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Abstract

The growth in technology on autonomous transportation systems is currently motivating a number of research initiatives. This paper first presents a survey of the literature on autonomous marine vessels in general. By identifying the main research interests in this field, we define nine thematic categories. The collected articles are then classified according to these categories. We show that research on autonomous vessels has increased dramatically in the past decade. However, most of the published articles have focused on navigation control and safety issues. Studies regarding other topics, such as transport and logistics, are very limited. While our main interest is the literature on autonomous vessels, we contrast its development with respect to the literature on autonomous cars so as to have a better understanding about the future potentials in the research on autonomous vessels. The comparison shows that there are great opportunities for research about transportation and logistics with autonomous vessels. Finally, several potential research areas regarding logistics with autonomous vessels are proposed. As the technology behind remote-controlled or autonomous ships is maturing rapidly, we believe that it is already time for researchers in the field to start looking into future water-borne transport and logistics using autonomous vessels.

Keywords: Autonomous ship, Autonomous Surface Vehicle, Unmanned Surface Vehicle, Survey

1 Introduction

Different types of autonomous technologies have been applied and integrated into our transport systems in the past decades. Today, with the technological breakthrough in areas such as artificial intelligence (AI), driverless or fully autonomous transportation is no longer just a dream but a reality on certain transport legs. For road transport, the concept of autonomous cars is being developed and tested by companies like Google and Tesla (Waymo, 2019; Tesla, 2018). For air-based transport, unmanned aerial vehicles (UAVs) or drones are also being introduced for delivery services (Koiwanit, 2018; Amazon, 2018). In the domain of maritime transport, the autonomization of vessels is also developing and intensively discussed in the shipping industry.

Each year about 90 percent of the global trade is carried by sea (ICS, 2017). Furthermore, maritime transport is the only option for the movement of large volume cargo among continents (Gu et al., 2018). Therefore, the shipping industry is vital for our global economy. However, this old business is now facing economic, environmental and social challenges. Traditional technical or operational solutions, such as building larger ships or slow steaming, have reached their limitations to overcome various problems. The new generation of technology, such as autonomous vessels, is believed to be a potential cure for the difficulties faced by the shipping industry (Kretschmann et al., 2017).

The interest in academia on automated marine vessels is also rapidly increasing. To the best of our knowledge, nevertheless, comprehensive reviews about research and studies in this field are limited. Campbell et al. (2017) wrote a survey paper on unmanned surface vehicles, but with a special focus on research about intelligent collision avoidance systems and the corresponding manoeuvres. Thieme et al. (2018) reviewed and investigated how far the existing ship risk models for collisions and groundings are applicable for risk assessment of marine autonomous surface ships. Schiaretti et al. (2017a) and Schiaretti et al. (2017b) conducted a survey regarding autonomous surface vessels including literature on classifications of autonomy levels and existing prototypes. Zolich et al. (2018) reviewed the major advancements on autonomous maritime vehicles and systems, highlighting communication and networking technologies. Liu et al. (2016) reviewed the historical and recent developments of unmanned surface vehicles and classified the existing guidance, navigation and control approaches proposed in the literature. While those papers present interesting reviews with a specific focus, we found no papers offering a comprehensive overview of the research conducted on autonomous shipping or navigation in all aspects. Therefore, the purpose of this review is to collect existing research papers regarding autonomous vessels in the literature and systematically categorize them based on their contents. The major findings of these papers in each category are also briefly summarized. Furthermore, we compare the literature on autonomous vessels with the literature on autonomous vehicles. We have two major contributions. First, the main body of existing literature on autonomous vessels (marine vehicles) is summarized and categorized. Second, the we point out weak points in the literature and thereby future opportunities based on the comparison between autonomous vessels and autonomous vehicles.

As for types of marine crafts, this review paper considers *vessel*, *ship* and *surface vehicle*. Vessels and ships are among the most common ones in the literature of shipping and maritime navigation. They have a relatively large size and can carry cargo or passengers during the navigation. Surface vehicles are usually much smaller. They are widely used in scientific experiments, prototype testing and other specific tasks with sophisticated environments, such as pollution monitoring or mine exploration (Liu et al., 2016). For simplicity we use the word *vessel* as the general term for water craft in this paper unless it is crucial to distinguish.

The paper is organized as follows. In Section 2, we introduce the methodology used to conduct this review and also define the categories used to classify the literature. In Section 3, we present an overview of the articles on each category. In Section 4, we present statistical features of this literature and compare it with its parallel in autonomous vehicles. In Section 5, we conclude the survey with some remarks and guidelines for future research.

2 Methodology and Categories

Since the literature offers different levels of autonomy and there are many types of marine vessels, it is necessary to define the scope of the survey with respect to these concepts. Lloyd's Register (2017) and Rolls-Royce (2016) have both defined different levels of autonomy applied in maritime navigation. The former divided the autonomy of maritime navigation into six levels while the latter defined ten levels of autonomy, see Table 1 and Table 2. Although there are some differences in these definitions, it is clear that the autonomy of maritime navigation is not necessarily a binary feature (either fully autonomous or fully manual). The level of autonomy increases gradually when human intervention decreases. Due to the development of the technology, it is generally agreed that it will not be possible to achieve full autonomy in maritime navigation in the short term. Unmanned ships with shore-based remote control or monitoring is very likely to be adopted initially. In this review, we included not only *autonomous* but also *unmanned* as main keywords to capture different levels of autonomy.

The articles reviewed in this survey are collected through three stages. First, we conducted a systematic search on the website of Scopus (2018), which is one of the largest databases of scientific journals, books and conference proceedings. As keywords, we used "autonomous ship", "unmanned ship", "autonomous vessel", "unmanned vessel", "autonomous surface vehicle (ASV)" and "unmanned surface vehicle (USV)". In the second stage, due to the large number of papers found, we further narrowed down the scope of the literature to journal articles or book chapters published in the last decade. We also excluded those papers which just mention or slightly discuss the related keywords, rather than focusing on them. In the last stage, this collection of articles was complemented with other articles that we came across naturally while conducting the survey, either because they were frequently cited in the previously selected articles or by tracking references to them. In the end, we had a total of 91 articles. Based on the main topics of these articles, we define nine thematic categories which we found useful for classification. The definition of these nine categories are listed in the following.

Table 1: Definition of autonomy level by Lloyd's Register (2017)

Level of autonomy	Description
AL 0: Manual steering	No autonomous function. All action and decision-making performed manually (note that some systems may have levels of autonomy, but with humans in the loop.), i.e. humans control all actions.
AL 1: On-board Decision Support	All actions taken by a human operator, but decision support tools can present options or otherwise influence the actions chosen. Data is provided by systems on board.
AL 2: On & Off-board Decision Support	All actions taken by human operator, but decision support tools can present options or otherwise influence the actions chosen. Data may be provided by systems on- or off-board.
AL 3: 'Active' human in the loop	Decisions and actions are performed with human supervision. Data may be provided by systems on- or off-board.
AL 4: Human in the loop	Operator/Supervisory: Decisions and actions are performed autonomously with human supervision. High impact decisions are implemented in a way that gives the human operators the opportunity to intercede and over-ride.
AL 5: Autonomous	Rarely supervised operation where decisions are entirely made and actioned carried out by the system.
AL 6: Fully autonomous	Unsupervised operation where decisions are entirely made and actioned carried out by the system during the mission.

- **Category 1** refers to the *safety* concerns of autonomous vessels, which can be further divided into three subcategories.

(a) *Collision avoidance*: One of the most important issues for any vessel is to avoid colliding with other objects, either dynamic (e.g., ships) or static (e.g., rocks), during its navigation. Collision avoidance becomes more challenging and critical when no human is on board monitoring the surroundings and controlling the vessel.

(b) *Cyber security*: The autonomous/unmanned vessel needs to communicate with the shore-based centre for monitoring or control purposes on a regular basis. Such communication strongly depends on wireless networks, which leads to high cyber security risks during the operation.

(c) *Other safety concerns*: In the literature, other safety concerns for autonomous ships, such as safety assessment and fault detection are also addressed. New approaches for safety assessment and fault detection are needed to ensure that all machineries are in proper status before sailing. A breakdown of autonomous/unmanned vessels during the navigation can lead to severe consequences.

Table 2: Definition of autonomy level by Rolls-Royce (2016)

Level	Description
1	The computer offers no assistance, human in charge of all decisions and actions
2	The computer offers a complete set of decision alternatives
3	Computer narrows alternatives down to a few
4	Computer suggests single alternative
5	The computer executes the suggested action if human approves
6	The computer allows human a restricted time to veto before automatic execution
7	The computer executes automatically, when necessary informing human
8	The computer informs human only if asked
9	The computer informs human only if it (the computer) decides so
10	The computer does everything autonomously, ignores human

- **Category 2** refers to *navigation control* of the autonomous vessel. Two subgroups are also defined under this category.

  (a) *Individual control*: This subcategory includes articles focusing on navigation control for a single autonomous/unmanned vessel. Related topics include path planning, trajectory planning, manoeuvring, steering and heading of the autonomous vessel.

  (b) *Group control*: In certain circumstances, multiple autonomous/unmanned vessels are required to finish the task. In such a case, fleet path planning and fleet formation control are necessary.

- **Category 3** refers to the *design* of the autonomous/unmanned vessel. Papers discussing the *general design* of the entire maritime navigation system or more specific design regarding each *sub-system*, for instance communication system or propulsion system, are included in this category.

- **Category 4** covers articles about reported *research projects* or experimental *prototypes* in this field.

- **Category 5** includes *economic analysis* of adopting autonomy technology in maritime logistics. A typical example is cost-benefit analysis of using autonomous vessels in shipping.

- **Category 6** collects the papers evaluating the *environmental impact* of autonomous/unmanned vessels, such as emission reduction.

- **Category 7** refers to *law and regulation* for autonomous vessels. The studies in this category discuss, for example, the change of current maritime law for the autonomy as well as liability issues in a marine accidents involving autonomous/unmanned vessels.

- **Category 8** covers articles discussing how to integrate autonomous vessels into *transportation and logistics*.

- **Category 9** consists of the papers offering *general introductions* of the concept of autonomous vessels.

3 Literature Review

In this section, we classify the collected studies on autonomous marine vessels based on the nine predefined categories, namely *safety*, *navigation control*, *design*, *project & prototype*, *economic analysis*, *environmental impact*, *law & regulation*, *transportation & logistics* and *general introduction*. Naturally, some articles address multiple topics which are relevant to different categories. In this case, this article is assigned to the multiple categories it belongs to. A brief review of the articles assigned to each category is also provided. A detailed reference list for each category can be found in Appendix A.

Category 1: Safety

In this category, articles discussing safety issues for autonomous vessels or USVs are reviewed. The topics in this category consists of collision avoidance, cyber security and other safety concerns.

- *Collision Avoidance*

  The International Regulations for Preventing Collisions at Sea (COLREGs) is the main guidance issued by the International Maritime Organization (IMO) in 1972 for collision avoidance purposes. A large number of research regarding collision avoidance in autonomous maritime navigation follow this regulation. Wang et al. (2018b) reported some preliminary results of a new algorithm called the local normal distribution-based trajectory for the USV. This approach ensures that the navigation of the USV complies with the COLREGs and avoids collision successfully. Naeem et al. (2016) modified the Artificial Potential Fields (APF) framework and developed a COLREGs-based collision avoidance technique for USVs which can handle both stationary and dynamic obstacles. Zhao et al. (2016) employed the Evidential Reasoning theory to detect collision risks and adopted the optimal reciprocal collision avoidance algorithm to generate COLREGs-compliant maneuvers. Campbell and Naeem (2012) integrated a heuristic Rule-based Repairing A* algorithm in a path decision-making framework incorporating the COLREGs. Beser and Yildirim (2018) presented a bearing only obstacle avoidance approach as a backup COLREGs compliance method when the lidar or radar fails. Naeem et al. (2012) reported a COLREGs-based collision avoidance strategy consisting of way-point guidance by line-of-sight coupled with a manual biasing scheme. Lu et al. (2016) used a probabilistic model checking technique for verifying three collision avoidance behaviours (steering, acceleration and deceleration) associated with the crossing situation in COLREGs. Lee et al. (2015b) proposed a heuristic search technique based on fuzzy relational products to ensure COLREGs-compliant and collision-free navigation for autonomous ships. Mei and Arshad (2017) proposed a navigation guidance system with APF which allows the ASV to decide whether to follow the COLREGs based on the encounter situations and avoid potential collisions. Other collision avoidance strategies with respect to COLREGs can also be found in Hu et al. (2017); Xu et al. (2018); Savvaris et al. (2014); Bertaska et al. (2015).

Besides the COLREGs related studies, Hong and Arshad (2015) introduced a balance-APF hybrid method which helps the ASV successfully avoid static obstacles in challenging situations. Serigstad et al. (2018) reported a hybrid dynamic window (HDW) algorithm which acts as both collision avoidance method and trajectory tracker for ASVs. Praczyk (2015) presents two neuro-evolutionary methods used to build the neural anti-collision system (ACS). Krishnamurthy et al. (2008) proposed a hierarchical obstacle avoidance system consisting of a wide-area planner based on the A* graph-search algorithm, a local-area planner based on GODZILA (Game-Theoretic Optimal Deformable Zone with Inertia and Local Approach) and a robust non-linear inner-loop controller. Hermann et al. (2015) described a radar and vision technologies based obstacle detection system for a high-speed USV. Bovcon et al. (2018) proposed a new segmentation model incorporating boat roll and pitch measurements from the on-board inertial measurement unit and a stereo verification scheme for obstacle detection with USVs. Statheros et al. (2008) examined different techniques including evolutionary algorithms, fuzzy logic, expert systems, and neural networks for autonomous ship collision avoidance.

Many other papers also discuss different strategies about collision avoidance but not as their main research focus. For example Burmeister et al. (2014); Rolls-Royce (2016) explained the importance of collision-free navigation for autonomous/unmanned vessels. Escario et al. (2012); Singh et al. (2018); Song et al. (2017); Kim et al. (2017a); Breivik and Loberg (2011); Niu et al. (2018); Mousazadeh et al. (2018); Liu and Bucknall (2018); Niu et al. (2016); Thakur et al. (2012); Wang et al. (2019b); Du et al. (2018); Ma et al. (2018); Crasta et al. (2018); Liu and Bucknall (2015); Yang et al. (2015); Liu and Bucknall (2016); Liu et al. (2017b); Ma et al. (2014) all considered obstacle avoidance in their studies regarding path planning for USVs which will be further reviewed later.

- *Cyber Security*

Hogg and Ghosh (2016) believed that an unmanned ship may have a reduced risk in traditional piracy due to the lack of crew to hold hostage but the exposure to a cyber-attack for an unmanned ship increases significantly. When the core system is hacked, the vessel can be hijacked and cause collision with casualties or pollution with environmental damage. To handle such new cyber security threats, the cost for the shipping companies with unmanned vessels will rise. Rolls-Royce (2016) pointed out the increasing concern on cyber security for autonomous or remotely operated ships which have a more vulnerable information and communication system compared to the conventional manned ships. Moreover, besides hacking, the international jamming or spoofing of the Automatic Identification System (AIS) or Global Positioning System (GPS) signal will also lead to cyber security issues and disturb the operation of autonomous or unmanned vessels. Danish Maritime Authority (2016) also explained the importance of including cyber security considerations in the design of autonomous maritime navigation systems.

- *Other Safety Concerns*

  Different from the conventional ships, the autonomous or unmanned vessel has no manpower on board to fix the machinery when it breaks down during operation. Hence, it is very important for the designers of autonomous or unmanned ships to identify and assess the potential risks. Wróbel et al. (2018) used a system-theoretic model to analyze the safety concerns of an autonomous merchant vessel based on the uncertainties during navigation. Recommendations for safety-driven design are also offered. Wróbel et al. (2016) conducted a hazard analysis associated with unmanned ships and listed the potential safety threats covering various aspects based on experts' opinions. Rødseth and Burmeister (2015) introduced a risk-based design method to identify critical safety and security risks and proposed corresponding solutions to address them. Wróbel et al. (2017) performed a what-if analysis based on historical maritime accident reports to assess the potential impact of unmanned vessels on maritime safety from a transportation perspective. Besides risk assessment, accurate and timely fault detection and isolation are also critical for safe navigation of autonomous marine vessels. A data-driven, model-free technique based on the Principal Components Analysis technique is proposed by Zanoli et al. (2012) to formulate the fault detection problem.

Category 2: Navigation Control

In this category, we review the studies about individual and group navigation control problems for unmanned vessels. The topics considered in this category include path or trajectory planning, path tracking or following, manoeuvring, steering, heading and swarm or formation control.

- *Individual Control*

  The most discussed issue in the literature regarding the control of one single autonomous vessel is the planning of its path or trajectory. Song et al. (2017) proposed a multi-layered fast marching method to generate feasible trajectories for a USV with a dynamic surrounding. Beser and Yildirim (2018) and Liu and Bucknall (2018) adopted a path planning method based upon the fast marching square algorithm. Liu et al. (2017b) developed an angle guidance fast marching square (AFMS) based path trajectory algorithm and integrated it into the control system of a prototype USV. The A* approach is also widely used in path planning for autonomous vessels, see example Singh et al. (2018) and Krishnamurthy et al. (2008). Campbell and Naeem (2012), Yang et al. (2015) and Ma et al. (2014) developed new algorithms based on this approach, including Rule-based Repairing A* algorithm, Finite Angle A* algorithm and Smoothing A* algorithm, to better optimize the path planning for USVs.

  Many other methods have been adopted in the research on trajectory planning. These include the APF method (Mei and Arshad, 2017; Naeem et al., 2016), Ant Colony Optimization (Escario et al., 2009, 2012; Zhu et al., 2016), multi-objective particle swarm optimization

(Hu et al., 2017; Ma et al., 2018), genetic algorithm (Kim et al., 2017a), integrated algorithm based on Voronoi diagram, Visibility algorithm and Dijkstra search algorithm (Niu et al., 2016, 2018), local normal distribution-based trajectory (Wang et al., 2018b), angular rate-constrained Theta* algorithm (Kim et al., 2014), model-referenced trajectory planner (Bertaska et al., 2015), GPU based algorithms and Markov Decision Process (Thakur et al., 2012), grey wolf optimizer (Wang et al., 2019b), Trajectory Unit method (Du et al., 2018), waypoint guidance by line-of-sight coupled with a manual biasing scheme (Naeem et al., 2012) and heuristic search based on Bandler and Kohout's fuzzy relational products (Lee et al., 2015b). Savvaris et al. (2014) and Iovino et al. (2018) also briefly discussed path planning in their research.

After the trajectory plan is generated, another important issue for the navigation control of an individual autonomous vessel is to ensure the accuracy in path following. Liu et al. (2018a) proposed a model predictive control approach based on adaptive line-of-sight (LOS) guidance to solve the path following problem for ASVs. Liao et al. (2016) adopted a backstepping adaptive sliding mode controller to solve the trajectory tracking problem. Zereik et al. (2013) introduced a Jacobian task priority-based approach for the path planning of USVs. The advantage of this approach is that without changing the architecture, further control tasks can be easily added. Zizzari et al. (2009) developed a guidance motion control law which guarantees bounded velocity commands and then applied it in the path following guidance control of a USV prototype. Ghommam and Mnif (2016) designed a robust controller based on adaptive sliding mode control and the radial basis function neural network. This controller handles the uncertainties of ocean currents and ensures robust path-following performance of ASVs under parameter variations and external disturbances. Bibuli et al. (2012) proposed a cascade control scheme for USVs which offers accurate performance in terms of straight line following. Larrazabal and Peñas (2016) designed a fuzzy logic controller and a gain scheduling PID controller optimized by a genetic algorithm for trajectory tracking of USVs. Brief discussions regarding trajectory following problems can also be found in Breivik and Loberg (2011); Sharma et al. (2012); Hong and Arshad (2015); Serigstad et al. (2018); Mousazadeh et al. (2018).

Besides path planning and following, other navigation control features, such as maneuvering, steering and heading are also addressed by researchers. Different neural network-based approaches are adopted in Peng et al. (2016); Fang et al. (2017); Jakovlev et al. (2017); Xu et al. (2018); Woo et al. (2018) for USV maneuver and course control. Li et al. (2018b) introduced an angular velocity guidance algorithm to address the challenges faced by the compact form dynamic linearization based model-free adaptive control method in the USV heading control problem. Liu et al. (2015) developed an adaptive gain-scheduling control design methodology to maneuver the USV when mass variation is experienced. The maneuver strategy of a single autonomous vessel is also briefly discussed in Statheros et al. (2008); Zhao et al. (2016); Rolls-Royce (2016); Klinger et al. (2017). Studies regarding other control issues, such as station keeping and motion state estimation, can be found in Sarda et al.

(2016) and Ma (2014).

- *Group Control*

  To finish certain tasks, multiple autonomous vessels are needed. Therefore, the group control of these vehicles in such scenarios becomes critical. One of the most popular formations used in group control of autonomous vessels is the leader-follower structure. Lu et al. (2018b) developed a distributed robust formation controller, based on directed graph theories, backstepping and the minimal learning parameter (MLP) algorithm, to handle the leader-follower control problem of ASVs in the presence of external uncertainties. Similarly, Lu et al. (2018c) also adopted the MLP algorithm together with the disturbance observer in their robust adaptive formation control scheme for USVs with leader–follower formation. Jin (2016) proposed a fault tolerant leader–follower formation control scheme for a group of ASVs with LOS range and angle constraints. Time-varying tan-type barrier Lyapunov functions are adopted in the scheme to address the two constraints and finite time convergence. Liu et al. (2018b) studied the output consensus problem of a leader-follower structured USV formation system. A network-based incremental predictive control scheme was proposed in this paper to fix the problems caused by network-induced delays and packet dropouts. Based on the leader-following strategy, Shojaei (2016) introduced a second order formation dynamic model to design the formation control system. Liu and Bucknall (2015) proposed a computer based algorithm based on the fast marching method to solve the path planning problem of a leader-follower USV formation. Liu and Bucknall (2016) also presented a formation path planning algorithm based on AFMS for a group of USVs with a leader-follower shape. Inspired by LOS guidance control laws, Kim and Kim (2018) developed a leader-follower motion control of multiple autonomous ships under a stealth strategy for military purpose. Besides the leader-follower structure, the virtual target approach is also a common choice for group control of multiple autonomous vessels. Bibuli et al. (2018) integrates a safety distance constrained A* approach with the virtual target approach to obtain the optimal trajectories for the USV fleet. Discussion of the control problem of multiple USVs can also be found in Simetti et al. (2012); Qin et al. (2017); Crasta et al. (2018).

Category 3: Design

Articles related to the design of autonomous vessels are reviewed in this category. The research focus here includes the general design of the entire autonomous maritime system and specific sub-systems of the autonomous vessels.

- *General Design*

  Burmeister et al. (2014) illustrated a comprehensive conceptual design for an autonomous dry bulk carrier. This design is proposed in the Maritime Unmanned Navigation through the Intelligence in Networks (MUNIN) project and consists of four sub-systems, namely an advanced sensor module, an autonomous navigation system, an engine monitoring & control system, and a shore control centre. Since the ship is unmanned, the advanced sensor module is needed to replace the officer of the watch and monitor the surroundings of the vessel. The sensor module will detect potential dangerous objects based on the data collected by radar, camera and satellite. The autonomous navigation system ensures the ship follows a predefined voyage plan. In the meantime, the system also helps difficult manoeuvres, such as collision avoidance and mooring in ports. The engine monitoring & control system brings more advanced condition monitoring functionalities which facilitate early failure prediction and detection and better maintenance. Experienced nautical officers and engineers will monitor the navigation in the shore control centre and be prepared to intervene when an emergency occurs. Similar design ideas can also be found in Danish Maritime Authority (2016) and Rolls-Royce (2016).

Perera et al. (2012) developed a control and navigation platform for ASVs. The overall system can be further described under the hardware structure and the software architecture. A command and monitoring unit (CMU) and a communication and control unit (CCU) are proposed for the system hardware structure. The ashore based CMU will monitor the operations of the vessel and release new commands through a wireless Ethernet communication linked with the CCU on board. The CCU will then execute orders and return operational information. For the software architecture, several software loops, for example a real-time loop and a TCP/IP loop, as well as a human machine interface are proposed for autonomous and manual control of the ship. The developed system is implemented and tested on a scaled self-propelled model of a real ship.

- *Sub-system Design*

Besides the general design of the entire system, the detailed design of specific sub-systems on ASVs also attracts great attention. Man et al. (2015) and Wahlström et al. (2015) focused on the human factor issues related with the design of a shore control centre. The former identified the potential gaps that may decrease the operator's situational awareness and affect the decision quality during navigation. The latter, on the other hand, presented an overview of human factor challenges, for instance information overload, negligence during changeovers, and lack of feel of the vessel, which will affect the operational efficiency of autonomous vessels. Both articles claimed that a better shore control centre design can solve the problems. Jakovlev et al. (2017) illustrated an integrated intellectual data communication network for a short-sea-shipping maritime information system which guarantees the adaptability and availability of information for autonomous vessels. Wróbel et al. (2018) applied System-Theoretic Process Analysis to offer valuable recommendations for innovative technical system design of autonomous vessels. Jin et al. (2018) proposed a heading and velocity controller design for USVs with backstepping technology. Makhsoos et al. (2018) and Khare and Singh (2012) focused on hybrid energy system design for USVs. The former proposed a system with solar power and 8KWh capacity lithium-ion battery. The hybrid system in the latter article comprises a solar array, an ocean wave energy converter, a fuel cell system, a diesel generator and a lithium ion battery pack, which ensures stable power supply for long duration missions. Hermann et al. (2015) described an obstacle detection system for a USV operating with high speed and agile maneuvers. Liu et al. (2017b) introduced an original design of the intelligent navigation system for a USV which is implemented and tested on a prototype. Rather than directly studying the design of the autonomous vessel, Heins et al. (2017) presented a multiphysics simulation model to evaluate the design of an autonomy management system and reduce the need for real-world trials.

Category 4: Projects and Prototypes

The project MUNIN - Maritime Unmanned Navigation through Intelligence in Networks – is a major research project regarding autonomous shipping funded by the European Commissions under its Seventh Framework Programme with intensive multinational and cross-industrial cooperations (MUNIN, 2016). Burmeister et al. (2014) offered a brief overview of the MUNIN project and outlined the contributions made in this project for the development of future e-Navigation solutions. Rødseth and Burmeister (2015) described a Formal Safety Analysis-based risk assessment method which was applied in the MUNIN project. In the meantime, the main results of the assessment and the corresponding application in the MUNIN project were also presented in the paper. Kretschmann et al. (2017) calculated the cost difference between the conceptual autonomous dry bulk carrier developed in the MUNIN project and a conventional bulker. Another research project, named Advanced Autonomous Waterborne Applications Initiative (AAWA) and funded by the Finnish Funding Agency for Technology and Innovation, aimed to study the specification and preliminary designs for the next generation of advanced ship solutions. The detailed contents and findings of this research project can be found in the project report by Rolls-Royce (2016). Both the MUNIN and the AAWA projects are also presented and summarized in a pre-analysis report on autonomous ship conducted by the Danish Maritime Authority (2016). Simetti et al. (2012) presented a research project based on the real-world application of USVs for security of civilian harbors. This project was conducted by the University of Genova and Selex Sistemi Integrati (an Italian defence and security equipment producer) and aimed to develop a solution for a USV team to intercept a suspect vehicle in port areas. Moreover, many experiments are also made on specific USV prototypes for different purposes. A summary of the literature in this category can be found in Table 3.

Category 5: Economic Analysis

Without plausible economic incentives, the new ideas will hardly find their way to practice. Hence, the economic analysis or cost-benefit analysis is also vital for the studies of autonomous vessels. Danish Maritime Authority (2016) claims that the adoption of autonomous technology

Table 3: Literature related with USV prototypes

Prototype Name	Article	Testing Purpose
Springer	Singh et al. (2018)	Path planning
	Sharma et al. (2012)	Autopilot system
	Liu et al. (2017b)	Path planning
Charlie	Zanoli et al. (2012)	Fault detection and isolation
	Bibuli et al. (2012)	Navigation, Guidance and Control (NGC) system
	Zizzari et al. (2009)	Path following and guidance control
CART and Trimaran	Fumagalli et al. (2014)	Visual and acoustic characterization
WAM-V USV14	Klinger et al. (2017)	Control with uncertain displacement and drag
WAM-V USV16	Sarda et al. (2016)	Station-keeping control
Halcyon	Heins et al. (2017)	Simulation model
Morvarid	Makhsoos et al. (2018)	Energy system
C-Enduro	Savvaris et al. (2014)	Collision avoidance
C-Worker 5	Iovino et al. (2018)	Path manger
Dolphin I	Li et al. (2018b)	Heading control
DH-01	Peng et al. (2016)	Steering
Aurora model	Perera et al. (2012)	Navigation and control platform

in shipping depends on the trade-off between lower crew cost and higher construction cost of the newbuildings. However, Hogg and Ghosh (2016) argue that the reduction of crew cost may be easily offset by the higher manning cost in the shore control centre and other additional costs in ports, such as mooring and cargo handling. Cross et al. (2017), Hogg and Ghosh (2016) and Rolls-Royce (2016) believed that the cost saving brought by reduced seaman salary is limited. They pointed out that the main potential for cost reduction comes from the removal of the on board infrastructure and facilities for crew's daily life, which will lead to increased cargo capacity as well as smaller and lighter vessels. Such arguments coincide with the findings in Kretschmann et al. (2017). The results show that reduced crew cost only will not be sufficient to promote autonomous shipping, but great economic benefit can be achieved through innovative ship design with better space utilization for unmanned vessels.

Category 6: Environmental Impact

Shipping is one of the major sources for different types of emissions, for example CO_2, SO_x and NO_x. The literature about emission reduction for the conventional ships is well developed. However, only few articles collected in this survey considered the environmental impact brought by autonomous vessels. Hogg and Ghosh (2016) and Rolls-Royce (2016) briefly discussed the potential emission reduction due to higher energy efficiency of unmanned ships.

Category 7: Law and Regulaiton

The existing maritime laws do not offer a practical legal framework for autonomous vessels to operate in international waters. Hogg and Ghosh (2016) argue that such incompleteness in law and regulation has become one of the main obstacles for the development of autonomous ships and therefore need to be fixed. Rolls-Royce (2016) offered a comprehensive analysis on the legal implications of remote-controlled or autonomous shipping from different perspectives including law of the sea, international conventions and liability rules. Karlis (2018) identified the main areas of ambiguity and potential operational difficulties found in today's crew related conventions, which may prevent shipowner from investing in this new technology. Danish Maritime Authority (2016) suggested that inspiration can be obtained from the legal progress for autonomous vehicles and reminded us that special attention should be paid to the transition period when unmanned and manned ships co-exist. Cross et al. (2017) asserted that it is possible to stretch the existing IMO regulations to fit the operation of remotely controlled ships while the update to cover fully autonomous ship remains challenging.

Category 8: Transportation and Logistics

We have found three entries in the transportation and logistics category. Rolls-Royce (2016) discussed how the autonomous vessel will redefine the entire shipping industry. New business relationships and networks,as well as new actors and their roles are the main drivers for this transition. Danish Maritime Authority (2016) proposed many ideas about potential application of autonomous vessels, for instance island ferries for rural areas, service vessels for offshore operations and tugboats in port. Zhu et al. (2016) presented a real-world application of USVs collecting maritime traffic information to facilitate the judgement and decision regarding other vessels' navigation. Since the literature in this category is relatively recent and limited, we foresee that important research about how autonomous ships will impact logistics and transportation is still to come.

Category 9: General Introduction

Since the topic of autonomous vessels is relatively new, a general introduction about this concept is needed in the literature. Readers may find such introductions in Burmeister et al. (2014), Danish Maritime Authority (2016), Cross et al. (2017), and Rolls-Royce (2016).

4 Analysis and Comparison

In this section, we perform a basic statistical analysis on the literature gathered. In addition, we perform a comparison between the analysis of the literature of autonomous vessels and the analysis of the literature of autonomous vehicles. The purpose of such a comparison is to explore the potential research opportunities in the field of autonomous vessels based on the experience obtained in the studies about autonomous vehicles.

First of all, we present a histogram regarding the number of articles published in each year for the past decade, see Fig. 1. A clear trend in this figure is that the popularity of research about autonomous ships is rapidly increasing. One of the main reasons for such a trend is that the autonomous technology for vessels has matured in recent years.

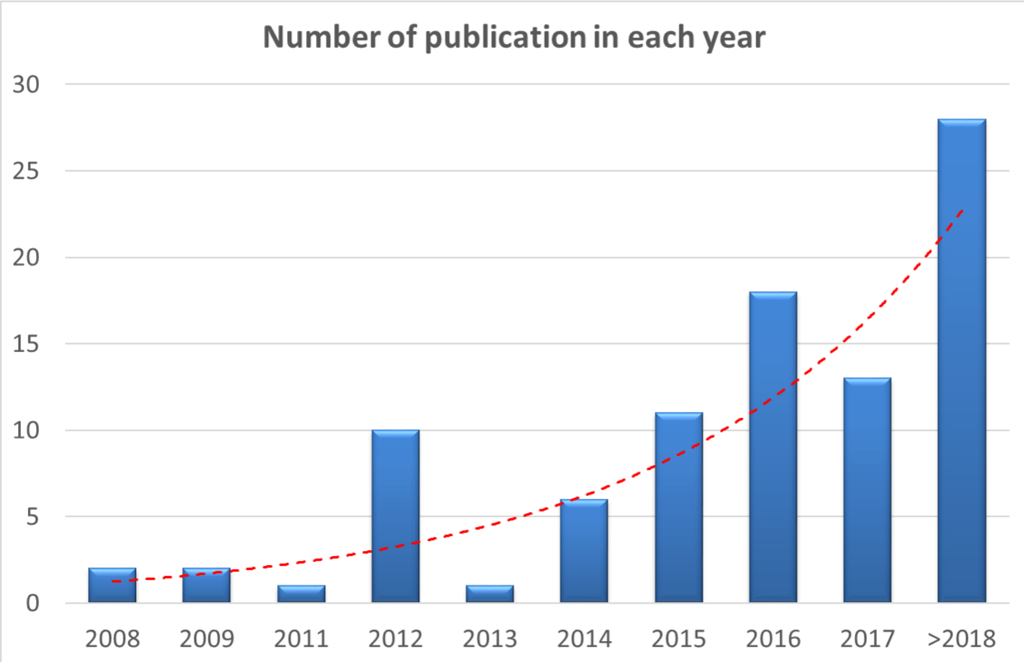

Figure 1: Publication data of papers studying autonomous vessels in each year

Secondly, we provide a geographical characterization of the literature in the field of autonomous vessels, see Fig. 2. In computing the number for each country, we have counted the number of articles in which a country is mentioned in the affiliation of its authors. If the author of an article has affiliation in different countries, each of these countries gets one point for this article. If a country appears two or more times in the affiliations of a same article, it only accounts for one point. We can see from the results in Fig. 2 that China, UK, USA and Norway have the highest number of publications on autonomous vessels. Aggregating all European countries, they create the region with the largest share of contributions, equivalent to 46 papers in total. In fact, several research projects, such as the MUNIN project and the AAWA project, have taken place in Europe and attracted a great amount of attention from the researchers in European universities and institutions.

The statistical analysis gives the distribution of the literature among the nine categories defined in this survey, see Fig. 3. If an article belongs to only one category, one point is assigned to this category. If the article belongs to multiple categories, the point is evenly distributed among these categories for the final statistics. Clearly, the category of navigation control and the category of safety have the largest shares (46% and 28%) of the literature, while the shares of the other categories are considerably more limited. The distribution coincides with the observation that most of the articles in this field are published in journals with strong engineering and technology background, see Fig. 4. However, such unbalanced development in the literature is to a certain extent understandable. Navigation control and safety concerns are the two most basic prerequisites for the practical application of autonomous vessels. Therefore,

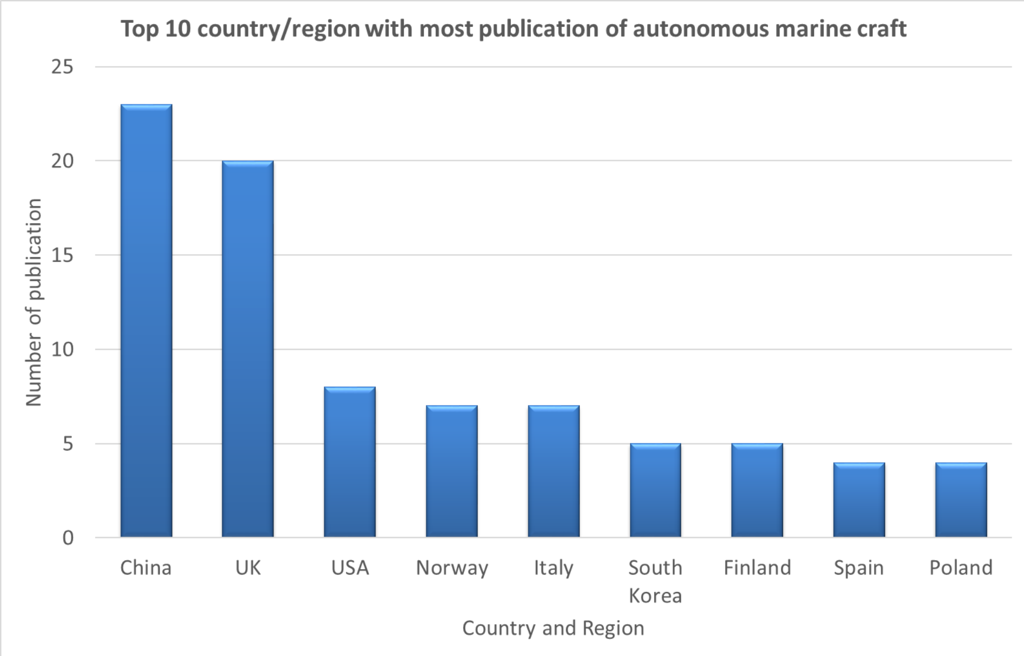

Figure 2: Top countries & regions with most publications of autonomous vessels

it is reasonable that these two categories have much higher priorities than the others in the beginning phase of this new technology.

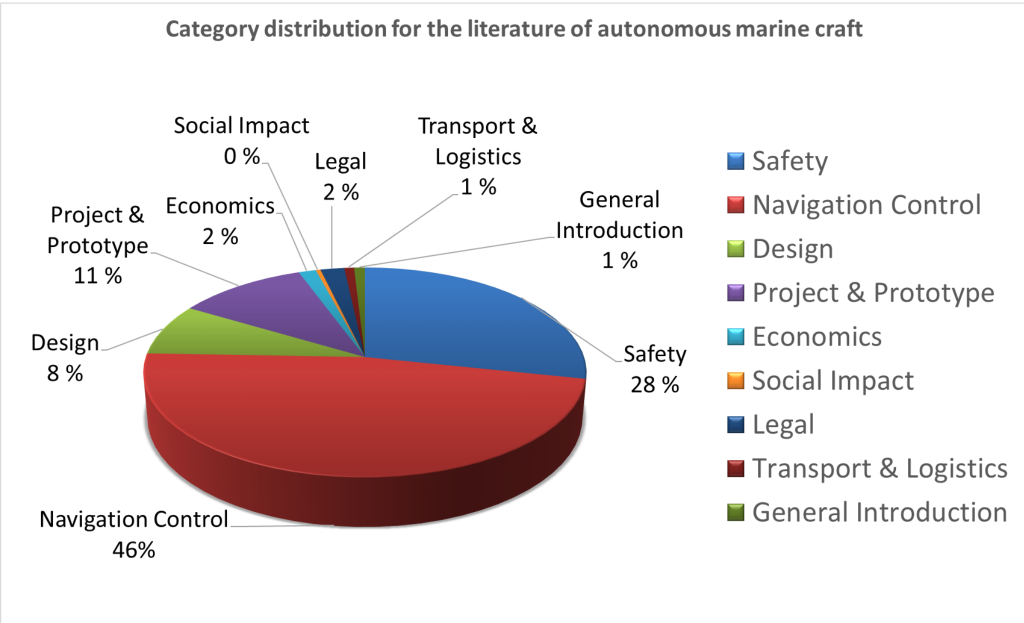

Figure 3: Category distribution of the collected literature regarding autonomous vessels

With the literature on autonomous vehicles in a more advanced stage of development (e.g. see reviews by Berrada and Leurent, 2017, and Bhoopalam et al., 2018), we found interesting to compare recent contributions on that stream to its counterpart in autonomous vessels and to distinguish some patterns. Fig. 5 summarizes this comparison.

Note that for autonomous vehicles, we considered only articles published after 2015. The main reason for a shorter time coverage here is that the autonomous vehicle literature is much

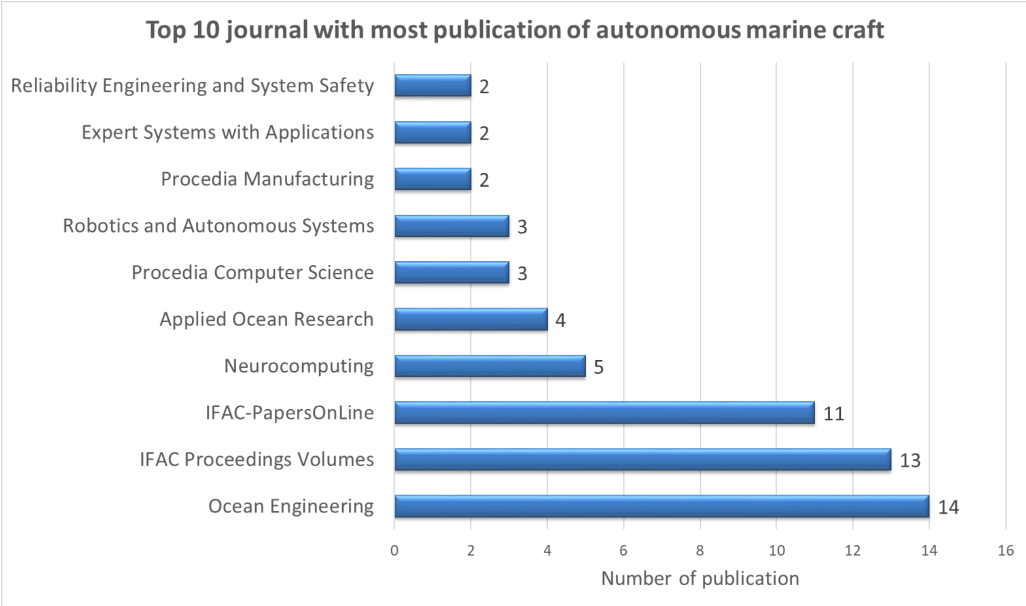

Figure 4: Top journals with most publications of autonomous vessels

more numerous than the autonomous vessels literature. Without a tighter time restriction, we would easily end up with more than one thousand articles related to autonomous vehicles, which is impractical for our survey purpose. The search was performed in Scopus (2018) and considered only journal articles. The search keywords include *autonomous vehicle*, *autonomous car*, *automated vehicle*, *automated car* and *automated driving*. In total, we gathered 161 qualified journal articles and classified them based on the same nine categories as defined in Section 2. The classification is outlined in Appendix B. The comparison of category distribution between the two streams of literature is illustrated in Fig. 5.

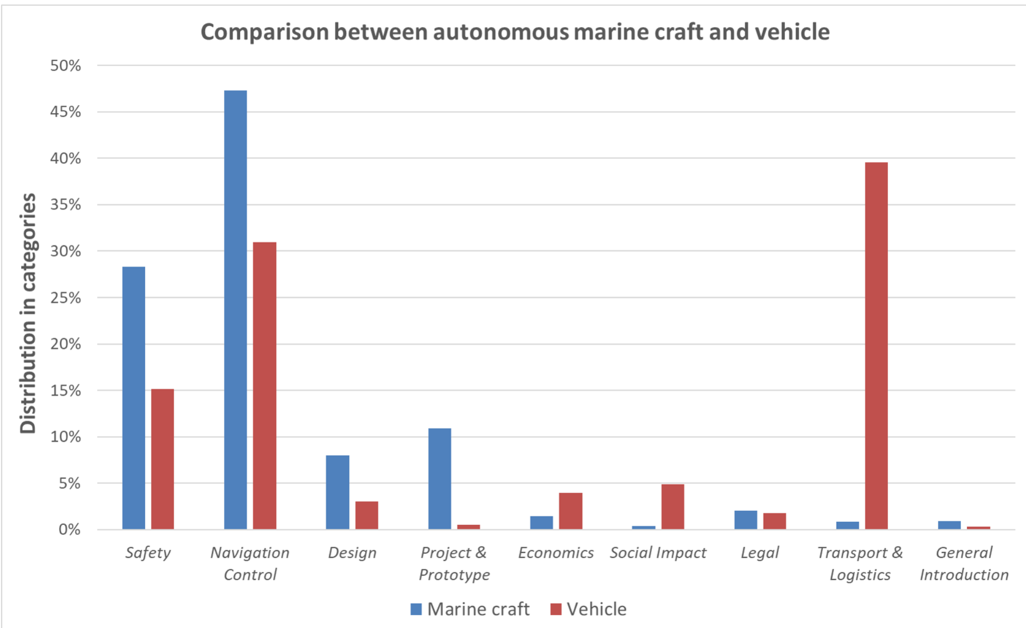

Figure 5: Comparison between autonomous vessels and vehicles

We observe that the general trends of distribution in most categories are very similar for both literature streams. The number of publication in safety and navigation control related topics are high while the studies in other categories including design, project & prototypes, economic analysis, environmental impact, law & regulation and general introduction, are limited. The only exception occurs in the category of transportation and logistics. While transportation and logistics has played a protagonist role in the recent literature on autonomous road vehicles, this category is not yet predominant in the literature on autonomous vessels. We conjecture that this difference is mainly caused by the different maturity levels of the two technologies. For example, it is remarkable that the project of Google self-driving cars started in 2009 and they have accumulated 300,000 miles self-driving experience during the last decade (Waymo, 2019). Tesla also lunched its autopilot project and finally commercialized it as a feature of its final product in 2014 (Tesla, 2018). Due to the high maturity of the self-driving technology, great attention from the logistics research community was attracted, which finally triggered the research gravity shift from fundamental topics (control and safety) to application topics (transportation and logistics). For autonomous vessels, the development of real-world applications is relatively slower. Therefore, the research priority still remains on the basic issues today (control and safety) and have not yet switched to transportation and logistics issues. The situation is gradually changing. In December 2018, Rolls-Royce and the Finnish state-owned ferry operator Finferries demonstrated the operational feasibility of the world's first fully autonomous ferry (Rolls-Royce, 2018). In the trial voyage, both navigation and docking are handled by the ferry with zero human intervention. Furthermore, the world's first fully electric and autonomous container ship, Yara Birkeland, will also be tested in 2019 and start fully autonomous operation by 2022 (Kongsberg, 2018). As technology matures, the commercialized application of autonomous navigation in shipping is expected in the near future, which leads to great research opportunities. Hence, we argue that it is the right time for the research community interested in autonomous vessels to shift their research focus from the basic control and safety studies to transportation and logistics applications.

5 Conclusion

We made a parallel comparison between the existing literature on autonomous vessels and autonomous vehicles. One can observe that in both cases there is significant work on navigation control and safety. That literature shows that in both cases we are achieving a level of maturity that may allow researchers to start working on realistic applications of autonomous technologies. Our results show that for autonomous vehicles that is indeed the case, particularly the literature in the category of transportation and logistic is booming.

However, it appears that the impact of autonomous vessels in the current logistic models is still an open question. Indeed, our review shows that there is little work done in that category. The technology of autonomous ships is developing rapidly, with a significant pace observed in the past few years. Those developments are delivering a mature technology that we believe is opening the opportunity to start investigating its impact on the logistic systems.

We foresee several application areas where autonomous vessels may impact the logistic systems. First, we think this technology allows us to rethink the operations of the vessels. For example, they may help to improve the delivery of services and the distribution systems in sparsely populated coastal areas. We believe that the flexibility on the operations introduced by the autonomous technologies may help to improve coverage for some services and the distribution of goods. It also poses the question of the management of mixed fleets with both conventional and autonomous ships, which may include multi-functional vessels with remote control. In particular, this problem may arise in a transitional period of migration from conventional vessels to autonomous vessels. Given the initial high costs of autonomous vessels and perhaps the need for infrastructure that can accommodate them, it is possible to have a transition period when both technologies will coexist. That assumes that there will be a transition to a fleet only of autonomous vessels. However, an open question is if a fully autonomous fleet is something desirable to ensure the robustness and reliability of the logistic networks.

Furthermore, the categories on economic analysis and environmental impact are worthy of more investigation as well. Improvements in those dimensions can be main drivers for expanding the use of autonomous vessels in transport and logistics. One may consider, for example, feasible newbuilding prices of autonomous vessels for commercialization and cost-benefit analysis in the category of economic analysis. In the category of environmental impact, emission reduction with autonomous vessels is a subject of study that may also contribute to such an expansion.

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Appendix

Appendix A: Classification of literature of autonomous vessels

- ### Category 1: Safety

Collision Avoidance

Wang et al. (2018b); Naeem et al. (2016); Zhao et al. (2016); Campbell and Naeem (2012); Beser and Yildirim (2018); Naeem et al. (2012); Lu et al. (2016); Lee et al. (2015b); Mei and Arshad (2017); Hu et al. (2017); Xu et al. (2018); Savvaris et al. (2014); Bertaska et al. (2015); Hong and Arshad (2015); Serigstad et al. (2018); Praczyk (2015); Krishnamurthy et al. (2008); Hermann et al. (2015); Bovcon et al. (2018); Statheros et al. (2008); Burmeister et al. (2014); Rolls-Royce (2016); Escario et al. (2012); Singh et al. (2018); Song et al. (2017); Kim et al. (2017a); Breivik and Loberg (2011); Niu et al. (2018); Mousazadeh et al. (2018); Liu and Bucknall (2018); Niu et al. (2016); Thakur et al. (2012); Wang et al. (2019b); Du et al. (2018); Ma et al. (2018); Crasta et al. (2018); Liu and Bucknall (2015); Yang et al. (2015); Liu and Bucknall (2016); Liu et al. (2017b); Ma et al. (2014)

Cyber Security

Hogg and Ghosh (2016); Rolls-Royce (2016); Danish Maritime Authority (2016)

Othe Safety Concerns

Wróbel et al. (2018, 2016); Rødseth and Burmeister (2015); Wróbel et al. (2017); Zanoli et al. (2012)

- ### Category 2: Navigation Control

Individual Control

Song et al. (2017); Beser and Yildirim (2018); Liu and Bucknall (2018); Liu et al. (2017b); Singh et al. (2018); Krishnamurthy et al. (2008); Campbell and Naeem (2012); Yang et al. (2015); Ma et al. (2014); Mei and Arshad (2017); Naeem et al. (2016); Escario et al. (2009, 2012); Zhu et al. (2016); Hu et al. (2017); Ma et al. (2018); Kim et al. (2017a); Niu et al. (2016, 2018); Wang et al. (2018b); Kim et al. (2014); Bertaska et al. (2015); Thakur et al. (2012); Wang et al. (2019b); Du et al. (2018); Naeem et al. (2012); Lee et al. (2015b); Savvaris et al. (2014); Iovino et al. (2018); Liu et al. (2018a); Liao et al. (2016); Zereik et al. (2013); Zizzari et al. (2009); Ghommam and Mnif (2016); Bibuli et al. (2012); Larrazabal and Peñas (2016); Breivik and Loberg (2011); Sharma et al. (2012); Hong and Arshad (2015); Serigstad et al. (2018); Mousazadeh et al. (2018); Peng et al. (2016); Fang et al. (2017); Jakovlev et al. (2017); Xu et al. (2018); Woo et al. (2018); Li et al. (2018b); Liu et al. (2015); Statheros et al. (2008); Zhao et al. (2016); Rolls-Royce (2016); Klinger et al. (2017); Sarda et al. (2016); Ma (2014)

Group Control

Lu et al. (2018b,b); Jin (2016); Liu et al. (2018b); Shojaei (2016); Liu and Bucknall (2015, 2016); Kim and Kim (2018); Bibuli et al. (2018); Simetti et al. (2012); Qin et al. (2017); Crasta et al. (2018)

- ### Category 3: Design

General Design

Burmeister et al. (2014); Danish Maritime Authority (2016); Rolls-Royce (2016); Perera et al. (2012)

Sub-system Design

Man et al. (2015); Wahlström et al. (2015); Jakovlev et al. (2017); Wróbel et al. (2018); Jin et al. (2018); Makhsoos et al. (2018); Khare and Singh (2012); Hermann et al. (2015); Liu et al. (2017b); Heins et al. (2017)

- ### Category 4: Projects and Prototypes

Projects

MUNIN (2016); Burmeister et al. (2014); Rødseth and Burmeister (2015); Kretschmann et al. (2017); Rolls-Royce (2016); Danish Maritime Authority (2016); Simetti et al. (2012)

Prototypes

Singh et al. (2018); Sharma et al. (2012); Liu et al. (2017b); Zanoli et al. (2012); Bibuli et al. (2012); Zizzari et al. (2009); Fumagalli et al. (2014); Klinger et al. (2017); Sarda et al. (2016); Heins et al. (2017); Makhsoos et al. (2018); Savvaris et al. (2014); Iovino et al. (2018); Li et al. (2018b); Peng et al. (2016); Perera et al. (2012)

- ### Category 5: Economic Analysis

Danish Maritime Authority (2016); Hogg and Ghosh (2016); Cross et al. (2017); Rolls-Royce (2016); Kretschmann et al. (2017)

- ### Category 6: Environmental Impact

Hogg and Ghosh (2016); Rolls-Royce (2016)

- ### Category 7: Law and Regulaiton

Hogg and Ghosh (2016); Rolls-Royce (2016); Karlis (2018); Danish Maritime Authority (2016); Cross et al. (2017)

- **Category 8: Transportation and Logistics**

  Rolls-Royce (2016); Danish Maritime Authority (2016); Zhu et al. (2016)

- **Category 9: General Introduction**

  Burmeister et al. (2014); Danish Maritime Authority (2016); Cross et al. (2017); Rolls-Royce (2016)

Appendix B: Classification of literature of autonomous vehicles

- **Category 1: Safety**

  Riaz et al. (2018); Yang et al. (2018); Bai et al. (2017); Schwammberger (2018); Combs et al. (2019); Favarò et al. (2018); Åsljung et al. (2016); Sheehan et al. (2018); Harper et al. (2016b); Németh et al. (2018); Guo et al. (2018); Ge et al. (2018); Shin and Yi (2018); Li et al. (2018a); Monica and Ferrari (2016); Bichiou and Rakha (2019); K. Chu et al. (2015); Bhavsar et al. (2017); Morando et al. (2018); Wiseman and Grinberg (2016); Xin et al. (2015); Zhao et al. (2017); Mammeri et al. (2016); Rosolia et al. (2017); Kim et al. (2017b); Perumal et al. (2016); Guo et al. (2016); Chen et al. (2018); Petit and Shladover (2015); Weiskircher et al. (2017); Ängskog et al. (2018); Cao et al. (2015)

- **Category 2: Navigation Control**

  Guo et al. (2019); Yang et al. (2018); Dreves and Gerdts (2017); Wen-Xing and Li-Dong (2018); Kawabata et al. (2015); Bai et al. (2017); Haddad et al. (2015); Guo et al. (2017); Ji et al. (2018); Guang et al. (2018); Zhu and Zhang (2018); Esiyok et al. (2017); Alcala et al. (2018); Gong et al. (2016); Gong and Du (2018); Nie et al. (2016); Németh et al. (2018); Shum et al. (2015); Zhang et al. (2018); Guo et al. (2018); Letter and Elefteriadou (2017); Tilg et al. (2018); Ge et al. (2018); Nguyen et al. (2018); Beregi et al. (2018); Müller et al. (2016); Wang et al. (2015); Marcano et al. (2018); Hegedüs et al. (2017); Zhong et al. (2017); Galluppi et al. (2017); Das et al. (2017); Wang et al. (2019a); González et al. (2017); Moreau et al. (2017); Freitas et al. (2018); Bichiou and Rakha (2019); K. Chu et al. (2015); He et al. (2015); Li et al. (2015); Liu et al. (2019); Boukhari et al. (2019); Wiseman and Grinberg (2016); Irani et al. (2018); Chen et al. (2017b); Rosolia et al. (2017); Kim et al. (2017b); Du et al. (2016); Perumal et al. (2016); Guo et al. (2016); Zhou et al. (2017); Huang et al. (2017); Weiskircher et al. (2017); Lee et al. (2015a); Cao et al. (2015); Funke and Gerdes (2016); Li et al. (2017, 2016)

- **Category 3: Design**

  Guang et al. (2018); Cheong and Lee (2018); Debernard et al. (2016); Ge et al. (2018); Coutinho et al. (2018); Feng et al. (2018)

- **Category 4: Projects and Prototypes**

  Freedman et al. (2018); Shladover (2018)

- **Category 5: Economic Analysis**

  Daziano et al. (2017); Masoud and Jayakrishnan (2017); Freedman et al. (2018); Harper et al. (2016b); Bösch et al. (2018); Clements and Kockelman (2017); Wadud (2017); Krueger et al. (2016); Fagnant and Kockelman (2015); Harper et al. (2018); Gawron et al. (2018)

- **Category 6: Environmental Impact**

  Igliński and Babiak (2017); Wang et al. (2018a); Ross and Guhathakurta (2017); Moriarty and Wang (2017); Wadud et al. (2016); Milakis et al. (2018); Fox-Penner et al. (2018); Gružauskas et al. (2018); Li et al. (2015); Marletto (2019); Harper et al. (2018); Gawron et al. (2018); Duarte and Ratti (2018)

- **Category 7: Law and Regulation**

  Favarò et al. (2018); Bruyne and Werbrouck (2018); Gružauskas et al. (2018); Mackie (2018)

- **Category 8: Transportation and Logistics**

  Sun et al. (2018); Levin et al. (2017); Pudāne et al. (2018); Hörl (2017); Liang et al. (2017); Zhang et al. (2017); Igliński and Babiak (2017); Gurumurthy and Kockelman (2018); Martinez and Viegas (2017); Vine et al. (2016); Wang et al. (2018a); Dia and Javanshour (2017); Bischoff and Maciejewski (2016a); Ross and Guhathakurta (2017); Cohen and Hopkins (2019); Freedman et al. (2018); Meyer et al. (2017); Buehler (2018); Levin (2017); Moriarty and Wang (2017); Ma et al. (2017); Walker and Marchau (2017); Hyland and Mahmassani (2018); Lokhandwala and Cai (2018); Fagnant and Kockelman (2018); Yi et al. (2018); Harper et al. (2016a); Scheltes and de Almeida Correia (2017); Kümmel et al. (2017); Wadud (2017); Farhan and Chen (2018); Milakis et al. (2018); Beirigo et al. (2018); Shen et al. (2018); Fox-Penner et al. (2018); Gružauskas et al. (2018); Puylaert et al. (2018); Ye and Yamamoto (2018); Iacobucci et al. (2018); Chen et al. (2016); Zhao et al. (2018); Chen et al. (2017c); Liang et al. (2016); Winter et al. (2018); Heilig et al. (2017); Krueger et al. (2016); Yap et al. (2016); Nasri et al. (2018); Rossi et al. (2018); Boysen et al. (2018); Cyganski et al. (2018); Bischoff and Maciejewski (2016b); Roy and de Koster (2018); A.Hensher (2018); Conceição et al. (2017); Babicheva et al. (2018); Chen et al. (2017a); Liu et al. (2017a); Loeb et al. (2018); Cantarella and Febbraro (2017); Yap et al. (2015); Calvert et al. (2017); Vitello et al. (2017); Zhao and Kockelman (2018); Levin and Boyles (2015); Lu et al. (2018a); Sherif et al. (2017); Duarte and Ratti (2018); Olia et al. (2018)

- **Category 9: General Introduction**

  Shladover (2018)

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