory prototype | Prototype | | |
| D5.1 | Platooning | ✓ | | | ✓ | | | | 1 | [35] |
| D5.2 | ANN for berthing | | | ✓ | | ✓ | | | 5 | [21] |
| D5.3 | ANN for berthing | ✓ | | ✓ | | | ✓ | | 6 | [50] |
| D5.4 | Quasi real-time control | | ✓ | | | | ✓ | | 7 | [30] |
| D5.5 | Laser ranging and docking | ✓ | | | | | | ✓ | 8 | [36] |

**Vessel Maneuvering.** When a vessel is able to berth (semi-) autonomously, one or two sailors could be removed from the vessel, which would reduce the operational costs. Mizuno et al. [30] proposed a quasi real-time optimal control scheme for automatic berthing. By using a multiple shooting method, they were able to even berth a small vessel at sea (D5.4). In [50], berthing vessels autonomously is discussed. An Artificial Neural Network (ANN) is applied with the help of auxiliary devices such as a thruster and a tugboat (D5.3). Another technology of autonomous berthing is using an ANN to learn to berth from the actual captain. A problem with this technology is that it only works on one specific port. Im and Nguyen [21] carried out a research on the ability of this system to also be able to berth in other ports. However, it was only able to berth from one approaching direction. Easier berthing can also be achieved from the quayside. Perkovic et al. [36] developed a laser ranging and laser docking system on the quayside that gives a hydrographic survey on the Port of Koper to the vessel (D5.5). Recently, NMT introduced a new Maritime European innovative project called NOVIMAR, where platooning of cargo vessels is investigated [35] (D5.1). A manned vessel acts as a leading vessel and the rest of the vessels that follow the vessel autonomously.

**Maintenance.** One of the main problems of autonomous sailing, especially for deep-sea vessels, is that no crew on board for maintenance purposes. An ASV needs a maintenance strategy that enables it to sail for weeks or months without breaking down. Lazakis et al. [24] introduced the Inspection Capabilities

**Table 6.** Table with developments.

| | **TRL 1** | **TRL 2** | **TRL 3** | **TRL 4** | **TRL 5** | **TRL 6** | **TRL 7** | **TRL 8** | **TRL 9** |
|---|---|---|---|---|---|---|---|---|---|
| **Navigation** | **D1.6** [40] *('12)*<br>Situation awareness | | **D1.1** [18] *('15)*<br>State estimation | **D1.2** [5] *('16)*<br>Obstacle detection | **D1.9** [18] *('15)*<br>Radar for SA | | **D1.3** [60] *('16)*<br>Obstacle detection | | |
| | | | **D1.7** [27] *('16)*<br>Multiple sensors for SA | **D1.8** [59] *('13)*<br>Lidar for SA | | | **D1.4** [56] *('14)*<br>Wind measuring | | |
| | | | | | | | **D1.5** [49] *('17)*<br>Sensor fusion | | |
| | | | | | | | **D1.10** [29] *('15)*<br>APRA for obstacle detection | | |
| **Guidance** | | **D2.13** [48] *('15)*<br>Use of terrestrial internet | **D2.5** [52] *('16)*<br>Plot PAD to create CA | | **D2.7** [61] *('15)*<br>Distributed CA over vessels | **D2.9** [57] *('14)*<br>Evolutionary algorithm | **D2.17** [50] *('17)*<br>Worldwide internet Facebook | **D2.1** [15] *('10)*<br>Collision Avoidance | **D2.4** [34] *('03)*<br>Line-of-Sight |
| | | | **D2.6** [25] *('16)*<br>TBA for CA | | **D2.8** [55] *('17)*<br>Real-time DCPA and TCPA | **D2.10** [22] *('16)*<br>Collision avoidance by MPC | | **D2.2** [43, 54, 9] *('05)*<br>Heuristic search algorithms | **D2.19** [65] *('14)*<br>Worldwide internet Google |
| | | | **D2.14** [14] *('13)*<br>Multi-hop network | | | **D2.12** [19] *('17)*<br>Path re-planning | | **D2.3** [23, 58] *('89)*<br>Potential field methods | **D2.20** [6] *('16)*<br>Worldwide internet SpaceX |
| | | | | | | **D2.15** [33] *('12)*<br>Switching between Internet sources | | **D2.11** [20] *('14)*<br>Collision Avoidance | |
| | | | | | | **D2.16** [32, 63] *('15)*<br>Mesh network among neighbouring vessels | | **D2.18** [30] *('14)*<br>ESA two way communication | |
| **Control** | | **D3.1** [64] *('17)*<br>Simplified control model | | | **D3.2** [2] *('15)*<br>$H_\infty$ controller | **D3.3** [46] *('15)*<br>$\mathcal{L}_\infty$ adaptive backstepping with command governor | **D3.4** [38] *('17)*<br>Semi-Autonomous inland vessel | | **D3.5** [16] *('16)*<br>Vessel automation system |
| **Hardware** | | | **D4.1** [17] *('17)*<br>Hybrid propulsion | **D4.5** [59] *('13)*<br>Disadvantages lidar | | **D4.6** [42] *('17)*<br>Low-cost Hydrographic Survey | | **D4.2** [26] *('17)*<br>Full-electric propulsion '17 | **D4.4** [41] *('13)*<br>LNG and Hybrid propulsion |
| | | | | | | | | **D4.3** [4] *('17)*<br>LNG-Electric propulsion '17 | **D4.8** [59] *('13)*<br>Lidar best sensor |
| | | | | | | | | **D4.7** [8] *('17)*<br>Network for depth-measurements | |
| **Overall** | **D5.1** [36] *('17)*<br>Platooning | | | **D5.7** [39] *('16)*<br>Maintenance Framework | **D5.2** [21] *('17)*<br>ANN for berthing | **D5.3** [51] *('12)*<br>ANN for berthing | **D5.4** [31] *('15)*<br>Quasi real-time control for berthing | **D5.5** [37] *('17)*<br>Laser ranging and docking for berthing | |
| | **D5.6** [40] *('12)*<br>Maintenance strategy | | | | | | **D5.8** [24] *('16)*<br>INCASS innovative maintenance system | | |

a) In each cell, from left to right: label, sources, year of publication. Next line gives the short description.
b) The grey marked area highlights the developments that will become commercial on a short term.

for Enhanced Vessel Safety (INCASS) project about an innovative maintenance system. This is a combination of software and hardware to make maintenance smarter (D5.8). Rødseth [38] proposed a framework for an unmanned engine room in the MUNIN project (D5.7). At last Rødseth and Burmeister [39] stated the importance of better maintenance strategies for ASVs (D5.6). Therefore, some research has been done for the maintenance of autonomous vessels, but that this particular aspect of autonomous sailing still needs more efforts.

### 3.6 Short-Term Development

Table 6 presents an overview of technology developments towards autonomous navigation. Developments appreciated with TRL 7, 8 or 9 are expected to become commercial on a shorter term (in 5 to 10 years).

The quality of SA increases as the software to detect obstacles becomes better. In the coming years, it will have a good supporting role for the captain. The ability to communicate at sea will make a big increase as multiple companies are setting up worldwide Internet coverage. Vessels will also increase the communication between each other and the quayside. The critical factor in removing crew from the board is at the moment the berthing of the vessel. Therefore a big increase of research towards autonomous berthing is expected, which could lead to a step towards autonomous sailing. The number of sustainable vessels will increase. The engines will be driven by LNG, Hybrid or Electrical propulsion.

## 4 Conclusions

Existing research provides a track from existing vessels to a remote-controlled vessel with reduced crews, an unmanned remote-controlled vessel, and at the end, a fully autonomous vessel. The first step is to equip existing vessels to realize autonomous sailing. In this paper, we focus on the technologies that make existing vessels “smarter”. A categorization of technologies is provided based on the basic architecture of ASV: Navigation, Guidance, Control, and Hardware. An overview of the development of the technologies in each category is presented. The Technology Readiness Level (TRL) is applied to indicate whether these technologies are likely to become commercial in the shorter term.

Based on the analysis, the developments of technologies will bring about a lot of changes on board to make existing vessels smarter in the next 5 to 10 years. Firstly, from the perspective of hardware, the accuracy of the sensors is expected to be improved while reducing the costs. This is the basis of a better situation awareness. Secondly, software-based systems could achieve a breakthrough. Data fusion and situation awareness come to mature and could provide the OOW with more accurate information. With the development of Computational Logistic, ship routing and scheduling can be accomplished without human. More Navigation assistance devices will be equipped on board to facilitate safe navigation. Autonomous trajectory tracking and autonomous collision avoidance system under the supervision of the OOW is expected to be implemented in the near future. Thirdly, autonomous motion control is also promising. Unmanned engine room in large merchant vessels will be realized in the foreseeable future. As the increasing concerns on emission, hybrid propulsion may be in the majority. Last but not the least, the considerable investment on the worldwide Internet will greatly promote the communication and cooperation between vessels and also infrastructures, which also provides the basis for remote control.

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