Review

Small Unmanned Surface Vessels—A Review and Critical Analysis of Relations to Safety and Safety Assurance of Larger Autonomous Ships

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Abstract: Autonomous ships represent an emerging paradigm within the maritime sector, poised to bring multiple advantages. Although numerous prototypes have been developed, the deployment of large autonomous ships has predominantly remained confined to domestic waters or specialized military applications. The extensive adoption of autonomous ships is hampered by several challenges, primarily centered around safety. However, the direct assessment of autonomous technologies on large-scale vessels can be very costly. Small-scale autonomy testing may provide a cheaper option. This study reviews the current small autonomous ship models used by maritime researchers and industry practitioners. It aims to evaluate how these autonomous models currently augment and can augment safety assurances on larger autonomous ships. The review identifies relevant very small Unmanned Surface Vessels (USVs), the main research groups behind them and their applications. Then, the current use of USVs for safety and safety assurance is analyzed. Finally, the paper suggests innovative strategies and research directions for using USVs for the safety assurance of larger autonomous ships.

Keywords: unmanned surface vessels; bibliometric analysis; systematic review; applications; safety; cybersecurity

1. Introduction

Autonomous ships are on the horizon [1], with numerous prototypes emerging in the maritime industry, showcasing a range of autonomous and remote-control capabilities [2–8]. These vessels are poised to enhance safety by reducing crew exposure to hazards [9] and reducing the likelihood of human errors in certain accident scenarios [10]. Additionally, they contribute to environmental sustainability by optimizing cargo and space allocation [11] and leveraging digital technologies necessary for energy efficiency, while also promoting gender equality [12]. The deployment of autonomous ships in the Arctic region holds the promise of improving operational efficiency and safety [13,14].

Nonetheless, autonomous ships adoption is slow, which is primarily attributed to a multitude of challenges, including regulatory hurdles, safety concerns, security issues, and cybersecurity threats [7,8,15]. Among these challenges, ensuring the reliability of collision avoidance systems stands out [16–19] since this is a key enabling system that must be rendered safe for the successful implementation of autonomous ships. Testing collision avoidance and the associated situational awareness systems presents its own set of difficulties, given that full-scale systems are inherently costly and the testing process can prove to be intractable [16,20,21]. Moreover, sea and shop trials typically occur during

the later stages of design, which can significantly increase the expenses associated with detecting and rectifying errors, as well [22].

In this regard, simulation-based approaches offer a promising way to expedite the verification process and the development of safety processes [20,21,23]. However, it is important to acknowledge that simulation-based methods have their limitations, as they rely on approximations of real-world environments and natural phenomena [24].

Alternatively, ship models can be leveraged to advance the development and testing of such technologies. The use of ship models for ship design, hydrodynamic analysis and ice resistance calculations has taken place since the late 19th century, with pioneering works by W. Froude, Kashteljan and others [25,26]. At present, the Energy Efficiency Design Index [27], hull performance calculations [28], ice-breaking [29,30] and ice resistance [31] calculations heavily rely on towing tank tests of small, geometrically identical models. Hence, it is worth investigating whether autonomous ship models can be employed to support safety cases for their full-scale counterparts.

Small Unmanned Surface Vessels (USVs) have found utility in a variety of applications, including in the development and validation of prototype control algorithms under typical operational conditions across various ship design phases [32–36]. They have also been employed in ice-covered environments [37], aiding in the enhancement of positioning algorithms [38,39], identifying ship hull parameters [40,41], testing ship collision avoidance scenarios [42], tracking fish [43], and facilitating operations near the shoreline [44,45]. Furthermore, ship models have been integrated into the assessment of the performance of multiple vessels operating in tandem, under both normal and abnormal conditions, to substantiate safety claims at full scale [46].

Previous reviews on USV applications have been documented in [47–52], with some references to safety and security applications. It is essential to note that these studies can be largely considered outdated, as they were published over a decade ago. A more recent review on USVs' state of the art systems, guidance, navigation and control techniques can be found in [53]. Yet, the safety and cybersecurity implications and applications were omitted from this study. Similarly a recently published review identified the key technologies in USVs, omitting to a large extent the safety and cybersecurity considerations [54]. In [55], 60 USVs of various size were identified to support the development of classifications of autonomy degree. The applications of USVs for disaster relief were reviewed in [56]. A recent comprehensive exploration of potential applications for USVs was presented in [57]. This review, conducted through a systematic and bibliometric literature analysis, incorporated a broad spectrum of applications, spanning from military to civilian domains. It also offered valuable recommendations for expanding the utilization of USVs, thereby contributing to their broader adoption and impact. Yet, it did not include specifics about their applications, architecture, equipment used or more detailed discussions on how they can contribute to safety.

So, notably, while small USVs have demonstrated their versatility in these domains, there remains a research gap concerning a detailed review of their architecture, use and potential contribution to safety and cybersecurity assurance. This paper endeavors to address this existing gap by comprehensively examining what small USVs are available, who are the researchers working on the small USVs, how the small USVs are currently utilized, especially in connection to safety, and how small USVs could theoretically contribute to maritime safety and cybersecurity assurance.

The primary scope of this investigation is directed towards civil applications, with a deliberate exclusion of military applications, considering the high sensitivity surrounding the topic. It is acknowledged that interested parties can readily access relevant information elsewhere [47–50,53,57–61]. Furthermore, the analysis within this study is specifically oriented towards very small USVs with an approximate displacement range of up to 100 kg, considering the logarithmic scale for USV classification in [49]. These very small USVs are analyzed in terms of their particulars, authors and authors' cooperation networks, utility and prospective contributions to safety and whenever applications can be found,

and also in relation to cybersecurity. It is worth noting that such USVs can be more easily operated by one or a maximum of four individuals, have substantially lower costs, and can concurrently serve educational and small-scale research objectives. In this way, the research findings can be of greater value to researchers who have limited budget and support. In the context of this paper, the term "USVs" encompasses both remotely controlled small vessels and those equipped with advanced autonomous capabilities [48]. Additionally, as most publications fail to disclose the cost associated with these USVs, cost information is not included in this review, but a lack of this information does not constitute a criterion for exclusion. Only the references that lacked substantial information, i.e., those related to the main particulars, were excluded. Also, publications from various sources were embraced, spanning from 2000 to 2023, not concentrating on Web of Science- or Scopus-related publications to incorporate to a greater extent perspectives from industry and researchers from poorer countries. It seems that this consideration serves the aim of the publication (finding the small USVs' current utilization) much better. Those studies which used simulations and not real USVs for algorithms verification and validation were excluded as well, as they do not demonstrate a practical exploitation of the very small USVs.

The contribution of the article stems from answering three research questions (RQs): (1) What very small nonmilitary USVs can be identified from the literature, what are their main particulars and characteristics and who are the leading research groups working on them? (2) How have very small USVs been used? and in particular (3) How have they been used in the context of safety and cybersecurity assurance? Additionally, research directions for how to more effectively use the small USVs in the context of the safety and safety assurance of larger autonomous ships are proposed.

2. Methodological Approach

The methodological approach employed includes several sequential steps. First, it centers on identifying small USVs and their particulars and the relevant research groups (step 1), and subsequently delves into comprehending their current utilization based on pertinent data obtained from identified sources (step 2). Following this, the analysis investigates how the current fleet of small USVs is used for safety assurance and safety-related purposes (step 3). Finally, the study incorporates pre-existing safety and cybersecurity issues associated with autonomous shipping from the known review studies to enhance the identification of directions for potential future research concerning ship model applications in the context of safety and cybersecurity assurance. A visual representation of these methodological steps is provided in Figure 1.

The process of identifying small USVs relevant to the present study started with an analysis of the references provided in the prior review studies [47–50,53–55,57]. Subsequently, this list was expanded through targeted keyword searches on Google Scholar using keywords such as "small USVs in the maritime", taking as input the first 50 responses from Google Scholar. Responses from OpenAI 3.5 regarding known USVs contributed to this list ("Can you refer to small USVs examples?") [62]. To maintain alignment with the PRISMA methodology [63], references lacking adequate information or falling outside the predetermined scope of the present analysis were systematically eliminated, specifically focusing on small USVs for civil applications with displacement ranging approximately up to 100 kg. Also, references in languages other than English were excluded.

Bibliometric analysis tools such as VOS viewer 1.6.18 [64] were used to identify the leading authors in the area based on the full-counting method, which determines the strength of the link among the authors based on the number of joint publications. Metrics calculated using MS Excel were used to identify the most popular hull forms, hardware and software used in very small USVs, as well as countries associated with USV designers. For the countries' metrics, in the case of multiple countries and authors, the first affiliation of the first author was used. As is demonstrated in the subsequent sections, such knowledge

of authors and the USVs characteristics is important when discussing the use of small USVs for safety and cybersecurity assurance.
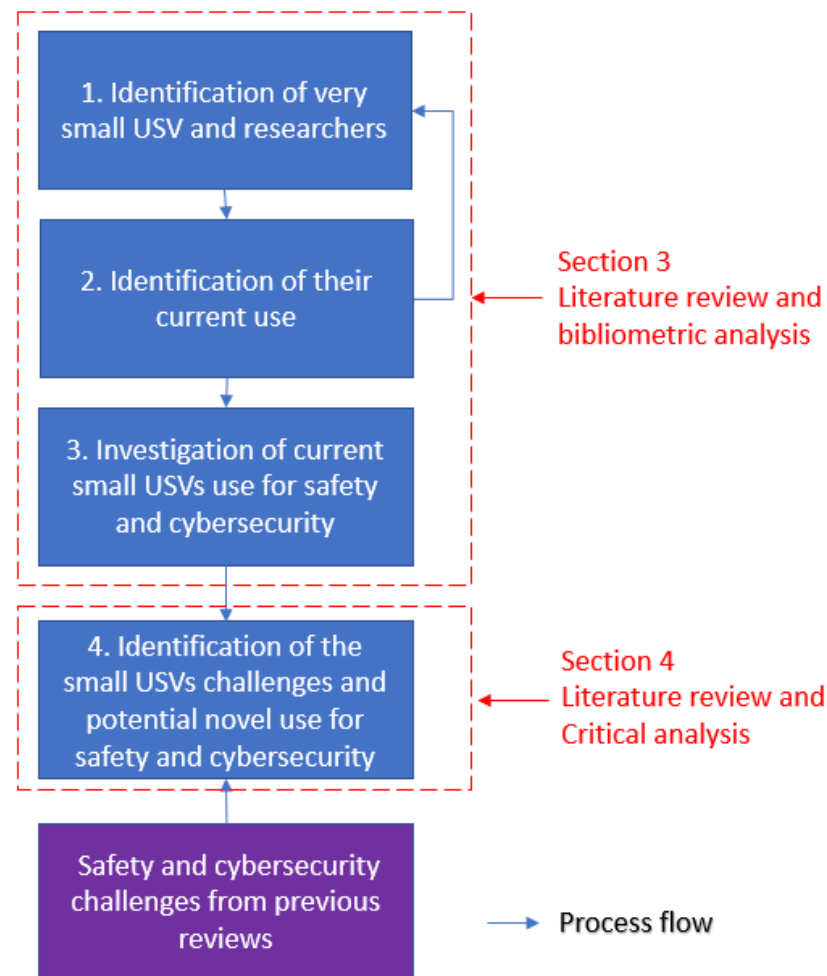

Figure 1. The methodological approach.

Following this, a second search was conducted, targeting leading authors of the USV-related publications from step 1, such as professors and permanent staff, by checking their profile publications on Google scholar and their research publications citing the original study, presenting the USVs already included in step 1. This secondary search aimed to deepen the understanding of the current utilization of the identified USVs. Also, this search contributed to the identification of additional relevant USVs, which is why a feedback loop from step 2 to step 1 in Figure 1 is provided. The generated database was then exploited to determine the current use of small USVs with greater rigor. To support the analysis, the terms map of the VOSviewer was exploited [64]. Furthermore, the references were systematically analyzed to identify their applications, as well as applications in ice-covered areas, and relevant metrics estimated using MS Excel.

During the third step using the identified USVs database, the ways that small USVs' use is currently linked to safety and cybersecurity were investigated in greater depth. To that end, the previously identified authors networks and terms-map-based analysis were employed. Keywords related to safety were searched along the identified USV-related publications' titles and abstracts, and relevant metrics were estimated using MS Excel. Based on the identified results, conclusions on the current link between safety and small USVs were derived.

It is worth noting that comprehensive reviews of safety and cybersecurity challenges pertaining to autonomous ships and underpinning the critical analysis step have been thoroughly covered in several earlier studies, as exemplified by references [1,7,8,15,65]. To maintain brevity and prevent redundancy with existing publications, we refrained from presenting this background information in the article itself. Instead, this foundational knowledge was directly incorporated into this analytical process. Interested readers can direct themselves to those articles.

Building upon this initial groundwork, including the identified USVs, their characteristics and use, authors' networks and ideas regarding how small USVs can contribute to ensuring safety and bolstering cybersecurity in the realm of autonomous shipping were explored, which is one of the critical contributions of this research article.

3. Results

3.1. RQ1: Related Very Small USVs and Leading Research Groups

In the preceding decades, numerous USVs have been developed. USVs with dimensions significantly exceeding those set in the scope (significantly more than 100 kg displacement), as in references [5,40,66–101], were excluded from this analysis (38+, and also many of the USVs referenced in [47–50,53–55,57]). Furthermore, this review did not include the USVs lacking sufficient specific information, such as those referenced in [44,102–111] and many other references (11+ in total). The security applications of USVs, as in [112–116] (5+), among many others uncited in this work, were also disregarded. A few references were inaccessible [117–119] (three in total), and thus not incorporated. The selected very small USVs and their primary characteristics and uses are detailed in the table in Appendix A (84 in total, with the last update day 30 September 2023), whilst the main highlights about the USVs and the leading researchers are provided in this section. The modest rate of inclusion can be ascribed to the relatively constrained emphasis placed by the researchers on the development of very small USVs (up to 100 kg) and the subsequent dissemination of associated research findings.

It can be argued that the database used, despite its limited scope, is of equal quality if not superior to that provided in other review studies. The analysis in [57] (involving 245 research studies) included review studies, military applications, studies with insufficient material and simulation studies, even datasets, which were excluded from the present analysis. Several of these studies (245) referred to the same vessel multiple times, as well, so in this way there were redundant applications in the present review (not counted multiple times but still included for other bibliometric analyses). Furthermore, the developed database also contained references from other reviews, which were not included in [57]. Moreover, this review encompassed 26 small USVs (Figure 2) and related research published starting from 2021, which was not included in [57]. So, this number of investigated small USVs (84) surpasses the quantity of small USVs examined in [57] and is also larger than in [55], despite focusing exclusively on very small USVs. This is attributable to the current review's more contemporary nature, its reliance on previous reviews and the implementation of some quality checks.

A substantial number of small USVs has been developed and made publicly accessible through publications originating primarily from the United States, China, South Korea, Portugal, Italy and The Netherlands (Figure 3). These countries alone contributed to 50 out of 84 identified small USVs (60%), albeit with USVs from a total of 28 countries being included in Appendix A. Among the research institutions, it is noteworthy that TuDelft from The Netherlands, KAIST from South Korea, and the University of Porto in Portugal have designed the highest single number of identified very small USVs.
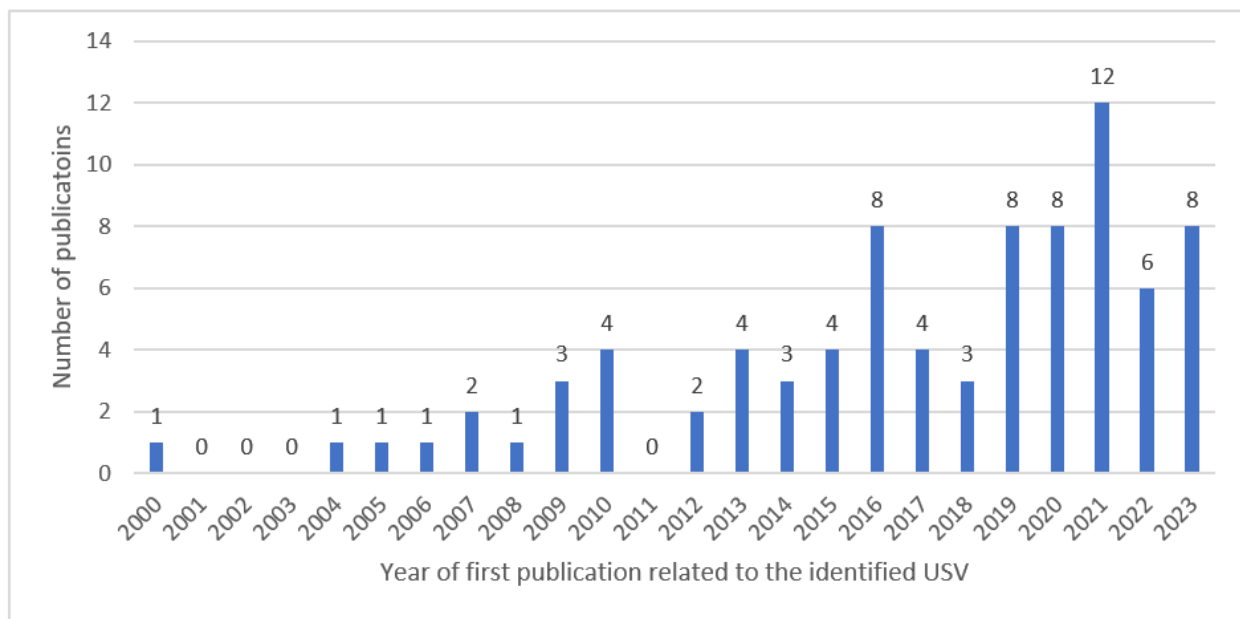
Figure 2. The small USVs included based on the first year of appearance in publications/references (including those published by 30 September 2023).
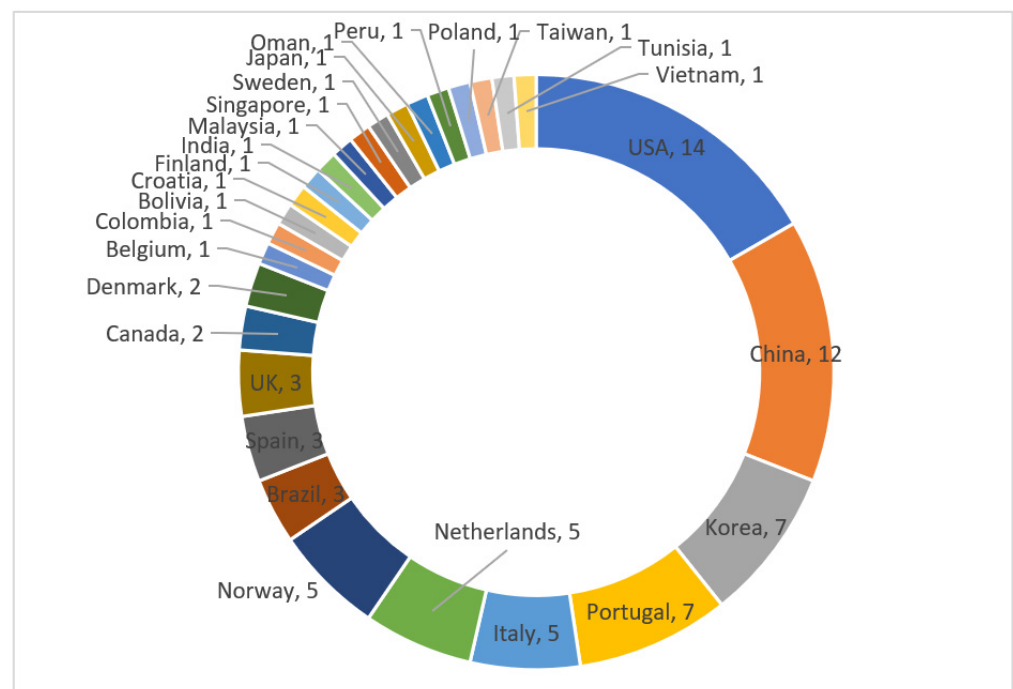
Figure 3. Identified very small USV number per country.

Almost half (41/85) of the USVs were catamarans or trimarans (Figure 4). Podded azimuth propulsors were reported to be in use several times, while others indicated the use of propellers and rudders. It is important to note that a subset of these USVs did not provide any information on propulsors, so this information type suffers from uncertainty. None of the very small USVs were engine powered, and they either had a battery pack or relied on solar panels and wave energy.

Figure 4. The most frequently employed hull types in very small USVs.

In terms of navigational systems, a vast majority of these models heavily relied on the Global Navigation Satellite System (GNSS) (in 83% of the cases) for the positioning and speed measurement. Additionally, many models employed an Inertial Measurement Unit (IMU) (44%), al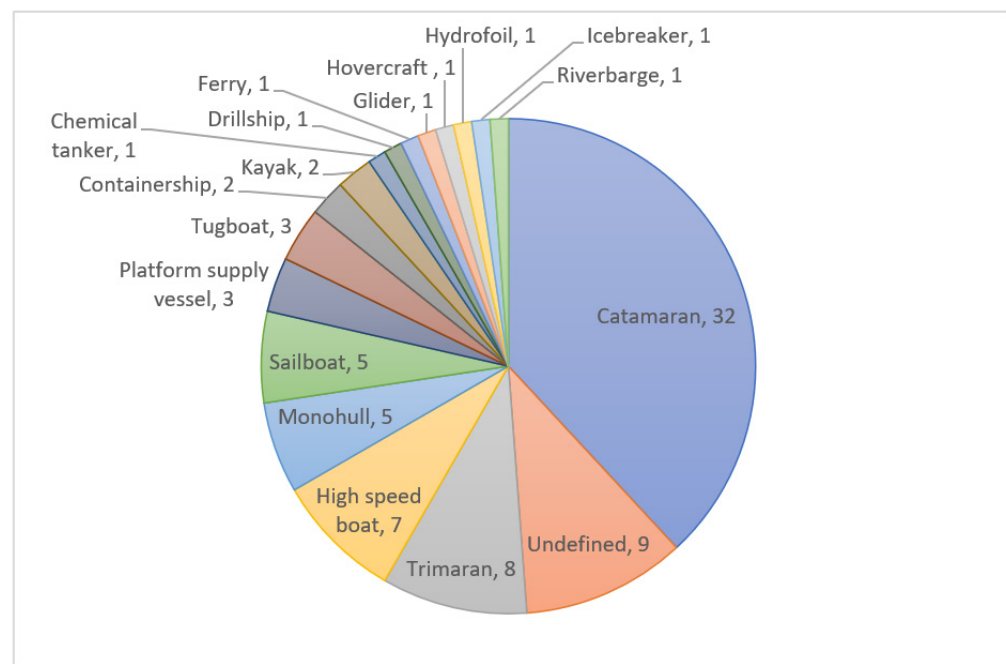though gyros and compasses were also commonly employed (22%). Furthermore, for the positioning and speed estimation and also object detection, laser scanners (i.e., LiDARs) (17%) and various types of camera (32%) were commonly cited components in these applications, although some references to the use of AIS (Automatic Identification System) (2%) were also made.

Based on the available but limited data, it is evident that among the software libraries and middleware, the Robot Operating System (ROS) variants emerge as the most popular choice (20% of all USVs), especially in the latest USVs. This middleware is followed by LabVIEW (7%) and by ArduPilot (4%). Within the ROS framework, C++ serves as the predominant programming language (7%), with a smaller number of USVs specifying the use of Python (5%) and JAVA (2%). The use of various Raspberry Pi hardware solutions was reported in 13% of the cases. However, it can be assumed that the use of ROS, Labview, ArduPilot, C++, Python and Raspberry Pi was more frequent, since not all the USVs included the complete hardware and software information.

The bibliometric analysis of the authors' network implemented using VOSviewer and the full counting method (which emphasizes the strength of links based on the number of joint publications) for the 183 references from Appendix A is provided in Figure 5. The letters' size and the radius of the bubbles are proportional to the number of documents published by the various authors, whilst the colors correlate with the year of publication.

The largest group in the network is the one connecting Brazil, with leading author Dr. Mathaus Ferreira da Silva, and Portugal, with leading authors Prof Nuno Cruz and Prof José Carlos Alves, both from the University of Porto. Other notable groups of researchers with active publishing on small USVs include groups from Italy, with Dr. Angelo Odetti and Mr. Gabriele Bruzzone among the leading authors, the group with prominent author Prof Jorge Cabrera Gamez from IUSIANI in Spain, the group with Dr. Donghoon Kim and Prof Myung Hyun from KAIST in South Korea, the group from Norway with leading author Prof Fossen from NTNU, Mr. Antonio Vasilijevic from Croatia (University of

Zagreb) and the group from The Netherlands with leading author Prof. Rudy Negenborn from TuDelft.
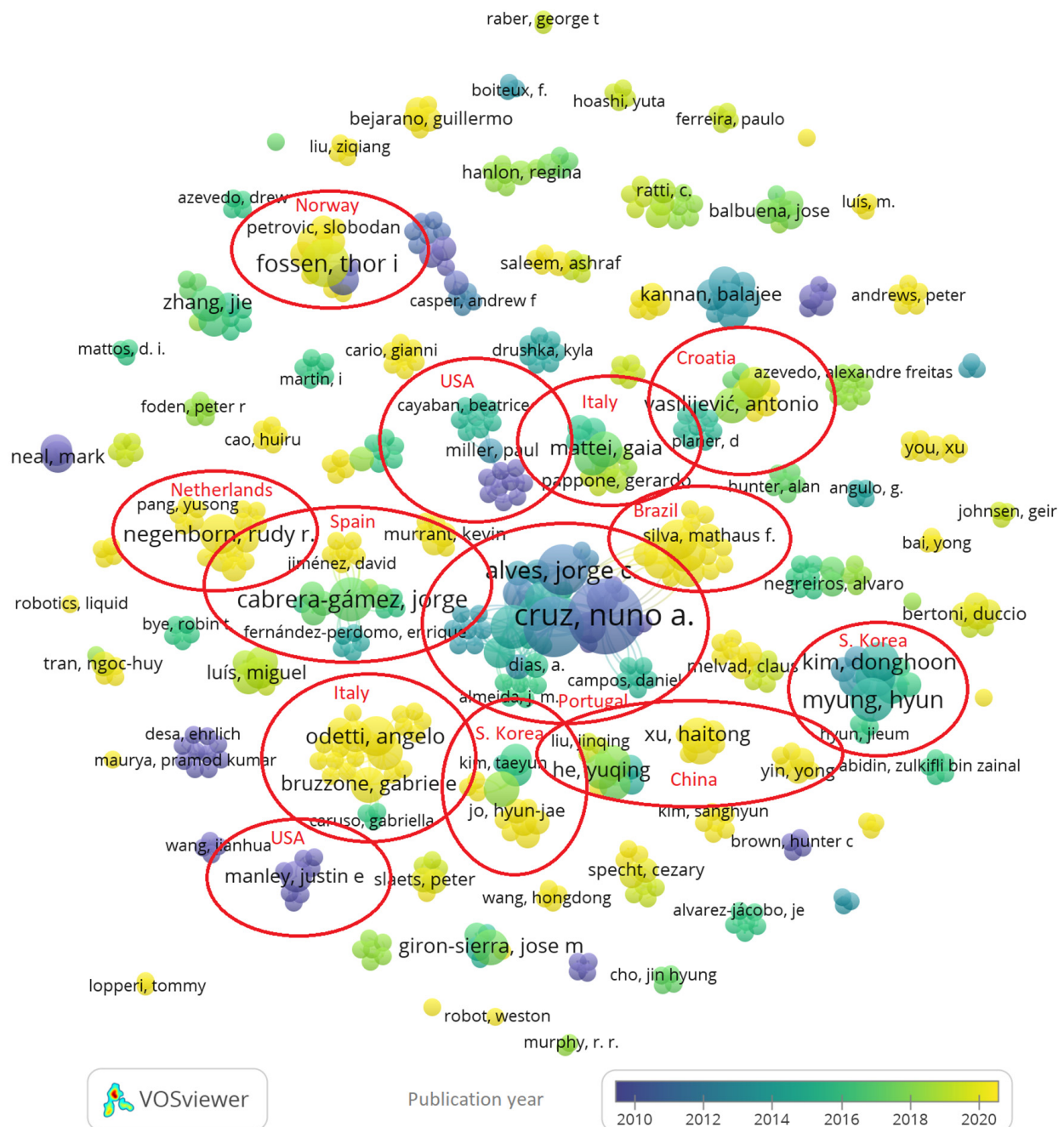
Figure 5. Investigated authors co-authorship network using full-counting method.

These identified groups correlate well with the leading countries of Figure 3, albeit there are some notable differences. For instance, the research on small USVs in the USA seems to be scattered among different organizations with no large interconnected group of researchers or persistent publications in the area. This finding is similar to the one presented in a bibliometric analysis on maritime cybersecurity [15]. Similarly in China there seems to be several different groups of researchers working on small USVs mostly independently from each other and located in Wuhan University of Technology, Northwestern Polytechnical University and Dalian Maritime University. Similar observations can be

made about the South Korea and Italy, where multiple disconnected (based on publications) research groups are present.

As it can be also observed, the research groups were largely detached from each other, but this was also anticipated from other reviews [15,120]. This is also in line with Figure 3, where it was found that authors stem from 28 different countries, so it is expected that the co-authorship network will be largely distributed in small "islands".

3.2. RQ2: Very Small USV Identified Use

A term map analysis was conducted using VOSviewer, based on the information available in the titles and abstracts of the 183 papers provided in Appendix A. In developing this map, a binary counting method was employed. In binary counting method, the occurrences emphasize the number of documents that a term appears. So, the larger the occurrences number in the documents, the larger the radius of the circle associated with the term. Lines are used to connect the terms that frequently appear together. The different colors are used to characterize the cluster of terms that frequently appear together.

Only terms that occurred at least three times were included. General terms such as "methodology", "water", "technology" were intentionally excluded from the map, as they do not contribute to the analysis purpose. Additionally, the term "USV" and relevant terms were excluded from the analysis, as the focus was on identifying other relevant terms, given that the frequent appearance of "USV" and its synonyms was expected. In this fashion more than 200 frequently appearing general terms were eliminated or merged during the preparation for terms analysis.

Finally, during the terms analysis, only the 95% most relevant terms were used, with relevance score calculated by VOSviewer. The terms were clustered in various groups using the default VOSviewer settings.

Out of 4115 terms present in the titles and the abstracts, only 148 met the set criteria and the results are presented in Figure 6. As it can be observed, the terms such as "algorithm", "path", "controller", "collision avoidance", "sensors" are the most frequently occurring terms in the database. Notably, sensors employed in USVs are also observant on the map or in the 148 selected keywords ("camera", "LiDAR", "GPS", "magnetometer", "multibeam sonars", "IMU"). Furthermore, the terms related to the operational environments such "lake", "river", "sea", "glaciers", "shallow waters", "port" and commonly used hull forms such as "catamaran" and "sailboat" appear throughout the term analysis.

Relevant terms within the context of USV applications encompass a wide array of functions and technologies. These terms shed light on how small USVs are utilized. Examples of specific applications and functions include "bathymetry", "detection", "mapping", "survey", "water quality monitoring", "temperature", "monitoring", "inspection", "safe and rescue", "robotic tool", "remote area" and "jellyfish removal". These illustrate some of the diverse roles that small USVs have played.

In addition to application-specific terms, the map includes technical terminology required for autonomous or remote operations. Terms like "collision avoidance", "communication", "autonomous navigation", "control system", "robustness", "identification", "localization", "autopilot", "estimation", "identification", "docking", "dimensional reconstruction", "leader" and various control techniques like "model predictive control (MPC)" and "Proportional-Integral-Derivative (PID)" are present. This is unsurprising as these technical aspects' achievements are fundamental prerequisites for the effective operation of USVs.

The bibliometric analysis using VOSviewer provided only a limited spectrum of answers. To gain a more systematic understanding of USVs use, the research and application types for each of the USVs were identified and presented in Appendix A. In Figure 7, the statistical analysis of these application types is presented with data aggregated manually. It is worth noting that some USVs had multiple roles and utilizations, leading to their inclusion in multiple categories. Therefore, the percentages in Figure 7 do not add up to 100%.
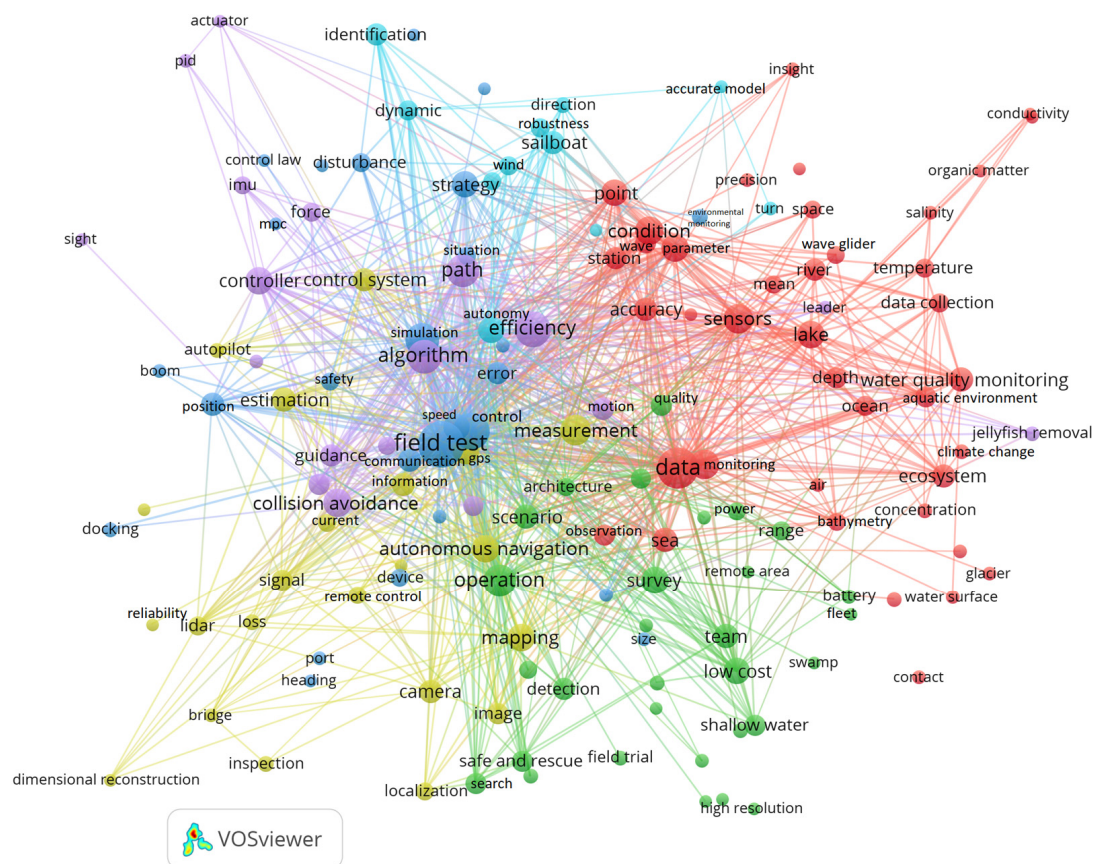
Figure 6. The terms map generated using title and abstract information.
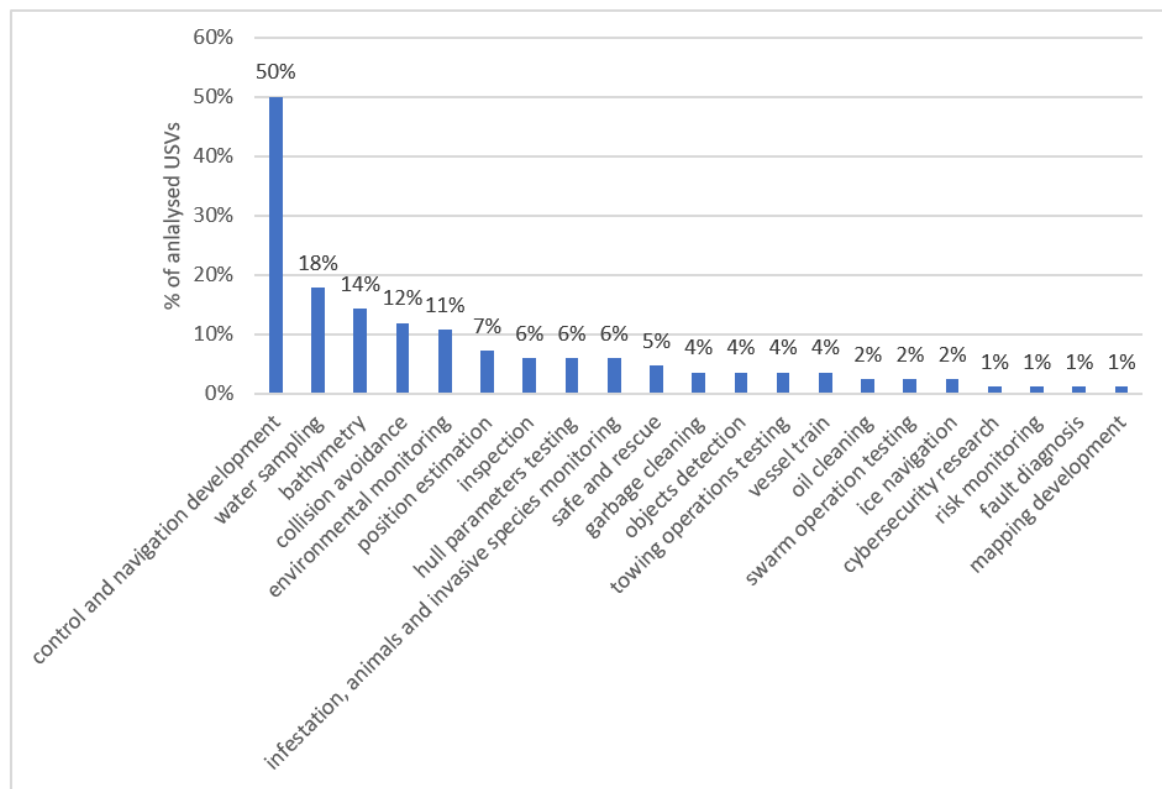

Figure 7. Exploitation of identified small USVs per category.

Figure 7 reveals that half of the vessels were primarily employed for the development and testing of novel control techniques or autonomous navigational algorithms. Approximately 18% of small USVs were developed for the purpose of water sampling in lakes, rivers and coastal areas. Another 14% of small USVs were used for bathymetry, while 12% were used for collision avoidance testing. About 11% served for weather and environmental monitoring, excluding water sampling. Additionally, a smaller percentage of USVs were involved in testing novel positioning algorithms, inspecting bridges and other structures, testing hull parameters in the replication of self-propulsion model tests, monitoring animals and invasive species and engaging in search and rescue operations (ranging from 5% to 10% of the investigated USVs in each type of operation).

Furthermore, a few analyzed USVs were deployed in activities like floating garbage cleaning, the development of datasets for object detection training, in testing towing operations and experimenting with the vessel train concept, where a fleet of small USVs was following the leading USV (each accounting for 4% of the investigated USVs). Occasionally, small USVs were used as platforms for developing solutions related to oil spill cleaning, testing swarm operations, or in assessing autonomous navigation in icy conditions. A very limited number of small USVs were utilized for purposes such as cybersecurity research, testing novel risk monitoring algorithms, diagnosing faults, and mapping local areas.

It is important to note that not all of the identified USVs were utilized for subsequent research and development purposes. As illustrated in Figure 8, 59 of the USVs found (70%) were mentioned in just one research paper or website. On the other hand, there was one USV, the WaveGlider, which was extensively used and mentioned in eight papers/references. This discrepancy can be attributed to several factors. It might be due to the limited scope of the present database. It could also reflect the fact that many small USVs were purpose-built as dedicated application platforms, with their primary role implementing a function they were designed for, rather than serving as subjects of extensive research and development.
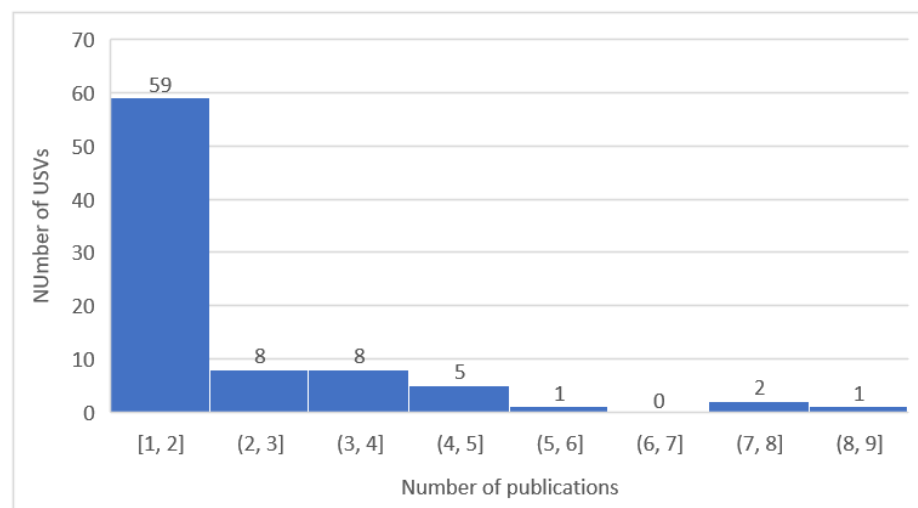
Figure 8. Distribution of the number of publications associated with each USV.

It is worth noting that only a few of the identified USVs, specifically those described in references [37,84,101,103,121–124], showcased advanced navigation capabilities in challenging sea-ice-covered environments. However, it is important to acknowledge that some of these USVs may have dimensions that differ from the specific criteria set for the present study (100 kg of displacement), which is why they were not fully analyzed in the database.

3.3. RQ3: The Current Use of Very Small USVs for Safety and Cybersecurity Assurance

Figure 5's network of authors shows little correlation with the author networks in Figure 7 from [7] and Figure 6 from [15], which focus on autonomous ship safety and maritime cybersecurity, respectively, although some of the researchers are present in at least two out of three. This discrepancy can be attributed to the distinct nature of these domains, each requiring unique skills, research backgrounds and expertise. It is challenging for leading experts to actively engage in research across all three areas simultaneously. This discrepancy highlights the potential lack of significant interconnections between current research on small USVs and safety and cybersecurity.

A deeper bibliometric analysis reveals that terms related to safety presence are not negligible. Keywords such as "safe and rescue," "reliability," and "safety" rank among the top 148 keywords according to VOSviewer analysis, appearing in 13% of selected publication titles and abstracts. Terms like "rescue" appear in 7% of references titles and abstracts, "risk" in 4% and "reliability" in 2%. Keywords like "cybersecurity" and "hazard" appear in only 1% of titles and abstracts. In total, 22% of the 183 publications titles and abstracts refer to safety and cybersecurity, indicating that while safety and reliability considerations are not completely overlooked in the small USVs domain, their presence is relatively limited, especially in the case of cybersecurity.

A more systematic analysis reveals that the primary safety-related applications of USVs lie in search (safety) and rescue operations [45,125–133], as already pointed out in Section 3.2. Additionally, USVs have been proposed for enhancing safety in various hazardous environments, such as water sampling near glaciers [122,123,134], remote regions [121], areas with wrecks [131] and for safeguarding against environmental threats like cyanobacteria blooms and invasive species [135–137]. Small USVs are also employed to identify navigational hazards on river, lake, canal, and sea floors [138,139] and to address oil spill incidents [140,141]. They support safety-related inspections [142], as well.

USVs are also leveraged for enhancing safety in various autonomous operations including tug operations [143,144], docking operations [34,39,145], collision avoidance [32,146] and in the improvement of safety in path following and navigational algorithms [32,142,147–152]. Furthermore, USVs are employed to develop risk-aware algorithms for decision-making based on risk [153,154], to ensure the general safety of USVs [155,156] and to develop fault tolerance based applications [45].

Conversely, the utilization of very small USVs in cybersecurity research is quite limited. Only a few instances were found, such as a practical demonstration of hijacking attacks in [157] and the development of ROS-based solutions against transmission cyber-attacks in [158]. This scarcity can be attributed to the emerging nature of the maritime cybersecurity domain and the challenges in scaling up results from small to larger USVs due to the differences in hardware/software (Section 3.2).

In conclusion, the findings indicate that safety- and cybersecurity-related aspects have not been extensively explored within the realm of small USVs. Nonetheless, existing applications demonstrate the potential of USVs to improve operational safety by replacing human involvement in perilous situations, identifying safety-related objects, monitoring environmental safety, and mitigating the impacts of disasters. Moreover, USVs have made significant contributions to enhance the safety of navigation, autonomy, detection, positioning, control algorithms and overall USV safety.

4. Potential Directions for Future Research in USVs Related to Safety

In the next section, the discussion concentrates on potential research directions integrating very small USV use and safety/cybersecurity research. The identified directions are based on the findings related to RQ3 and also the directions for further safety/cybersecurity research in connection to the autonomous ships proposed in [7,8,15]. They are grouped under the categories related to the algorithms' verification (Section 4.1), sensors' verification (Section 4.2), hazard identification and risk assessment for larger autonomous ships (Section 4.3), safety assurances of communication systems and cybersecurity en-

hancement (Section 4.4) and extended applications of small USVs for accident mitigation (Section 4.5).

4.1. Very Small USVs for Safety Assurance of Control, Collision Avoidance and Navigation

Undoubtedly, ensuring the safety of autonomous navigation algorithms constitutes one of the greatest obstacles to a wider adoption of autonomous ships [7,8]. As was observed in Figure 7 and Section 3.3, small USVs are widely used for the development and testing of novel control techniques.

In this way, the results of the control techniques can be a useful way to verify the functionality of the collision avoidance techniques, algorithms or novel control techniques and augment the safety case for a control, navigation and collision avoidance algorithm. However, it is important to acknowledge that the direct extrapolation of these findings from small-scale models to larger vessels is not straightforward. Various factors, such as Reynolds, Cauchy, Froude and geometrical similitude, hull roughness effect, thrust, advance, cavitation and wake coefficients disparities between the autonomous model and autonomous ship wield a substantial influence on the type of resistance proportions and propulsion efficiency encountered by the actual ship in comparison to the small scaled model [28,30,159–162]. The development of collision avoidance algorithms and vessel train concepts is substantially influenced by collision similitude metrics based on Time to Closest Point of Approach (TCPA) and Distance to the Closest Point of Approach (DCPA) [46], which will require another type of scaling [46].

Consequently, these factors play a pivotal role in shaping the controller settings for speed, rudder, and path-following algorithms if extrapolated to larger vessels. This challenge becomes even more intricate if the controller incorporates machine learning-based control techniques, as the adjusting machine-learning controller might require better explainability between input and output relationships [163]. Some indications of this research being conducted can be found in [46,164], although fairly few details have been released. The careful consideration and investigation of these factors' impacts on scaling up could constitute an area of interesting research.

Scaling up operations to handle adverse weather conditions presents an additional challenge, given that many USV applications have been demonstrated in calm waters and favorable weather conditions (see Appendix A), with few notable exceptions, as in [39,165–167]. Nevertheless, it should be emphasized that autonomous navigation in adverse weather conditions is important in preventing potential accidents [9,168]. It is noteworthy that the formalization of this process for small USVs has not been observed in any of the examined publications, despite expressions of concern in [41].

Testing in adverse weather conditions will require wave generators in tanks, which will increase the cost of testing. Furthermore, the discrepancy in equipment type might result in the need for careful consideration for ensuring that similar GM is achieved in the small USV employed. The problem with stability due to uplifted camera, LiDAR or useful equipment is one of the reasons why so many small USVs were designed with a catamaran or trimaran hull, as observed in Section 3.2. So, this might yield another challenge to be addressed, but probably it will not be a critical one.

Control algorithms scaling up from small USVs to larger vessels present several additional challenges, notably due to the discrepancy in sensors and actuators' types and quality. It is imperative to account for the disparities in sensor types used on small USVs compared to those employed on actual ships, as was concluded in Section 3.2. This is since the performance of control algorithms can be significantly influenced by sensor quality and the resolution and dynamics of sensor/actuators. Furthermore, on small USVs, space limitations can potentially constrain sensor and actuator resolution, but not essentially. Moreover, small USVs might utilize lower-quality sensors and actuators compared to their larger ship counterparts. It is important to recognize that the dynamics of propulsors may diverge [169], as small USV actuators are generally electrically powered (Section 3.2), which

may not hold true for larger ships equipped with internal combustion engines or other propulsion systems.

In addition, the utilization of distinct software and hardware computational tools on ship models, such as ROS-based ones and LabVIEW (Section 3.3), compared to those deployed on actual ships, can introduce another factor that affects the accuracy and performance of control algorithms. Of course, this obstacle can be overcome, with large, unmanned ships running on ROS2, but this might be highly unlikely. So it might be difficult to implement the full software assurance just using USVs, and it will need to complement other state-of-the art approaches for software assurance such as testing for software in the loop, hardware in the loop, etc. [65].

To support safety assertions in collision avoidance, it is imperative to define a dedicated set of collision avoidance test scenarios, as emphasized in previous studies [7,20,24,170]. While COLREGs (International Regulations for Preventing Collisions at Sea) can serve as a foundational source, their application can be further enriched [24]. This is particularly relevant because, compared to larger ships, the cost of testing USVs is significantly reduced. To achieve this, the development of a fleet of USVs becomes essential, enabling the testing of USV interactions with various types of ships and objects, and thereby enhancing comprehensiveness [16,20,21,24,106]. Some indicative research has been demonstrated in [38,42,171]. Furthermore, the diverse roles and functions of USVs can also serve as valuable sources for generating collision avoidance scenarios for testing and validation [172]. This multifaceted approach ensures that collision avoidance algorithms and safety measures are thoroughly evaluated across a spectrum of realistic scenarios and operational contexts.

Research focused on small USVs encompasses very few instances where novel fault-tolerant control and fault-tolerant techniques are investigated and tested [45]. While it may not be possible to directly apply these techniques to larger USVs due to the differences in equipment, it is a useful approach to initially assess their efficacy on small USVs before considering their implementation on larger systems.

4.2. Very Small USVs for the Safety Assurance of Sensory Systems

As evident from the table provided in Appendix A and Section 3.2 results, a notable difference exists between the sensory systems employed by small USVs and those used on larger vessels. Small USVs predominantly rely on GNSS, LiDARs and, in specific cases, cameras for navigation, rarely using radar or AIS commonly present on ships [173]. Consequently, sensor fusion solutions developed for USVs that do not incorporate AIS and radar may not be directly transferrable to larger ships. However, it should be underscored that this is subject to the specifics of each individual case and can be investigated in future research.

It is worth noting that the performance requirements for GNSS on USVs are generally stricter or at least similar to those for typical vessels due to the USVs size. Thus, positioning algorithms that are proved successful through GNSS testing on small USVs can potentially be adopted for larger vessels, so USVs can potentially prove a valuable platform for GNSS novel algorithm development to be applied in larger ships.

Similarly, the effectiveness of positioning algorithms employing cameras or a combination of GNSSs and cameras can be validated on small USVs, as in [39]. This can constitute valuable evidence for implementing similar camera-based or other sensor-based positioning on larger vessels. However, it is important to recognize that the detection ranges of cameras or sensors used on small USVs may need to align with the scaled requirements for larger ships [174].

Nonetheless, small USVs, when equipped with appropriate cameras and sensory systems akin to those on larger autonomous ships, can serve as valuable platforms for aggregating the essential training data for object detection and recognition in a variety of operational environments. Examples of such development initiatives have been demon-

strated in [44,175–177]. This advancement is vital, as highlighted in [7,178], to address the evolving demands of autonomous navigation and safety.

4.3. Very Small USVs for Hazard Identification and Risk Assessment

The utilization of small USVs for risk identification, as observed in larger USVs [179], has not been widely reported or the reports are very scarce, at least based on the present survey (Section 3.3). This can be attributed to the relatively small scale of risks associated with small USVs, rendering the implementation of risk assessments less cost-effective and, in many cases, unnecessary, or making the publishing of relevant results uninviting. However, there have been reports on the testing of online risk monitoring algorithms in medium size USVs [153,180] or risk-aware control algorithms [154], which holds significance in the context of self-aware autonomous systems [7,181,182]. Pertinent real-time risk assessment algorithms can be preliminarily tested on small USVs before being considered for deployment on larger vessels or USVs, considering the scale factor's impact on maneuverability.

Furthermore, small USVs can be employed to assess safety performance in specific critical scenarios, as has been reported in [46], akin to what is implemented for larger USVs [183]. These data can contribute to the augmentation of the risk assessment framework for larger USV models, especially in navigation. However, it should be noted that it cannot entirely replace it due to disparities in equipment. The explanation is provided below.

The technical risk sources differ significantly between small and large USVs because of the substantial variations in equipment. Additionally, maintenance risks and management risks vary between these categories of USVs [184]. While the human–machine interaction risks on small USVs may share some similarities with those on larger ships, they will not be identical, primarily due to the aforementioned differences in equipment and operational context [183,185]. Consequently, the risk profiles for small and large USVs are distinct and need to be assessed separately.

However, the disparities in navigational hazards between small and large USVs are considerably reduced. In terms of navigational hazards, the deployment of small USVs equipped with automatic detection and recognition algorithms within the operational areas relevant to larger USVs could serve to identify these hazards and assess their frequency of occurrence. This approach allows small USVs to contribute to the refinement of risk assessments for larger USVs, ultimately reducing uncertainty and improving overall risk assessment quality, overcoming the limitations of AIS data [186] in a similar way as they currently do with the bathymetry data (Sections 3.2 and 3.3).

4.4. Very Small USVs for the Safety Assurance of Connectivity Systems and Cybersecurity

The majority of the reported USVs have been documented as using WiFi or radio communication systems for remote control, which can be very unsecure [187]. However, in some instances, there have been mentions of 3G/4G communication technologies. It is anticipated that 4G or even 5G will become prevalent in larger USVs in vicinity to the shore [188]. Potentially, it will become feasible to assess the reliability of these communication protocols (4G/5G) or even satellite communications on small USVs [189,190], allowing for the identification of issues that may also be relevant to larger USVs [56].

As has been demonstrated in Section 3.3, there have been very few publications focused on cybersecurity research in connection to the small USVs. Future applications could involve the testing of more advanced cybersecurity control measures, such as intrusion detection systems and novel cryptographic approaches, while continuing to evaluate the impact of cyberattacks on small USVs in accordance with findings from [15] or while investigating the impact of adversarial attacks [191]. The concepts and models developed for small USVs can be of practical benefit for larger USVs, even though the direct applicability may be impeded due to differences in equipment, associated vulnerabilities and software used.

4.5. Very Small USVs for Search and Rescue Disaster Relief Operations

Numerous small USVs have been reported for use in search and rescue operations, as well as in disaster relief efforts, as reported in Section 3.3 and other review studies [56]. While these small USVs may not be directly relevant in the context of safety assurances for autonomous ships, they represent a significant and noteworthy application. The use of rescue and other USVs holds potential in remote and dangerous areas, as they can offer a means of assisting in emergencies and improving response speed in areas such as the Arctic [192] or can replace humans, thus reducing the risks [9].

5. Study Limitations

This article predominantly centers on very small USVs. This choice was made considering that small USVs are often more accessible and cost-effective for educational and research purposes. While extending the research to larger USVs might yield additional insights, it is worth noting that some of the findings presented in this review are likely to be applicable to larger USV types, as well. It is anticipated that the scaling of results from larger USVs to their relevant autonomous counterparts might be easier due to the reduced impact of scale factors.

It is important to recognize that one of the limitations of this study is the exclusion of security and military applications of small USVs. This exclusion may have led to a restricted identification of relevant cybersecurity studies. Consequently, the conclusions drawn from this study with respect to cybersecurity are primarily relevant to civil applications and should be treated with caution.

Furthermore, since the present analysis primarily focused on safety-related aspects and research-oriented publications, it has a limited incorporation of industrial perspectives. This limitation was partially mitigated through Google and OpenAI searches, but most of the examined applications still revolve around academic publications.

6. Conclusions

In this article, the investigation has centered around exploring how very small USVs can contribute to enhancing safety and cybersecurity assurance in civil applications. This exploration was conducted through a comprehensive literature review, bibliometric analysis and investigation of aspects associated with the safety and cybersecurity of autonomous ships.

The primary findings of this study are as follows:

- Significant ongoing research into very small USVs (those with a displacement of less than 100 kg) is taking place in countries such as the USA, China, South Korea, Portugal, Italy and The Netherlands.
- Catamaran and trimaran hulls have gained popularity among the very small USV applications.
- GNSS-based navigation seems to be the predominant option for the positioning of very small USVs, although cameras and LiDARs are also used.
- Small USVs use has been largely confined to the development of navigation and control techniques. However, other applications include water sampling and analysis, bathymetry use and the testing of collision avoidance techniques and environmental monitoring.
- The research on very small USVs seems somewhat detached from research on safety and cybersecurity assurance, with no leading experts overlapping with the two areas, although there are indications of connections between these areas.
- Very small USVs offer a valuable platform for testing and demonstrating the safety and reliability of various algorithms, including those related to positioning, navigation, collision avoidance, leader-following, detection, recognition, fault tolerance, and risk monitoring. However, when applying these algorithms to larger ships, it is essential to consider similitude factors related to hydrodynamics, ice conditions, collision avoidance, hardware and software.

- Very small USVs can serve as platforms for collecting navigational data and object detection/recognition data, thus reducing uncertainty in assessing risks associated with navigation.
- Furthermore, very small USVs can play a role in assessing the impact of different attack scenarios on navigational systems, but not in a vulnerability assessment due to different hardware/software. Small USV use may be able to contribute to the development of novel communication protocols, prototype defense systems against cyberattacks, and the evaluation of communication link performance in both shore and remote areas, such as the Arctic.
- Additionally, small USVs may have applications in search and rescue operations in remote regions, potentially reducing response times and enhancing emergency response capabilities.

It is anticipated that the results of this study will serve as inspiration for researchers in their challenging endeavors, spark ideas for funding organizations, and foster greater interconnection between research areas encompassing safety, control, design, artificial intelligence and mechatronic engineering. Future research could extend to incorporating larger USVs (with displacements ranging from 100 kg to 10 tons) and investigating their utility for safety and cybersecurity.

Appendix A. Table Including Investigated Small USVs

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
1	Hendrik	2019	KU Leuven	Belgium	River barge 154 cm × 20 cm 32 kg	Raspberry Pi, Navio2, Gyro, LiDAR, GPS, ROS	-Control algorithm development -Model testing	River	2	[42,171]
2	Yellowfish	2022	Universidad Loyola	Bolivia	Catamaran 24 kg	Raspberry Pi, Navio2 (GPS, IMU, Radio) Ardupilot	-Testing of estimators -Estimation of state dynamics	Lake	2	[33,193]
3		2013	Instituto Tecnológico de Aeronáutica	Brazil	Catamaran 120 cm × 120 cm	GPS, thrusters, IMU, digital compasses	-Position algorithms improvement	Lake	2	[194,195]
4	AERO4River	2021	Federal University of Juiz de Fora	Brazil	Catamaran 140 cm 20 cm 20.8 kg	Aerial thrusters and servos, GPS, PID control,	-Control algorithms development, inspections, sensors placement, ship parameters identification	River	5	[148,152,196–198]
5	N-Boat	2016	Federal University of Rio Grande do Norte	Brazil	Sailboat 0.9m	WiFi, GPS, Wind sensor	-Control development using various techniques and their testing, water monitoring	Lake	5	[150,199–202]
6		2021	St John's University	Canada	Platform supply vessel	Cameras, IMU, propellers, bow and aft thrusters	-Development of ice navigation techniques	Ice towing tank	2	[37,151]
7	Eddy	2021	York University	Canada	Trimaran	GPS RTK, cameras, IMU, ROS, sonar sensor	-Infestation and invasive species monitoring	Lakes	1	[203]
8	WS-USV	2014	Shenyang Institute of Automation	China	Monohull 260 cm × 80 cm 70 kg	Rudder with propeller, GNSS, freeway radio	-Water sampling -Detection system development through images -Model parameters identification	Lakes and rivers	4	[44,175–177]
9	Zhi Long N1	2022	Dalian Maritime University	China	Trimaran 175 cm × 50 cm 40 kg	Double propeller and rudder, GPS with RTK, LiDAR, Cameras, ROS C++	-SLAM and positioning improvement	Harbor area	2	[204,205]
10	Pallas	2020	Wuhan University of Technology	China	Inland container vessel 100 cm	GPS, IMU, ROS	-Collision avoidance testing	River	2	[42,206]
11	AquaSentinel	2023	Ocean Alpha	China	Trimaran hull design 165 cm × 70 cm, 42 kg	Side scan sonars, echo sounders, Doppler sensors, radar sensors, cameras, communication system, waterjets	-Hydrographic survey -Inspections -Bathymetry survey -River velocity survey	Harbor areas/sheltered areas	1	[207]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
12	Qiuxin No.5	2023	Wuhan University of Technology	China	Tugboat 227 cm × 65 cm	GPS, gyro	-Controller optimization and tuning	River	1	[208]
13		2022	Shanghai Jiao Tong University	China	Catamaran 200 cm × 119 cm 120 kg	GPS RTK, wave radar, 2 thrusters, ROS	-Testing control techniques -Testing of follow the leader algorithm (vessel train)	River	1	[209]
14	Hong Dong 1	2023	Shanghai Jiao Tong University	China	150 cm × 74 cm	IMU, GPS, LiDAR	-Testing ship detection using LiDAR	Swimming pool	1	[143]
15		2020	Guangzhou Institute of Technology	China	Catamaran 80 cm × 180 cm 5 kg	ARM microcontroller, satellite communication, photovoltaic, WiFi, water quality analysis device, gyroscope, magnetometer, GPS	-Water quality monitoring	Lake	1	[210]
16	USBV I-II	2010	State Oceanic Administration	China	Catamaran 280 cm × 150 cm 100–130 kg	DGPS, IMU, Compass, echo sounder, camera, weather station, propellers	-Bathymetry Testing of controllers Sensors testing	Coastal area	4	[211–214]
17		2009	Shanghai Maritime University	China	Catamaran 270 cm × 148 cm 100 kg	Two propellers, LAN, NMEA, cameras, GPS	-Surveillance, quality sampling, hydrological survey, search and rescue	Coastal area	1	[132]
18	USCV	2020	Guangxi University	China	Catamaran 133 cm × 95 cm 50 kg	Remote control system	-Garbage cleaning, system development	Harbors, rivers	1	[215]
19		2021	Zhejiang University of Water Resources and Electric Power	China	Undefined	GPS, LiDAR, Camera, WiFi, IMU, ROS, radio communication, thrusters	-Garbage cleaning, system development, autonomous navigation development	Harbor, rivers	1	[146]
20		2016	Universidad Tecnologica de Bolivar	Colombia	Monohull 130 cm 17 kg	Raspberry Pi, GPS, IMU, radio, Matlab, simulinki, Navio+	-Control testing, environment monitoring	lakes	2	[216,217]
21	PlaDyPos/ PlaDyBath	2015	University of Zagreb	Croatia	New type 35 cm × 35 cm 25 kg	GPS, Doppler speed sensor, compass, IMU	-Control development and verification -Scanning the sea bed -Bathymetry	Lakes, sea	4	[140,218–220]
22	ARCAB	2019	Aarhus University	Denmark	Trimaran 80 cm × 100 cm	GNSS receivers, FPV camera LabVIEW	-Assessment of climate change impact -Collection of surface water samples in hazardous area	Sea, close to melting icebergs	1	[122]
23	NORDACC	2023	Aarhus University	Denmark	Trimaran 93 cm× ?	GNSS receivers, FPV camera LabVIEW	-Assessment of climate change impact -Collection of surface water samples in hazardous area	Marine bay, melting iceberg	1	[123]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
24	AL	2023	Aalto University	Finland	Icebreaker 135 cm × 38 cm 20 kg	LiDAR, GPS, IMU, WiFi, RP4, Arduino Mega, 3 Azimuth thrusters	Research	Ice and wave towing tank	1	[147]
25	ROSS	2007	National Institute of Oceanography	India	184 cm × 36 cm 108 kg	RF, GPS, 2 BLDC motors	Ocean remote sensing	Open ocean	1	[221]
26	BAICal	2022	LASA, University of Calabria	Italy	Four buoys connected together 10 kg	GPS with RTK, Azimuth thrusters, IMU, Raspberry Pi, Python, ROS	-Collection of environmental data -Remote web application testing -Navigation system development -Fault diagnosis and control development	Lake, close to sea shore	1	[45]
27	SWAMP	2020	University of Genova	Italy	Catamaran 123 cm × 110 cm 58 kg	IMU, GPS, WiFi, Arduino, Raspberry Pi	-Monitoring close to glaciers -Water sampling -Bathymetry -Landing/take off platform -Power management development	Shallow water operations	4	[155,222–224]
28	MicroVega	2015	University "Parthenope" Napoli	Italy	Catamaran 135 cm × 85 cm 14 kg	SONAR, IMU, GPS, 2 motors, camera, underwater camera, Linux, Arduino, RTK, WiFi, Tritech StarFish and TrackStar, Arduino Mega, Raspberry Pi, C++	-Bathymetric data acquisition, collision avoidance testing	Lakes, close to coast	4	[225–228]
29	Shark USSV	2016	Institute for coastal marine environment	Italy	Undefined 90 cm × 75 cm 40 kg	Four propellers Linux, GPS, AHRS, WiFi, camera, C++	-Water sampling in proximity to glaciers Towing operations	Glaciers	2	[134,229]
30	WeMo	2020	University of Siena	Italy	Undefined 12.7 kg	Arduino Uno, GPS, sonar, pH, oxidation-reduction, salinity, oxygen, flow rate, sonar, sensors	-Environmental monitoring, navigation control	River	2	[230,231]
31		2019	Tokai University	Japan	Catamaran 88 cm × 35 cm	Very little information	-Position estimation, collision avoidance, garbage recognition, position detection algorithm development and testing	Pool	1	[232]
32		2014	KAIST	Korea	Trimaran 2.8 m × 1.5 m 80 kg	LiDAR, cameras, GPS, WLAN, PC modules, trolling thruster system	-Development of navigation and mapping algorithms -Testing of geophysical navigation	Lake	3	[142,233,234]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
33	Orange-Duck	2019	KAIST	Korea	Trimaran 180 cm × 90 cm 60 kg	IMU, GPS, 2D LiDAR, 3D LiDAR, heading reference system,	-New positioning system development	Close to offshore structures	1	[235]
34	JEROS	2012	KAIST	Korea	Catamaran150 cm × 110 cm 50 kg	GPS, IMU, 2 thrusters, cameras	-Jellyfish removal -Path planning algorithm testing -Formation following algorithm, jellyfish detection	Coastal area	5	[236–240]
35		2016	KAIST	Korea	Catamaran 100 cm × 25 cm	Propeller, rudder, camera, GPS, IMU, LiDAR	-Bridge inspection	Rivers, lake	1	[241]
36		2022	Inha University	Korea	Catamaran 144 cm × 77 cm	GPS, Arduino, ROS, Python, LiDAR, Raspberry Pi	-Collision avoidance development	Towing tank	1	[38]
37	PASS Mk II	2023	Pukyong National University	Korea	Catamaran 120 cm × 60 cm 15 kg	GPS with RTK, IMU, Raspberry Pi, Arduino, Azipods	-Control algorithms development and testing	Towing tank	1	[34]
38		2023	Pukyong National University	Korea	Monohull 200 cm × 49 cm	Uknown	-Testing of control algorithm with gain tuning using free running test data	Lake	1	[242]
39		2016	IIUM	Malaysia	Catamaran 100 cm × 92 cm	ArduPilot, telemetry, GPS, compass, sonar sensor	-Bathymetry	Lake	1	[138]
40	UNIGE	2020	TuDelft	The Netherlands	Tugboat 97 cm × 30 cm	-IMU, GPS, ultrasonic sensors, azimuth thrusters	-Ship control algorithm development -Collision avoidance testing	Towing tank	1	[42]
41	Tito-Neri	2020	TuDelft	The Netherlands	Tugboat 145 cm 16.9 kg	Accelerometers, distance measurement sensors, gyro, GPS, encoders, camera, ROS, Python, Arduino	-Ship control algorithm development -Testing of follow-the-leader algorithm (vessel train) -Testing towing operations	Towing tank, lakes, rivers	5	[42,144,243–245]
42	Grey Seabax	2021	TuDelft	The Netherlands	Offshore ship 175 cm 19 kg	Accelerometers, distance measurement sensors, gyro, GPS, encoders, camera, ROS, Python, Arduino	-Ship control algorithm development	Towing tank	1	[243]
43	Delfa 1	2021	TuDelft	The Netherlands	Catamaran 5 kg	Gyro, GPS, Cameras	-Ship control algorithm development	Towing tank	1	[243]
44	Roboat	2018	Roboat	The Netherlands	Urban Ferry 90 cm × 45 cm 9 kg	ROS, RTK GPS, IMU, LiDAR	-Navigation system design -Testing of control techniques -Testing of leader-follower algorithm	Port	3	[246–248]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
45	Otter	2021	Marine Robotics	Norway	Catamaran 200 cm × 108 cm	GNSS, IMU, Stereo cameras, WiMax radio, LiDAR	-Control algorithms development and testing -Position, speed algorithms improvement and testing -Visual based algorithms -Injecting cyberattack scenarios to navigation system -Development of encryption algorithms -Online risk monitoring testing	Harbor	8	[35,39,145,149,153, 157,158,249]
46	CSAD	2017	MClab	Norway	Drillship 258 cm × 44 cm	Arduino, IMU, WiFi bridge, Qualisys, LabVIEW	-Hydrodynamic experiments -Wave parameters estimation	Towing tank	2	[250,251]
47	SailBuoy	2014	MET Norway	Norway	Monohull 2 m 60 kg	Satellite communications, GPS, Temperature, Oxygen sensor	-Sea water monitoring	Gulf of Mexico	1	[252]
48		2016	NTNU	Norway	High speed boat	Thrusters, dynamic positioning, GPS, IMU, Linux, Arduino, temperature, pressure, humidity sensors	Inspection of aquafarms, control development	Close to aqua farms	1	[253]
49	Cybership II	2004	NTNU	Norway	Supply ship 125 cm × 29 cm 24 kg	LabVIEW, WLAN	-Ship parameters identification - Formation maneuvering testing		3	[144,254,255]
50		2019	Sultan Qaboos University	Oman	Catamaran 90 cm 15 kg	Raspberry Pi, ROS, GPS, IMU, cameras, oil sampling mechanism	-Navigational algorithm for oil spill response	Sea	1	[141]
51		2017	Pontificia Universidad Catolica del Peru San Miguel	Peru	Catamaran 130 cm × 90 cm 50 kg	GPS, WiFi, bathymeter, sampling device, IMU, Raspberry Pi 3, camera, radio	-Bathymetry, task allocation algorithms testing	Lake	2	[256,257]
52		2017	Gdynia Maritime University	Poland	Catamaran (dimensions unknown but seemingly small)	Echosounder, GPS RTK, 2 propellers, Pixhawk, ATmega8	-Hydrographic survey	Lakes, sea	2	[139,258]
53	ROAZ	2013	INESC TEC	Portugal	High speed boat 90 kg	WiFi communication, GPS RTK, IMU	-Search and rescue operations -Positioning algorithm testing	Coastal area	4	[125–128]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
54		2021	CENTEC	Portugal	Containership 324 cm × 43 cm 108 kg	LabView, GPS, IMU, rudder, propeller	-Model parameters estimation -Collision avoidance testing with other ships	Lake	2	[259,260]
55		2021	CENTEC	Portugal	Chemical tanker 258 cm × 43 cm	LabView, GPS, IMU, rudder, propeller, WiFi, wind sensor	-Model parameters estimation -Shallow water effect investigation -Collision avoidance testing -Collision avoidance testing with other ships	Tank	3	[32,260,261]
56	Zarco	2007	University of Porto	Portugal	Catamaran, sailboat 150 cm 50 kg	WiFi, GPS, Compass, C++, Linux	-Research, underwater surveys, station keeping algorithms development, wind propulsion testing, bathymetry data, sonar technology development	Rivers	8	[129,262–268]
57	FEUP (FASt)	2008	University of Porto	Portugal	Sailboat 250 cm × 67 cm 50 kg	Linux, WiFi, modems, wind vane, anemometer, radiocommunications, compass, GPS, inclinometers, voltage, light temperature, moisture sensors, ANSI Solar panels	-Ocean observation, coastal surveillance, reconfiguration testing, speed controller testing, navigation controller testing	Coastal area	6	[156,165,269–272]
58	UCAP	2013	University of Porto	Portugal	Monohull (high speed) 90 kg	WiFi, GPS, IMU, PID controllers,	-Search and rescue operations	Coastal area	1	[125]
59		2018	Instituto de Telecomunicações	Portugal	High speed boat	ROS, Linux, pH, water temperature, salinity, depth, turbidity, conductivity sensors, IMU, GPS, Camera, Raspberry Pi, 2 thrusters, Bluetooth	-Communication networks testing and development -Swarm algorithm development	Pond	4	[273–276]
60	ELFIN	2023	Weston Robot	Singapore	Catamaran 100 cm × 75 cm		-Water sampling with remote or automatic control	Harbor	1	[277]
61	A-Tirma G1 and G2	2014	Instituto Universitario SIANI	Spain	Sailboat 1 m × 0.25 m 4.3 kg 2 m × 367 cm 42 kg	RF, GPS, Compass, Wind, Inclinometers, C++	-Research, fish monitoring, design optimization	Coastal area	5	[278–282]
62		2015	Universidad Complutense de Madrid	Spain	Highspeed boat 0.8 m–1 m 3.4–3.9 kg	ARM microcontroller, GPS, radio link, compass, C++	-Towing operation testing, navigational control, oil cleaning operations, buoys deployment operations	Lake	4	[283–286]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
63		2021	Universidad Complutense de Madrid	Spain	Catamaran 10 kg	Radio link, GPS, IMU, compass, temperature, pH, conductivity	-Water monitoring	Lake	1	[135]
64	Deep Vision	2022	KTH	Sweden	Catamaran (dimensions unknown, but small as judged from the pictures)	Wireless radio, IMU, GNSS RTK, sonar, Arduino mega, AIS	-Research	Close to coast	1	[287]
65		2019	National Sun Yet-san University	Taiwan	Kayak, 363 cm × 91 cm 88.5 kg	GPS, LiDAR, camera, Pixhawk, radio communication	-Autonomous sailing, remote communications, smart 3D mapping, real-time image detection and identification	Coastal area	1	[288]
66		2021	Naval Academy	Tunisia	Monohull 314 cm 85 cm	Sonar, weather vane, anemometer, GPS, Video, IMU, siren, LiDAR, Arduino	-Control algorithm development	Coastal area	2	[289,290]
67		2006	University of Wales	UK	Sailboat 1.5 m	GPS, compass, wind	-Research, monitoring, control techniques development	Lake	3	[291–293]
68		2018	University of Leeds	UK	Trimaran 56 cm × 45 cm	GPS, remote control, sonar	-Bathymetry close to glaciers	Lakes	1	[294]
69		2017	University of Bath	UK	Catamaran	Manual control, GPS, ROS, IMU, satellite communication, IMU, optical camera, sonars, Linux	-Bathymetry, navigation and guidance testing, objects detection	River	1	[295]
70	Wave-Glider	2010	Liquid Robotics	USA	Glider type Comparable to paddle board	Solar panel, battery, AIS, GPS, speed and customized sensors, gliding system	-Oceanographic research -Environmental monitoring (fish, tsunamis, met ocean, hydrocarbon) -Mammals and acoustic monitoring	Open ocean	9	[154,167,296–302]
71	sUSV	2019	University of Southern Mississippi	USA	Board 100 cm	ArduPilot, cameras, GPS	-Data collection platform at the coral reefs	Near coastline	1	[303]
72	Sea-RAI	2009	University of South Florida	USA	Catamaran 190 cm × 120 cm	Acoustic cameras, GPSs, video cameras	-Inspection in the aftermath of hurricanes	Rivers	2	[130,131]
73	BathyBoat	2010	University of Michigan	USA	High speed boat 97 cm 16 kg	GPS, IMU, Sonar, rudder, radio communication	-Bathymetry and fish finding	Lakes	1	[121]

a/a	Model Name	Year First Mentioned	Owner	Country	Type and Size (Length × Beam, Displacement)	Sensory, Software and Propulsion Systems	Utility	Operational Area	RN	Ref
74	AutoCat	2000	Massachusetts Institute of Technology	USA	Catamaran 180 cm × 130 cm	Two motors, two Astroflight motor controllers	-Research	Rivers	1	[304]
75		2020	Washington State University	USA	Hydrofoil monohull and Trimaran 61 cm × 16.5 cm 65 cm × 41 cm	Cameras, GPS, radios, CAN bus, Arduino Mega	-Research	Lake	1	[305]
76	SCOUT	2005	Massachusetts Institute of Technology	USA	Kayak 3 m 82 kg	GPS, compass, WiFi, RF modem	-Research -Sampling platform	Coastal area	2	[306,307]
77	Smart Emily (Emily)	2013	Texas A&M University	USA	Board, 10 kg	GPS, remote control, android application	-Search and rescue operations	Coastal area	2	[47,133]
78	CRW	2012	Carnegie Mellon University	USA	40-70 cm	WiFi, 3G, Arduino mega, sonars, fluorometer, gyro, camera, IMU, GPS	-Water quality monitoring, depth buoy verification, flood disaster mitigation -Collision avoidance testing using smartphones -Fleet control development	Lakes, canals	3	[308–310]
79	MARV	2016	Santa Clara University	USA	Catamaran, 106 cm × 60 cm 25 kg	WiFi, GPS, Sonar	-Research	Lakes, ponds	1	[311]
80	USNA sailboat	2010	United States Naval Academy	USA	Sailboat 2 m × 0.3 m 30 kg	WiFi, GPS, Compass, Wind	-Competition, navigation, power management, collision avoidance development	Coastal area	3	[312–314]
81	Kingfisher	2016	Clear Path Robotics	USA	Catamaran 135 cm × 98 cm 28 kg	Linux, WiFi, GPS, remote control, 2 thrusters, vacuum system, flow rate calculator, water sampling sensors	-Water sampling	Lakes	3	[137,166,315]
82		2009		USA	Catamaran 2 m × 1 m 100 kg	Temperature, salinity, conductivity, salinity, turbidity, solar panels, wireless communication	-Water sampling	River	2	[316,317]
83	SMARTBoat 5	2019	SMART Lab	USA	Hovercraft 104 cm × 99 cm	ROS, camera, GPS, IMU, duct fans	-Cleaning from garbage	River lake	1	[136]
84	VIAM-USV2000	2021	Ho Chi Minh City University of Technology	Vietnam	Catamaran Seemingly small	ROS, GPS, LiDAR, WiFi, C++	-Path following, obstacle avoidance	Lake	2	[318,319]

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