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A Bibliometric Analysis and Overall Review of the New Technology and Development of Unmanned Surface Vessels

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Abstract: With the significant role that Unmanned Surface Vessels (USVs) could play in industry, the military and the transformation of ocean engineering, a growing research interest in USVs is attracted to their innovation, new technology and automation. Yet, there has been no comprehensive review grounded in bibliometric analysis, which concentrates on the most recent technological advancements and developments in USVs. To provide deeper insight into the relevant research trends, this study employs a bibliometric analysis to examine the basic features of the literature from 2000 to 2023, and identifies the key research hotspots and modeling techniques by reviewing their current statuses and the recent efforts made in these areas. Based on the analysis of the temporal and spatial trends, disciplines and journals' distribution, institutions, authors and citations, the publications relating to the new technology of USVs are assessed based on their keywords and the term analysis in the literature; six future research directions are proposed, including enhanced intelligence and autonomy, highly integrated sensor systems and multi-modal task execution, extended endurance and resilience, satellite communication and interconnectivity, eco-friendly and sustainable practices and safety and defense. The scientific literature is reviewed in a systematic way using a comparative analysis of existing tools, and the results greatly contribute to understanding the overall situation of new technology in USVs. This paper is enlightening to students, international scholars and institutions, as it can facilitate partnerships between industry and academia to allow for concerted efforts to be made in the domain of USVs.

Keywords: Unmanned Surface Vessel (USV); research trends; bibliometric analysis; research hotspots; VOSviewer

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1. Introduction

In recent years, unmanned vehicles have grown in popularity, with an ever-increasing number of applications in industry, the military and research within air, ground and marine domains [1]. This evolution has led to the emergence of sophisticated and self-sufficient watercrafts capable of undertaking complex tasks with minimal human intervention. USVs (Unmanned Surface Vessels), characterized by their autonomous navigation, operation and decision-making capabilities, represent a critical intersection between cutting-edge technologies and maritime operations [2]. By integrating advanced technologies such as Artificial Intelligence (AI), machine learning, computer vision and automation, USVs can not only optimize their operational efficiency but also enhance safety and reduce the risk of human errors. These vessels are equipped with a range of sensors, including radar, lidar and various imaging systems [3], enabling them to perceive and respond to dynamic marine environments effectively.

The application of USVs extends to diverse domains, including but not limited to, maritime surveillance, oceanographic research, marine resource exploration and environmental monitoring. For example, Tianyu Ma highlights the importance of USVs as weapons for various applications, and describes key technologies such as high-performance crafts, control systems, communication technology, collision avoidance and mission planning [4]. The collaborative system of Multiple Unmanned Surface Vehicles (MUSVs) has shown broad prospects in the field of civil and military applications [3]. To enhance the accuracy, a combined Nonlinear Model Predictive Control (NMPC) for the position and velocity tracking of under-actuated surface vessels, and the collision avoidance of static and dynamic objects into a single control scheme with side slip angle compensation and environmental disturbance counteraction, was presented and achieved high validity [5]. A novel path-planning methodologies for autonomous maritime vessels, including USVs, has been developed to operate efficiently in intricate and dynamic marine settings. This approach ensures rapid, reliable and definitive navigational solutions, even in scenarios characterized by multiple mobile maritime vessels and stationary hindrances, while also accommodating the variable and unforeseen maneuvers of surrounding vessels [6]. With the advent of machine learning, more research was focused on communication, remote sensing and connected automation, exemplified by a new autonomous data collection with dynamic goals and communication constraints for marine vehicles [7]; it was also focused on a powerful unmanned boat remote-control platform that can realize remote display sensing data, remote motion control functions and can ensure the unmanned boat under the safety requirements of various experiments [8], as well as a concurrent kinematic control tactic introduced for the landing of Unmanned Aerial Vehicles (UAVs) on USVs to mitigate the challenges of diminished precision and potential landing failures caused by the USVs' surface motion due to wave activity [9].

Despite increasingly growing interest in USVs, there is a lack of a systematic overview of solutions proposed in the scientific literature. Among exemplary review articles, there are a few focused on challenge analysis [2,10,11], collision avoidance methods [12–14], path planning [14–16] and control and autonomy [17,18]. However, according to the search results of WoS, there is a notable absence of a systematic literature review and featured bibliometric analysis regarding USVs in the context of the new technology applied in automation development, with a specific emphasis on assessing the development of the automation and future developments.

Therefore, this paper aims to provide a comprehensive overview of the literature relevant to USVs, with a focus on the technological developments, operational automation and the current state of research in the field. Through a meticulous analysis of existing scholarly works, this paper seeks to identify key trends, challenges and future prospects for the integration and proliferation of USVs in maritime applications. By examining the trajectory of the research and technological advancements in this domain, this paper aims to contribute to the collective understanding of the evolving field of USVs and their potential implications for the maritime industry and related fields.

In contrast with previous studies, this paper has three contributions. It is the first attempt at a bibliometric-based review of USVs, which comprehensively examines the basic features of the literature and identifies the current hotspots. Second, the focus is more concentrated on the new technologies and new methods utilized in USVs. Third, the future research directions and detailed analysis of different angles are highlighted to advance the knowledge in this area.

The paper is structured as follows: in Section 2, the methods used in the study are described. Section 3 presents the results showing, respectively, the bibliographic and comparative analyses. A discussion is provided in Section 4, while Section 5 summarizes and concludes the paper.

2. Data and Methodology

2.1. Research Framework

To offer more comprehensive insights into the advancement of cutting-edge technology in respect of USVs, this investigation conducted a systematic retrieval of scholarly articles focusing on USVs from the Web of Science (WoS) Core Collection database. Compared with other databases, WoS core database is more widely used and authoritative, and relevant published high-quality articles [19–23] have adopted WoS as their supporting database. Through the application of bibliographic analysis, this research delineated the prominent areas of investigation and the methodologies employed in the exploration of subjects related to USVs. The research framework is graphically represented in Figure 1 for reference.

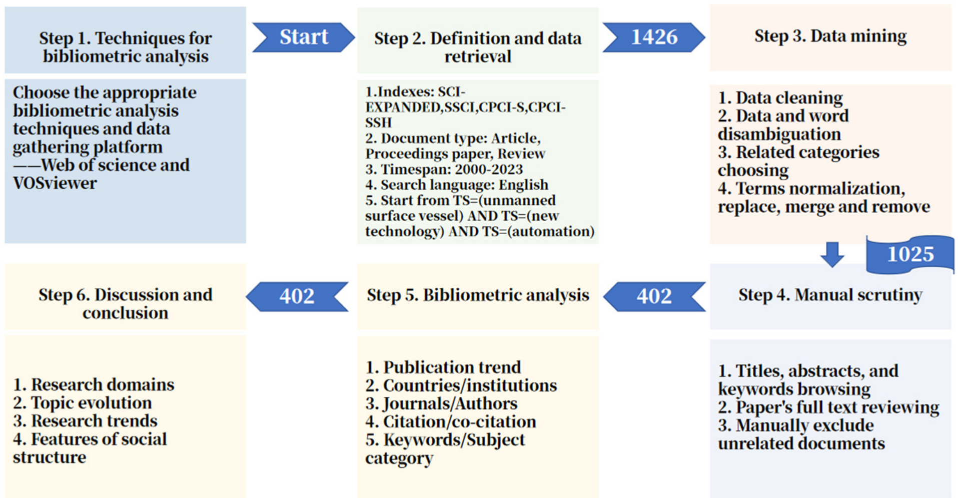

Figure 1. Research framework.

2.2. Bibliometric Methods and Visualization Tools Used in the Analysis

In this research, the utilization of bibliometric mapping methods and tools facilitated the visualization of scientific data through diverse procedures. Bibliometric mapping, as a research methodology, involves the application of quantitative techniques to visually depict the scientific literature derived from bibliographic data.

VOSviewer, a software tool developed by Van Eck and Waltman in 2010, specifically designed for the analysis and visualization of the scientific literature, was used in this present work. VOSviewer is a software widely used in the bibliometric field and in different disciplinary areas [24,25]. VOSviewer offers the capability to depict co-authorship networks among authors, institutions and geographic regions, co-citation networks of articles and journals, as well as co-occurrence networks of keywords and terms. This tool leverages clustering techniques for the visual detection of structural patterns within the research domain, and harnesses text-mining functionalities for recognizing trends and patterns in the addressed topics [26]. In this paper, the version 1.6.19 of VOSviewer was used for further research.

For a comprehensive understanding of the techniques and concepts underpinning bibliometric mapping, Li et al. [27] have provided an informative overview. Moreover, VOSviewer has gained widespread utilization in the realm of bibliometric analysis within the marine science field, as evidenced by various studies [20,28–40]. For a detailed examination of these applications, please refer to Li et al. [27].

Furthermore, two parameters, Impact Factor (IF) and H-index, were utilized in this paper to measure the impact of the journal or author. The IF and the H-index are two prominent metrics utilized to assess the significance and widespread influence of a publication [20]. They serve as valuable benchmarks when making informed decisions regarding the choice of journals and publications within a particular research domain. The ArcGIS, a comprehensive Geographic Information System (GIS) software that enables users to create, manage, analyze and visualize spatial data was utilized to facilitate the understanding of complex geospatial relationships of the publications, to aid in decision-making processes and to support the creation of detailed maps and visualizations for various applications.

Lastly, this study made use of the data analysis functionalities of WoS, in conjunction with VOSviewer, to conduct citation analysis and track the number of publications per year, with the overview methods shown in Figure 2.

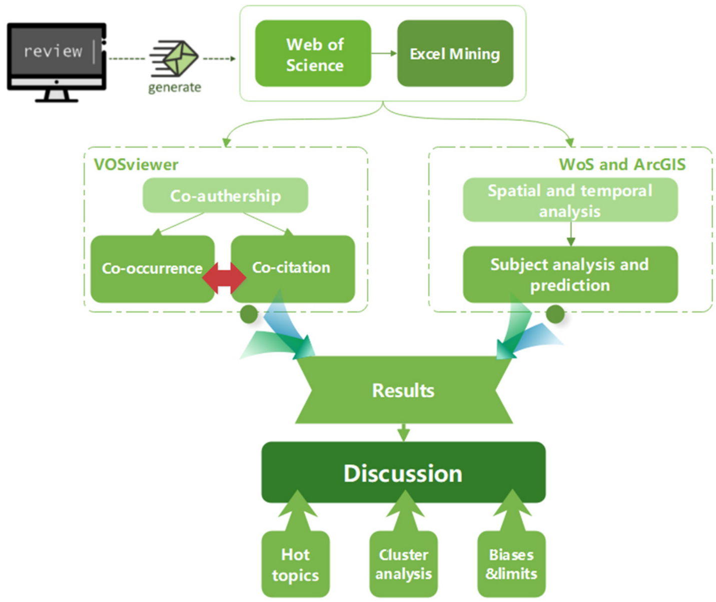

Figure 2. Flowchart for the methods applied in this research.

2.3. Data Extraction and Exclusion Criteria

The process of preparing the dataset comprised three distinct stages. First and foremost, the initial step (Stage 1) involved the formulation of a well-defined search strategy and the acquisition of relevant data. Subsequently, the acquired dataset underwent an initial screening (Stage 2) before proceeding to the final stage (Stage 3), where two distinct methods were employed for data refinement. The complete process of determining the dataset was visually depicted in Figure 3 and was elaborated upon in subsequent sections of this part.

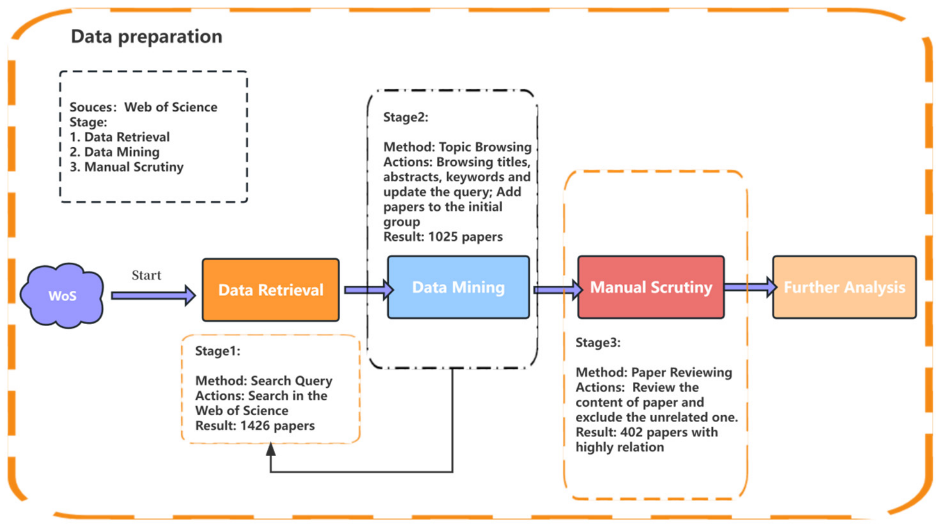

Figure 3. The process of determining the final data sample.

In the first stage of dataset compilation, a meticulously crafted search query was employed to gather the initial collection of documents. The query was solidly found in 2 themes: USVs and new technology. So that more insights into frontier developments would be taken, the choice of WoS as the primary data source was grounded in its recognition as a comprehensive and widely accepted repository of abstracts and citations from high-impact scientific publications [41]. The documents were sourced from the principal WoS Core Collections, namely the Science Citation Index Expanded (SCI-EXPANDED) and the Social Sciences Citation Index (SSCI).

As for the design of the search query, a methodology of vocabulary iteration was utilized to add more synonyms. For instance, the abbreviation of *USV* could be also interpreted as the *unmanned surface vessel, unmanned surface vehicle, autonomous surface vessel, automatic surface vessel*, et al. The main key 10 steps of query are shown in the Appendix A Table A1.

Furthermore, the field of USVs has likely seen rapid growth and evolution in the past two decades. The 2000s onwards was a period where significant regulatory and industry changes occurred, impacting USV deployment and integration into various sectors. Reviewing the literature from this period allowed us to track these changes and their implications. Hence, the timespan was restricted to a period from 2000 to 2023 to support the novelty. In this paper, documents preceding 2 November 2023 were obtained and downloaded.

The second phase of data selection entailed a rigorous evaluation of the documents obtained from WoS. This evaluation was primarily centered on scrutinizing the document titles, abstracts and associated keywords, including both Author Keywords and Keywords Plus, as the search query was accordingly updated over and over again until it had been searched for throughout the database. Documents meeting the initial validation criteria were identified as relevant and were earmarked for further analysis. The iteration of the search query is shown in the Appendix A. These qualified papers were included in the new dataset and were forwarded to the next step of filtering and determining the final sample (1025 papers).

Thence, during the third stage of dataset preparation, all documents underwent a thorough manual scrutiny to assess the content and title against the predetermined criteria by excluding unrelated documents. Papers meeting these criteria were then categorized into the final group, and, eventually, 402 scientific documents were included in the final data sample. The documents contained 225 articles, 170 proceeding papers and 7 review articles. The final data sample would be applied in bibliometric analysis.

3. The Results of the Bibliometric Analysis

3.1. Publication Trends

Figure 4 illustrates the annual number of papers with strong relevance to the new technology of USVs, and shows the predicted trends for the future. It is evident that the number of annually published papers has overall steadily increased since about 2014. According to the dataset retrieved from WoS, the earliest paper directly on USVs, written by Portuguese scholars in English, was published in September 2003 [42]. The number of articles in Chinese was relatively low before 2007; this period can be regarded as the initial stage of the internationalization of USV research in China. Additionally, Figure 4 shows that the total number of articles published worldwide has seen an approximately curvilinear growth since 2013. Therefore, 2014 can be considered a pivotal year in the internationalization of new technology in USV research. After that, the number of publications assumes a trend of growth, in companion with a polynomial simulating curve colored in orange, showing that it is likely to keep this tendency and to reach a summit in 2023 or years afterwards.

To obtain more insights into the concurrence of citations and publications, the time trends of publications in terms of publications and citations are also presented in Figure 4. The results show an overall increasing trend of research on USVs during the period from 2000 to 2023. This trend can be approximately divided into the following three stages: in (1) 2000–2013, the number of publications was minimal and increased slowly, producing fewer than 15 publications; in (2) 2014–2019, publications were driven by several special reports on USVs [43] and commitments using some new methods [44], and the research interest in considering USVs as promising auxiliary strategies had begun to increase. During this stage, the number of publications and citations increased from 11 to 57 and from 50 to 325, respectively; from (3) 2020–present, there is a stable stage in development, as the number of publications is always higher than the previous ones, along with a peak at 64 in 2022, during which time the average annual publication reached 40–60 documents.

Note that the soaring increase in citations clearly demonstrates the concentrated focus in this field and forecasts the popular direction of USVs.

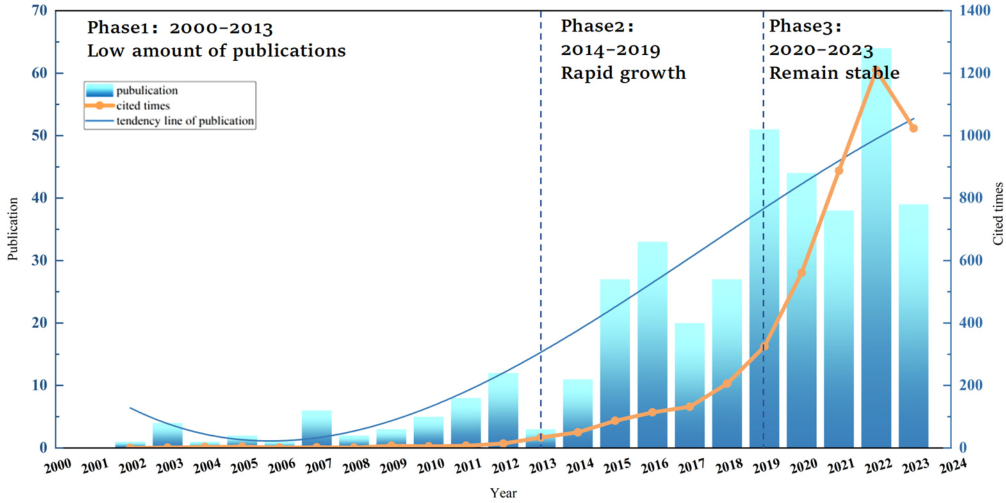

Figure 4. Total publications and citations on USV during 2000–2023.

3.2. Social Structure Analysis

3.2.1. Influential Authors Analysis

Scholars with substantially highly cited publications often dominate the conceptual and methodological trend of the pertinent research field and exert an influential impact on the development of the field [45]. Hence, it is essentially vital for us to identify the influential scholars so that we can gain more insights into the academic discourse.

To eliminate the ambiguous influence of these authors, we have made a detailed comparison among the top 10 productive authors and exhibit the information of their name, institution and some indicators of their contributions, as Table 1 shows. The results of the authors' productions show that the top 10 productive authors have, together, published 80 articles, accounting for nearly 20% of the total publications. As is listed in Table 1, the most productive and most cited author is Yuanchang Liu, from University College London, with 13 publications and 338 citations, followed by Kristan Matej, from University of Ljubljana, with 9 publications and Bucknall Richard from University College London with 8 publications. Moreover, Bucknall Richard was the second most cited author, with 251 citations. With 31.38 citations per paper, he also took the lead as the author with the highest average number of citations, demonstrating that his research received relatively significant attention from others. Note that Dalian Maritime University stood out with a larger number of prolific authors compared to other institutions, underscoring the significant contribution of this institution and its researchers within the USV research community.

Further, the analysis of an author's collaboration is essential and is carried out in lots of articles for the following reasons:

(1) Revealing leading knowledge providers: the analysis of an author's collaboration network can identify the central figures or leading knowledge providers in a specific field; in this case, slip-and-fall incident research. These are the experts or authors who have made significant contributions to the body of knowledge in this domain.
(2) Understanding social networks: beyond identifying individual experts, this analysis also delves into the social networks that exist among these authors. It reveals how these experts collaborate, communicate and share ideas, shedding light on the dynamics of knowledge creation and dissemination within the field.
(3) Interest for early career researchers: early career researchers can benefit from such analyses when entering a new research domain. By identifying the key figures and their collaborative networks, they can find mentors, potential collaborators and resources to accelerate their research and integration into the field.

(4) Interest for external stakeholders: external stakeholders, such as industry professionals, policymakers or organizations interested in slip-and-fall incident research, can use this information to connect with world-class experts in the field. It enables them to seek advice, collaboration or expertise from those who are well-established in the domain.

Table 1. Top 10 most productive authors on USV.

Rank	Author	Institution	TP	TC	AC	H-Index
1	Yuanchang Liu	University College London	13	338	26.00	7
2	Kristan Matej	University of Ljubljana	9	231	25.67	6
3	Bucknall Richard	University College London National Engineering Research Center for Water Transport Safety	8	251	31.38	5
4	Yun Li	Shanghai Maritime University	8	62	7.75	5
5	Yan Peng	Shanghai University	8	31	3.88	3
6	Guofeng Wang	Dalian Maritime University	8	101	12.63	4
7	Dongdong Mu	Dalian Maritime University	7	101	14.43	4
8	Pers Janez	University of Ljubljana	7	209	29.86	5
9	Yunsheng Fan	Dalian Maritime University	6	82	13.67	3
10	Yuqing He	Chinese Academy of Sciences	6	40	6.67	3

Notes: TP = Total publications; TC = Times cited; AC = Average number of citations per publication.

Meanwhile, the selective inclusion of authors is needed to create a visually clear collaboration network, and it is common to limit the number of authors included. In this research, authors who have published more than two articles on the new technology of USVs were the target. This selective approach ensures that the collaboration network included individuals with a substantial body of work in this specific area, thereby emphasizing the most relevant and experienced contributors in Figure 5.

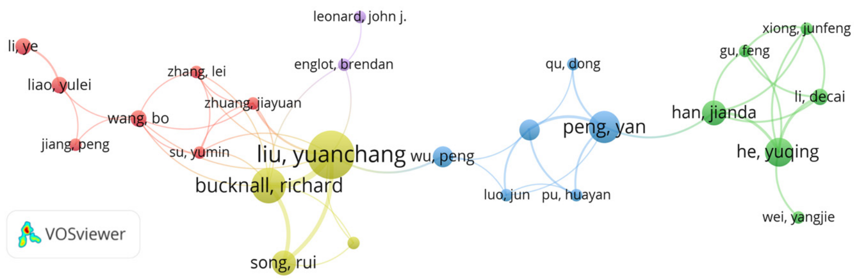

Figure 5. The network of author collaboration using analysis of the co-authorship.

In both visual representations, the size of the nodes corresponds to the number of publications attributed to each author [45]. The connecting lines between nodes depict instances of collaboration between these authors. In Figure 5, the color of a node signifies the specific clusters to which an author belongs. These clusters represent networks of authors whose collaborative work was evident through shared co-authorship relationships. The detailed setting for the parameters used for the figure was provided in Appendix A Table A2.

Authors can be categorized into distinct clusters based on the extent of their collaborative efforts, thereby revealing various sub-communities within the field of USV research. The authors analyzed were divided into five clusters. For example, Yuanchang Liu stood out as a pivotal figure within his group and had a substantial network of 22 collaboration links in the broader global research field. Similarly, authors such as Bo Wang (7), Yan Peng (10) and Yuqing He (12) took prominent roles within their respective groups. Further, at an individual level, with average publication year, it is noteworthy that the most recently active authors in USV included Bo Wang (2022), Peng Jiang (2021.5), Xinyu Zhang (2021) and Yulei Liao (2020). These scholars not only have exhibited high productivity but have also demonstrated significant activity, particularly in recent years.

More specifically, the authors of the red cluster mainly collaborated on system approach and validations of USV. The yellow cluster was more focused on the motion framework and navigation planning algorithms of USVs, while the purple cluster shared the early perception and navigation methods of USVs. Additionally, the blue cluster conducted cooperation in tracking control and neuro-adaptive control, and the green cluster worked on the detection and identity of USV.

3.2.2. Institutions Analysis

A total of 474 institutions were involved with the 402 documents in this study. Figure 6 illustrates the collaborative networks among institutions that have published more than two articles related to USV, with a total of 54 institutions meeting the threshold. In a manner similar to Section 3.1, Figure 6 delineates clusters of these institutions based on the strength of their collaborative ties. The size of the nodes in these network representations corresponds to the number of articles these institutions have contributed to the domain within our dataset. The lines connecting these nodes signify instances of collaboration among these institutions. The thicker the line, the more jointly authored articles the two connected institutions have published. Nodes sharing the same color indicate a higher level of collaboration in the new technology of USV research compared to others. The detailed setting for the parameters used for the figure was provided in Appendix A Table A2.

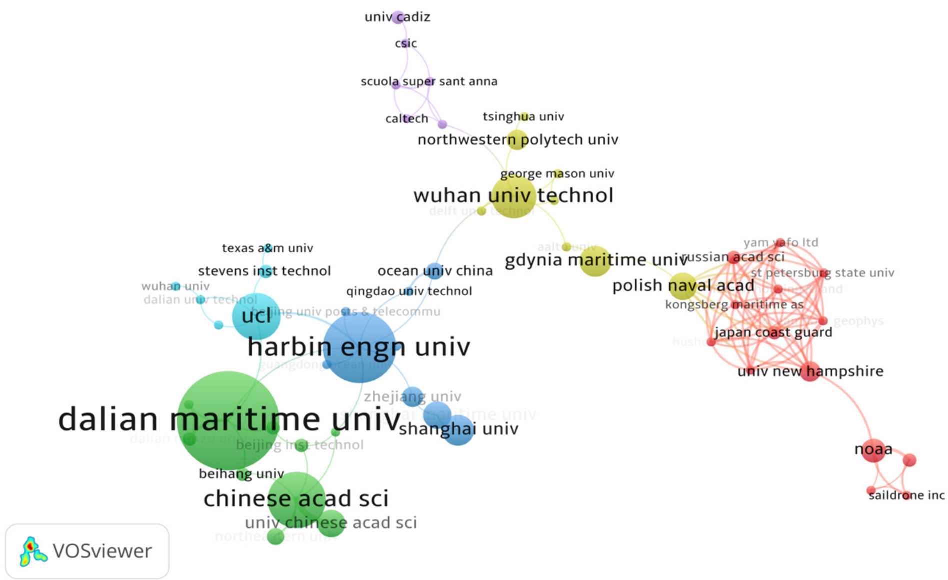

Figure 6. The network of institution collaboration using analysis of the co-authorship.

Figure 6 provides further insights into the collaborative research field, particularly highlighting the significant role of Dalian Maritime University. This institution stood out as the most prolific contributor, with a total of six collaborative links and 31 documents, primarily from Dalian Minzu University, UCL (University College London) and Southeast University. Notably, Dalian Maritime University also engaged in partnerships with universities in nearby northern cities, primarily Beijing and Harbin, thanks to their geographical proximity. Consequently, Dalian Maritime University served as the central hub within the green cluster due to these collaborative connections. Deduced from the light blue cluster, UCL, a university with the most productive author, acted as an important channel to conduct collaborative research with other institutions. As for the blue cluster, the institutions within this group were primarily situated near the ocean, encompassing areas like Zhejiang, Qingdao and Shanghai. In this cluster, Harbin Engineering University emerged as the focal point of collaborative activities. The yellow cluster, on the other hand, shows the strong link between Chinese institutions and European institutions, with Wuhan University of Technology playing a central role. Of particular interest was the fact that Polish Naval Academy had established connections with institutions in different regions, as it had 21 total link strengths, facilitated through its partnership with University of New Hampshire (UNH). Hence, UNH, became a crucial link in the red cluster, components of which were tightly intertwined and supported with each other and display a lasting and practical cooperation relationship. Lastly, the purple cluster consists of universities and research institutions in America, Singapore and Italy, etc., with National University of Singapore acting as the core of this cluster.

Among these institutions, Dalian Maritime University demonstrated the highest level of productivity, having authored 31 research papers. It was followed by Harbin Engineering University with 21 publications, Chinese Academy of Science with 15 and University College London with 13 publications. As evidenced in authors' analysis in Section 3.1, University College London had a dedicated team engaged in USV research, playing a central role in this specific domain. Furthermore, in accordance with Table 2, Shanghai Jiaotong University and Shanghai Maritime University were the top two institutions with the latest and highest average publication year, denoting that they were conducting most of the new technology research in recent years and paying sufficient attention to the burgeoning development of USVs.

Table 2. Bibliometric network and citation information of the top 16 most productive institutions.

Rank	Institution	Country	TP	TC	AC	TLS	APY
1	Dalian Maritime University	China	31	428	13.81	18	2020.2
2	Harbin Engineering University	China	21	160	7.62	17	2019.0
3	Chinese Academy of Science	China	15	91	5.69	14	2015.8
4	University College London	England	13	338	26.00	13	2019.2
5	Shenyang Institute of Autonomous CAS	China	12	57	4.75	12	2015.7
6	Wuhan University of technology	China	12	266	22.17	17	2019.4
7	University of Ljubljana	Slovenia	7	101	14.43	3	2018.7
8	Norwegian University of Science Technology NTNU	Norway	9	141	15.67	11	2020.2
9	Gdynia Maritime University	Poland	8	262	32.75	4	2014.1
10	Jiangsu University of science technology	China	8	5	0.63	8	2019.2
11	Korea Maritime Ocean University	Korea	8	100	12.50	14	2021.1
12	Shanghai University	China	8	53	6.63	11	2019.7
13	National Oceanic Atmospheric Admin NOAA USA	USA	7	48	6.86	12	2016.3
14	Shanghai Maritime University	China	7	29	4.14	9	2021.7
15	Harbin Institute of Technology	China	6	41	6.83	4	2019.8
16	Shanghai Jiaotong University	China	5	27	5.40	3	2021.8

Notes: TP = total publications; TC = times cited; AC = average number of citations per publication; TLS = total link strengths; APY = average publication year.

In spite of comparatively high total publications, institutions such as Shenyang Institute of Autonomous CAS, Gdynia Maritime University and Chinese Academy of Science embody an old APY of 2015.7, 2014.1 and 2015.8, respectively. The most cited or influential work of these institutions in the dataset is approaching a decade old. This could suggest that they made significant contributions to the field around that time. However, the older APY might also indicate a potential decrease in either the quantity or the impact of recent publications. It is importantly conduced that the institutions may have maintained their research momentums until 2014 or 2015, and then shifted its focus to other areas.

In addition, it should be noted that the table clearly demonstrates China's leading role in the field, as evidenced by the significant number of publications from the country.

Specifically, 10 out of the top 16 institutions are based in China, with the country dominating even more impressively among the top 6 institutions, 5 of which are affiliated with China.

3.2.3. Countries and International Cooperation Analysis

In terms of geographical distribution, a total of 55 countries and regions have participated in publishing 402 articles and reviews, while 30.9% of these countries contributed only one paper. Figure 7 illustrates the geographical distribution of publications from 2000 to 2023. The result shows that China took the lead with the largest number of publications at 177, followed by the United States with 68, England with 34, South Korea with 29 and Poland with 25.

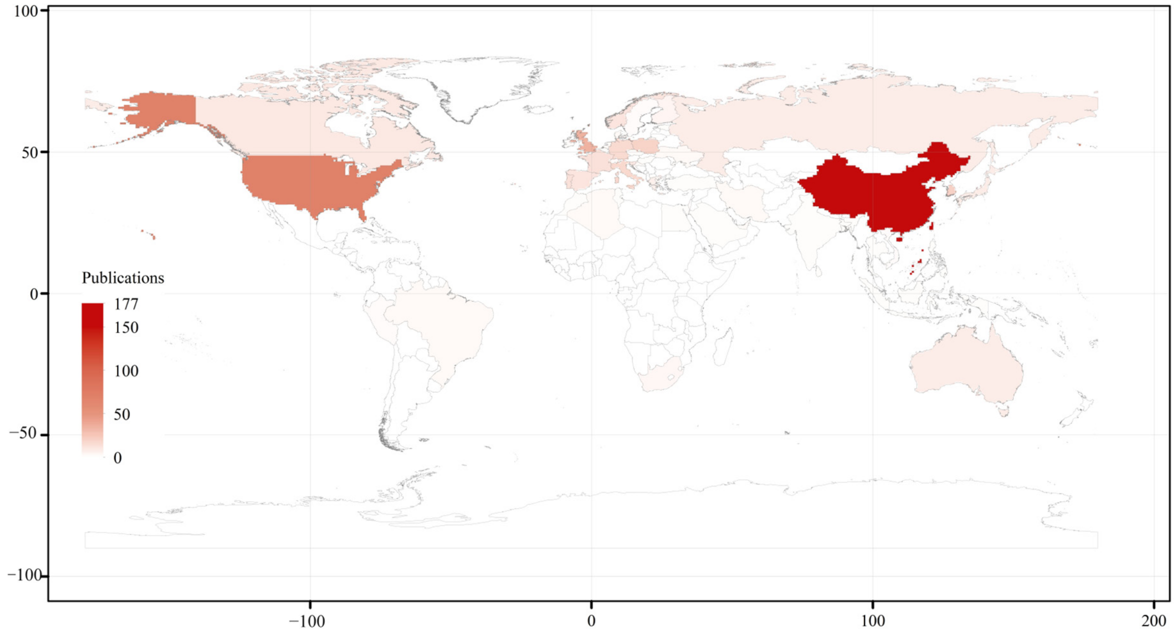

Figure 7. The distribution of publications arising from various countries.

When it comes to the total number of citations in Table 3, China (1655), the United States (1315), South Korea (702) and England (685) stood out, highlighting the substantial influence of these countries in this field.

Table 3. Total citation of the top ten countries.

Rank	Country	TC	AC
1	China	1655	8.40
2	USA	1315	19.39
3	South Korea	702	35.10
4	England	685	20.83
5	Bangladesh	413	413.00
6	Poland	332	17.47
7	Slovenia	231	23.10
8	Australia	223	27.88
9	Finland	157	31.40
10	Norway	146	12.17

Notes: TC = times cited; AC = average number of citations per publication.

Despite a smaller quantity of publications, Bangladesh and (413) Sweden (61.5) received a higher average number of citations than most other countries, indicating the exceptional quality of research conducted in these two nations. Overall, as per the statistics, the developing countries indeed had a limited global impact in the field of the USV in terms of publications and citations, as only two developing countries ranked within the top 15 productive countries.

To find the internal connection in the distribution, the international cooperation was analyzed by mapping countries based on the co-authorship. The detailed setting for the parameters used for the figure is provided in Appendix A Table A2.

It is well known that close research collaborations between countries drive technological and research advancements. Figure 8 illustrates the collaborative relationship among countries by examining co-authorship patterns. It is worth noting that the substantial number of publications on the new technology of USVs originated from China, as there was significant international cooperation between China and other countries, indicating that the research in this field factually requires a particular international cooperation. The network was constructed by using the full-counting method, with a minimum threshold of two documents per country, leading to the inclusion of 35 countries in the analysis. To normalize the data, association strength was applied. The color-coded overlay represents the year of publication, and the thickness of the links is proportional to the overall strength of the collaborations.

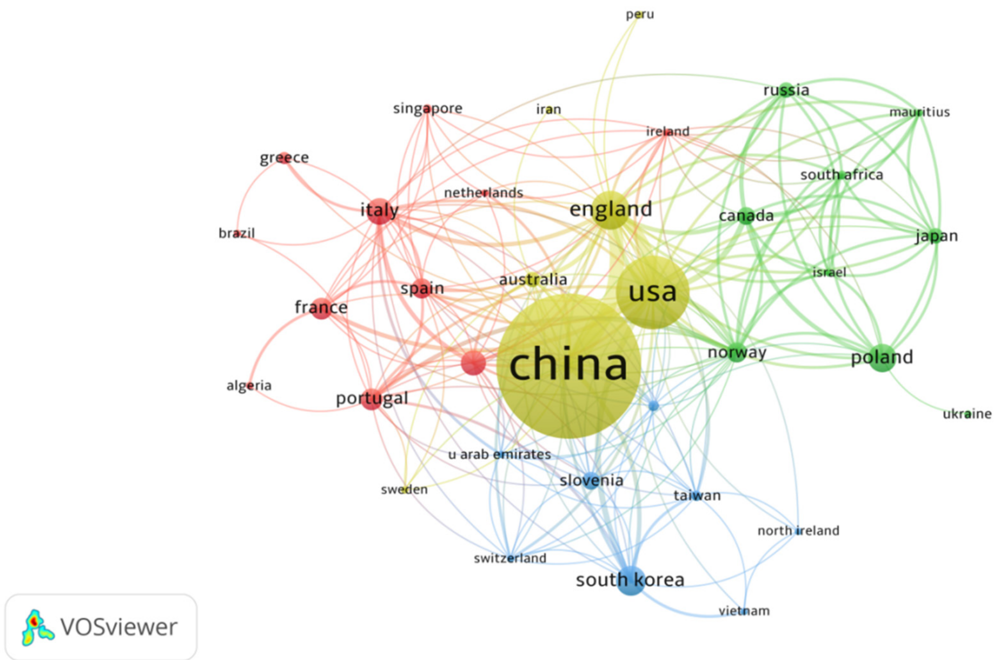

Figure 8. The network of international collaboration using analysis of co-authorship.

The international collaboration network reveals the presence of four primary clusters. Notably, China emerged as the most active collaborator, with the strongest link (10) established with England. It can also be inferred that Chinese researchers were currently responsible for the majority of document productions, as indicated by the color-coded data, and their collaborative network extended prominently at the international level. Additionally, note that a strong circle featured by the European region is shown in the red cluster, where Italy dominated the cooperative links in the red cluster, primarily conducting collaboration with England, Germany and Greece, along with some publications for a single time with other countries. South Korea and Poland took the privilege to engage in more contact with other countries in their clusters, respectively.

Figure 9 also presents information about the average publication year of each country, an indicator that tells us which country is more in tune with the era. It is palpably understood that France, Spain, Switzerland and the United Arab Emirates have the average latest publication year, showing that they have done much work in the past 3 years, whereas the USA (the United States), Canada and Japan, have published most of the papers 6 years ago, and still need to carry on researching new technology in the future.

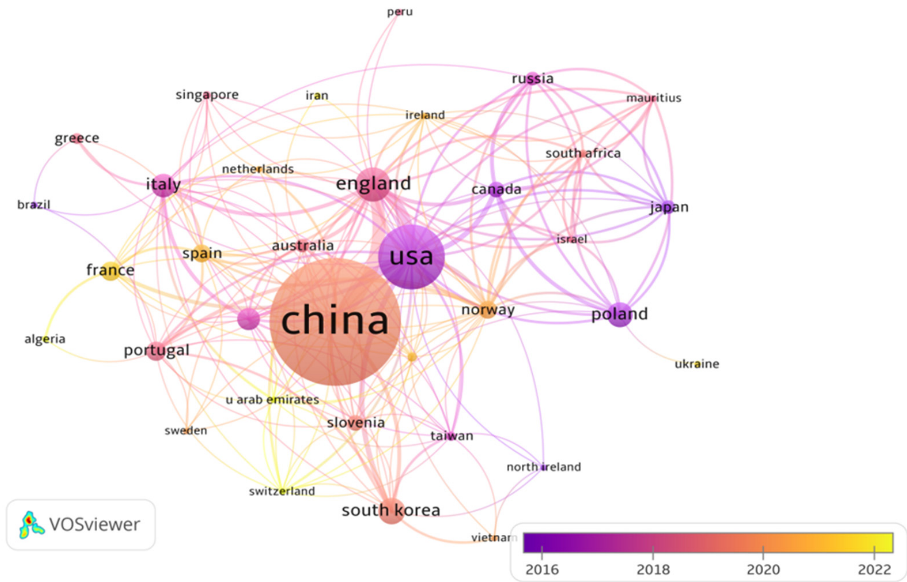

Figure 9. The network of international collaboration using analysis of co-authorship.

3.2.4. Disciplines and Subjects Analysis

The examination of the new technology in USVs as an interdisciplinary research field included a comprehensive spectrum of 77 distinct discipline categories, and disciplines with over 14 publications are visually represented in Figure 10. Within this diverse landscape of disciplines, it is notable that Engineering Electrical Electronic, Oceanography, Engineering Marine, Engineering Ocean and Automation Control Systems have prominently emerged as the dominant domains of study, as the publications related to these disciplines surpass 15%. To illustrate, the category of "Engineering Electrical Electronic" stood out as the most prolific with 108 publications, which account for a substantial 26.86% of the entire corpus of scrutinized documents. Following closely, "Oceanography" demonstrated its prominence with 103 publications, contributing significantly at 25.62%, while "Engineering Marine" occupied a vital role with 99 publications, representing 24.63% of the total.

Figure 10. Publication by subject category. Note: the number means the total number of publications by one subject. Source: Web of Science.

Within this interdisciplinary context, it is also intriguing to observe the presence of computer science disciplines among the top 10 most abundant categories. Disciplines such as "Engineering Electrical Electronic", "Robotics", "Computer Science Artificial Intelligence" and "Computer Science Information Systems" have secured their positions, underscoring the multifaceted and collaborative nature of new technology in USV research.

3.3. Citation and Co-Citation Network Analysis

3.3.1. Publications Citation and Co-Citation Analysis

Citation analysis is a way of measuring the influence and quality of a publication by counting the number of times that the publication has been cited by other publications [27]. The retrieved 402 papers were cited 3862 times by 3793 publications from 1270 publication sources. A total of 1881 out of 3793 publications were published by Chinese Institutions, which accounted for 49.60% of the citing publications. On top of that, out of 402 retrieved papers, 112 papers were never cited as of 1 October 2023; 235 papers, over half of the publications, were cited fewer than five times by any other publications.

Table 4 presents a compilation of the ten most extensively cited scholarly works in the domain of USV new technology authored by global researchers. Notably, the paper titled "6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions" by Chowdhury et al. [46], was considered both the most cited publication and the one with the highest average citation count. This article, while focusing on the subject of 6G wireless communication, offered a comprehensive review of research developments pertaining to the application and prospects of 6G and reveals potential cultivation in USVs. The second most frequently cited article, written by Lyu et al. [6] and published in 2019, presented a real-time and deterministic path-planning method for USVs in complex and dynamic navigation environments. In this paper, a modified Artificial Potential Field (APF), which contained a new modified repulsion potential field function and the corresponding virtual forces, was developed to address the issue of Collision Avoidance (CA) with dynamic targets and static obstacles, including emergency situations [6]. Additionally, among the recent frequently cited literature, Hover et al. [47] developed and applied algorithms for the central navigation and planning problems on ship hulls to achieve a closed-loop control relative to features such as weld lines and biofouling, thus laying a cornerstone for operations on naval ships. Furthermore, it is worth mentioning that in the top 10 most highly cited publications, 6 of them were concentrated on the path-planning research of USVs, from the objective of collision avoidance to the real-time algorithms, showing tremendous attention from scholars to these aspects.

Table 4. Top 10 most highly cited publications on USV.

Article	Title	TC	ACY
Chowdhury et al., 2020 [46]	6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions	415	103.75
Lyu et al., 2019 [6]	COLREGS-Constrained Real-time Path Planning for Autonomous Ships Using Modified Artificial Potential Fields	164	32.80
Hover et al., 2012 [47]	Advanced perception, navigation and planning for autonomous in-water ship hull inspection	157	13.08
Jahanbakht et al., 2021 [48]	Internet of Underwater Things and Big Marine Data Analytics-A Comprehensive Survey	129	43.00
Song et al., 2019 [49]	Smoothed A* algorithm for practical USV path planning	125	25.00
Lazarowska, A, 2015 [50]	Ship's Trajectory Planning for Collision Avoidance at Sea Based on Ant Colony Optimisation	116	12.89
Tsou et al., 2010 [51]	The Study of Ship Collision Avoidance Route Planning by Ant Colony Algorithm	116	8.29
Kahveci et al., 2013 [52]	Adaptive steering control for uncertain ship dynamics and stability analysis	99	9.00
Kristan et al., 2016 [53]	Fast Image-Based Obstacle Detection From USV	88	11.00
Kim et al., 2014 [54]	Angular rate-constrained path planning algorithm for USV	88	8.80

Notes: TC = times cited; ACY = average citations per year.

Co-citation, as originally articulated by Small [55] in 1973, refers to the frequency of instances where two documents are jointly referenced by other scholarly works. Employing co-citation analysis, a valuable method for assessing the resemblance between documents and revealing thematic structures within a research field, publications were organized into distinct clusters, as expounded upon by Li et al. [27] in 2020. Among the 10,108 references found within the 402 retrieved publications, a mere 1053 references received citations two or more times.

Figure 11 presents a graphical representation of the co-citation network, encompassing references that garnered citations exceeding seven occurrences within the retrieved publications of new technology in USV research. To conduct this analysis, VOSviewer was used as a powerful tool. The resultant network comprised 52 references that satisfied this citation frequency criterion. In this depiction, the sizes of the spheres correspond to the frequency of citations that each publication has received. Furthermore, the distinctive colors assigned to these spheres denote their affiliation with specific clusters, signifying overarching thematic patterns prevalent within the research domain. The detailed setting for the parameters used for the figure is provided in Appendix A Table A2.

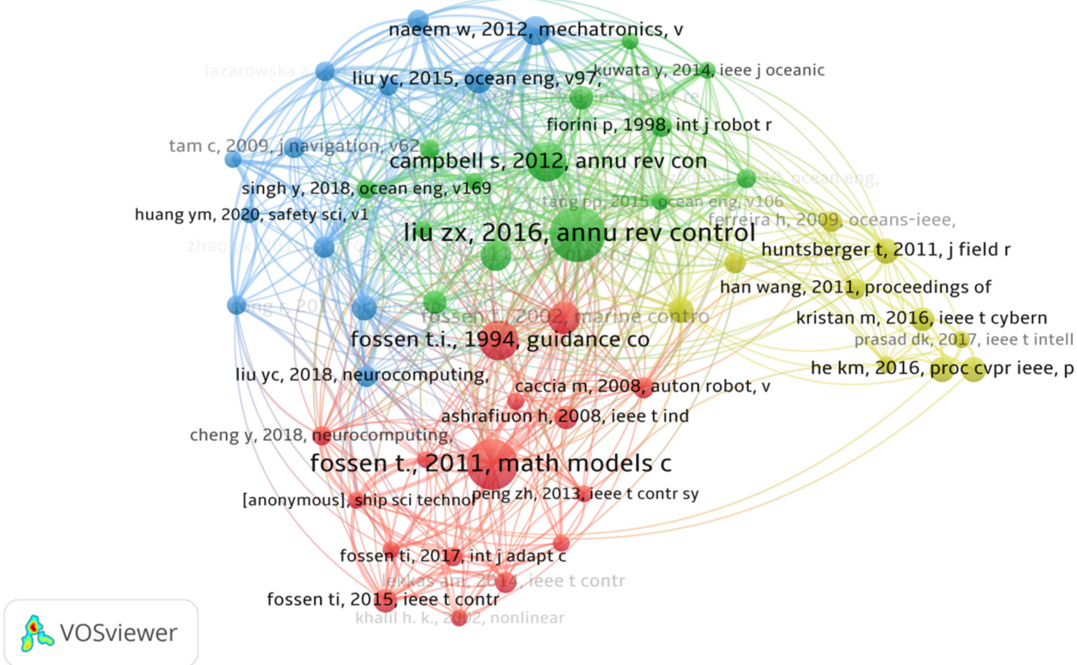

Figure 11. Co-citation network of references cited more than seven times in USVs.

Note that the total link strength within this network carries significant implications, as it reflects the cumulative intensity of connections between each unit. Notably, higher total link strength values signify closer inter-relationships with other units, underscoring their prominence within the co-citation framework.

As illustrated in Figure 11, these 52 references were effectively partitioned into four distinct clusters based on their co-citation associations. The demarcation of these clusters served as a valuable analytical approach for explaining the primary research themes characterizing each group. This identification process drew upon a comprehensive analysis of the titles and abstracts of the references comprising these clusters, thus shedding light on the fundamental narrative patterns underpinning the discourse within the research community.

The red cluster is the largest, with 16 references, primarily dedicated to the marine model control and control system. Within this cluster, the work titled "Handbook of Marine Craft Hydrodynamics and Motion Control", authored by Thor I. Fossen [56] in 2011, emerged as the most frequently cited publication, with 26 citations, and exhibited the highest total link strength of 76, thus establishing its pivotal role as the central reference in this thematic cluster. The green cluster is the second largest cluster, with 14 references. This cluster emphasizes the overview of USVs, robot automation and visual remote sensing. The article "Unmanned surface vehicles: An overview of developments and challenges" by Zhixiang Liu [2] in 2016 can be considered the core publication in this cluster, with the high citations (29) and total link strength (91), followed by the blue cluster with 12 references, primarily centered on the navigation and the neurocomputing application. Notably, the article titled "COLREGs-based collision avoidance strategies for unmanned surface vehicles", authored by W. Naeem et al. [57] in 2012, had the highest citation count at 13, and boasted the most substantial total link strength (78) within this cluster, thereby meriting recognition as the central reference shaping the discourse in this thematic group. Conversely, the smallest cluster, denoted by the color yellow and located at the right of the network, includes 10 references. The predominant themes in this cluster revolved around AI applications, such as deep learning, obstacle detection, object detection and autonomous visual perception. The article titled "Stereo Vision-Based Navigation for Autonomous Surface Vessels", authored by Terry Huntsberger et al. [58] in 2011, occupied the central position within this cluster, marked by the highest citation count of 11 and the most significant total link strength of 34.

3.3.2. Distribution and Co-Citation Analysis of Journal Sources

The final phase of the bibliometric analysis involved an investigation of the sources of the documents contained within the dataset. The analysis is needed to identify which journals are most frequently read and productive in the field of new technology in USV and to provide the scholars with tips for contributing to their manuscripts. The 402 retrieved articles were published from 295 unique publication sources. The sources with at least eight published documents are presented in Table 5, while mapping is depicted in Figure 12.

Table 5. The top six most productive journals on USV research.

Rank	Journal	TP	TC	AC	IF
1	*Ocean Engineering*	28	344	12.29	5.0
2	*Journal of Marine Science and Engineering*	16	89	5.56	2.9
3	*Sensors*	15	250	16.67	3.9
4	*IFAC-PapersOnLine*	14	80	5.71	/
5	*Applied Sciences-Basel*	9	100	11.11	2.7
6	*IEEE Access*	8	104	13.00	3.9

Notes: TP = total publications; TC = times cited; AC = average number of citations per publication; IF = influence factor.

The preeminent sources in this context are primarily represented by two distinguished journals: *Ocean Engineering* (OE) and *Journal of Marine Science and Engineering* (JMSE). The total amount of papers published through the two journals, numbering 21 and 15, respectively, constituted nearly 11% of all articles within the data sample. It is noteworthy, however, that a considerable discrepancy existed in the quantity of documents between the fourth-ranked source and the subsequent source in the collation, as elucidated in Table 5. *Sensors*, being in the third position, exhibited one publication fewer than that of JMSE, but demonstrates the highest average citation in the list, followed by *Ocean Engineering* with the second highest average citation (12.29). This is also consistent with the journal's impact factor ranking, where *Ocean Engineering* and *Sensors* have a relatively high impact factor among the top six most productive journals in the list. Additionally, there were also substantial groups of journals with either two or just one published paper, indicating that the papers in this field were not centralized but scattered in their quality, to some extent.

The journal co-citation analysis is a valuable method for categorizing journals by subject and pinpointing the key journals within each category. This is particularly beneficial for researchers seeking to identify the most pertinent and influential journals related to their specific research area. Hence, the sources were also analyzed in terms of how often they were cited together, a concept known as co-citation [26]. Herein, the relationship between the two publications is determined by the number of documents that reference both of them [26]. This bibliometric network method was employed to visualize the interconnections among the sources. A minimum threshold of 60 citations per source was set, resulting in 28 sources meeting this criterion. The strength of these connections was determined by the number of citations. Through fractional counting and fractionalization, four clusters were identified as a means of normalizing the data in Figure 12. The detailed setting for the parameters used for the figure is provided in Appendix A Table A2.

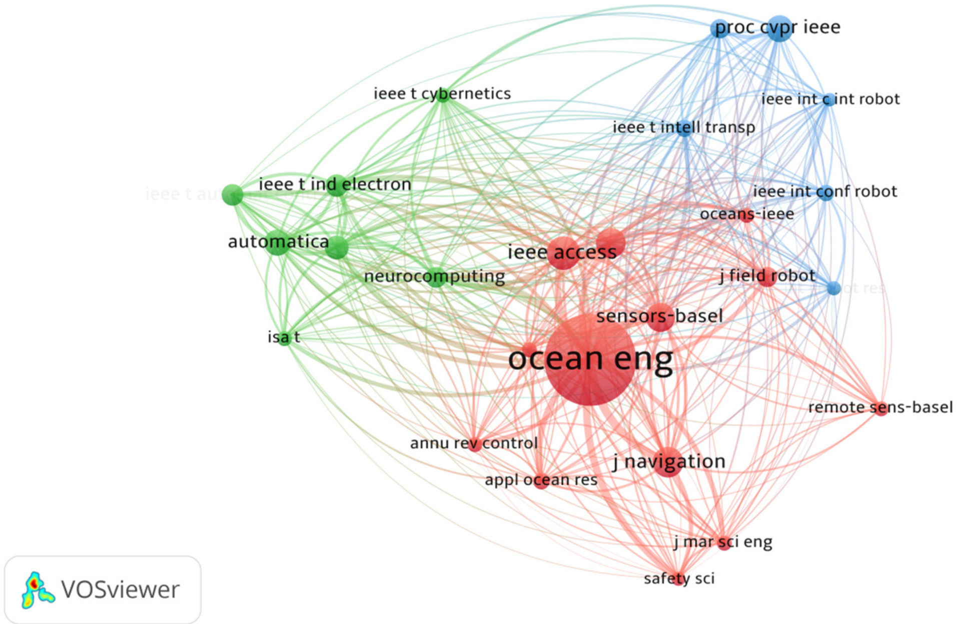

Figure 12. Co-citation network of journal sources.

The co-citation analysis reveals that *Ocean Engineering* and *IEEE Access* were the most significant sources. Interestingly, the cluster associated with *IEEE Conference on Computer Vision and Pattern Recognition* included several sources in the field of computing and robotics, such as *International Journal of Robotics Research*, *IEEE International Conference on Robotics* and *IEEE Transactions on Intelligent Transportation Systems.* These sources were connected to documents discussing regulations pertaining to maritime transportation design and maritime robotics innovation.

The second prominent cluster is centered around *Ocean Engineering*, a journal that encompassed sources related to marine engineering, ship dynamics, ship navigation and similar topics. The role of *Ocean Engineering* in the network is clear, acting as a bridge between safety and navigational-related sources on one hand, and sources focused more on mechanical engineering and hydrodynamics, such as *Journal of Field Robotics*, *Sensors*, *Remote Sensing* and *Applied Ocean Research* on the other hand. This suggests that the sources focusing on algorithms and models for path-planning and evasive maneuvers frequently cite documents chiefly originated from *Ocean Engineering*.

The third cluster primarily consists of automation control journals, strongly associated with publications like *Automatica*, *IEEE Transactions on Control Systems Technology*, *IEEE Transactions on Cybernetics* and *ISA Transactions.*

3.4. Keywords and Term Analysis

The content found within keywords, titles and abstracts serves as valuable data for deducing the primary subject matters and emerging patterns in a particular research domain. This is achieved through the application of text mining methodologies, as demonstrated by the study conducted by Li and colleagues in 2021 [27]. In the current research project, a co-occurrence analysis of keywords and a co-occurrence analysis of terms were carried out by VOSviewer software. The former one shows the research hotpots in a single special point while the latter one provides a more comprehensive elaboration of hot topics by involving the extraction of textual strings from the keywords, titles and abstracts of all publications contained within the database under investigation. The amalgamation of the two analyses can display a profound image of this field.

3.4.1. Keywords Analysis

Keywords usually contain valuable information regarding the intended focus of the author. The co-occurrence analysis of keywords is widely used to reveal the interconnection of keywords and to help readers gain insight into research hotspots and future trends [59]. In Figure 13, a visualization of the most significant keywords is presented, which included both the author's keywords and keywords plus.

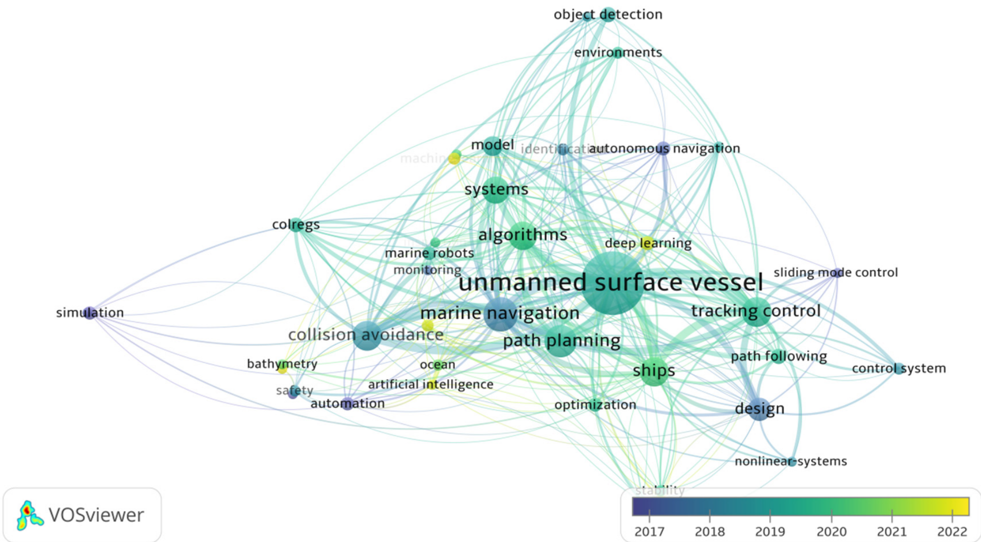

Figure 13. Co-occurrence network of USV keywords.

This visualization was based on the frequency of their shared occurrences in the documents under analysis. A total of 1734 keywords were identified by VOSviewer from the 402 retrieved articles. Among these, over 1500 terms appeared only once or twice, and 46 terms appeared more than five times, which is set as the criteria. A method of normalization was employed using association strength. The weights assigned to the keywords were calculated based on their frequencies, and the different clusters were distinguished by color-coding.

The analysis focused on new technology in USV development, leading to the identification of keywords predominantly associated with this domain. Notably, emerging trends were discernible within the dataset. High-frequency keywords highlighted the keen interest of researchers in new concepts such as path-planning algorithms, marine navigation, the design of systems and collision avoidance. Additionally, related keywords, though less frequent, included e-Navigation, marine robots, machine learning and sensor fusion. This heightened focus on collision-avoidance could be attributed to the advancements in e-Navigation and the issue of COLREGs.

Furthermore, the terms, i.e., control system, multi-agent systems, nonlinear-systems and tracking control indicated researchers' utilization of real-time or historical traffic data for developing novel systems grounded in AI. This shift could be linked to the progressive integration of AI in the shipping industry, as evidenced by relevant studies [60–70]. Additionally, the inclusion of environments, identification, remote sensing and object detection in the ranking suggested a growing inclination towards environmental perception in maritime decision-making process.

The research within the field of USVs has evolved significantly over the years. In 2017, the foundational aspects of simulation, autonomous navigation, and sensor technology formed the key areas of scholarly attention. Afterwards, the focus transitioned towards enhancing capabilities in monitoring, path planning and identification, laying the groundwork for more intricate system functionalities. By 2018, the emphasis shifted to the practical application of these technologies, with a heightened focus on collision avoidance, control systems, safety measures and environmental perception. The year 2019 marked a pivot towards the integration of sensor fusion and system identification, signaling a trend towards multifunctionality and the amalgamation of diverse technologies. The period from 2020 to 2022 witnessed a surge in AI-centered research, characterized by the incorporation of advanced AI algorithms, such as deep reinforcement learning, machine learning, and neural networks, and the utilization of satellite data and computer vision. These developments underscore a broader trend of enhancing communication and intelligent decision-making capabilities in USVs.

3.4.2. Term Analysis

A total of 11,270 terms, derived from keywords, titles and abstracts, were identified using the VOSviewer from the 402 retrieved articles. Among these, 9486 terms only appeared for one time and 448 terms appeared more than five times. To identify the hot topics in USVs, a restriction was set to include terms that appeared at least 10 times; a total of 109 terms, as 60% of the most relevant terms, were extracted, mapped and clustered in two-dimensional space.

Figure 14 illustrates the clustering of terms within new technology in the USV research domain, with an additional temporal dimension incorporated. In this depiction, the average publication year of each term's appearance within the research domain has been computed and assigned to each corresponding node on the map. Warmer, redder nodes signify more recent term appearances. A comparative analysis of the temporal factors in the three clusters revealed that terms within Cluster 1, encompassing multiple USVs, control strategy, external disturbance and stability, along with Cluster 2, associated with machine autonomy, numerical simulation and communication, as well as Cluster 3, featured by environmental identification and monitoring, were relatively recent in their emergence.

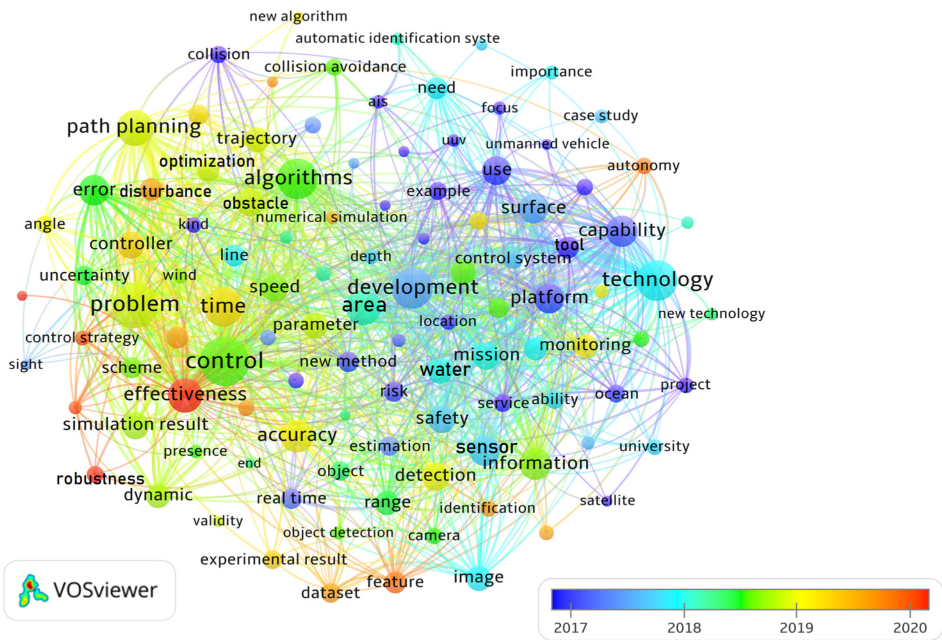

Figure 14. Term clusters of USV domains.

Comprehending the causes behind USVs constitutes a significant aspect of this research domain. The innovation of algorithms and the development of computer science have long been pivotal components of investigating the origins of new technology in USVs. This research area has historically scrutinized technological variables such as robustness, effectiveness, optimization, validity and accuracy. In recent years, a surge in research activity has been observed within Cluster 1, dedicated to the exploration of new vehicle forms with AI, and the new technology in control, communication and detection contributing to USVs.

4. Synthesis and Summary

4.1. Past and Current Trends

As is depicted in Figure 4, before 2008, there was a notable scarcity of English-language scholarly articles in the domain of USVs, perhaps due to the sluggish and outdated technology development. However, subsequent to this period, there has been a remarkable and approximately linear growth in the volume of such publications. Presently, China ranks first globally in terms of the total number of publications in this field. One plausible catalyst for this development could be traced to a series of advances in technology, such as the deep learning put forward by Hinton et al. [71] in 2006 and some national policies like Maritime Power Strategy (2012). With the development of AI and the accomplishments of unmanned underwater vessels, the focus has transferred from the underwater field to the surface field, thus forming an all-ranging application of unmanned vessels.

Currently, the publication in this field is predicted to keep soaring, and is likely to reach a new breakthrough, in line with the development of ChatGPT and 6G communication technology.

4.2. The Features of Social Structure

Considering the leading scholars in the field of new technology in USVs globally, Yuanchang Liu from University College London, Kristan Matej from University College London, Bucknall Richard from University College London and Yun Li from Shanghai Maritime University were the top four most productive authors, and Bucknall Richard had the highest average citations among all the authors, which testified to his powerful contribution and influence in this field.

As for the most productive institutions related to this realm, Dalian Maritime University, Harbin Engineering University, Chinese Academy of Science and University College London were the top four most productive institutions. It is intriguing to find that the four institutions were within or extremely close to the coastal regions, a compelling reality condition that provides them with abundant resources and scientific conditions. Moreover, Bo Wang, Peng Jiang, Xinyu Zhang and Yulei Liao not only exhibited high productivity but have also demonstrated significant activity, particularly in the last 3 years.

With regard to the international cooperation on new methods in USV research across the world, China, England, USA and South Korea were the alliances most frequently collaborating in USVs. International cooperation sometimes was confined to restricted international cooperation, since a noticeable link circle emerges with a majority of the European continent. On top of that, international cooperation was also embodied in institutions; Dalian Maritime University, UCL, Harbin Engineering University, Polish Nava Acad, National University of Singapore were the core institutions carrying out the collaboration between the regional institutes or international institutes, in their respective clusters, showing a strong capability to launch international cooperation and resource integration. There is telling evidence that the institutions in China have a strong mutual cooperation link with each other, in the domestic regard.

In terms of geographical distribution, China was the pioneer, with the largest number of publications at 177, followed by the United States with 68, England with 34, South Korea with 29 and Poland with 25. However, the most productive countries were located in economically developed coastal areas and areas with more universities in ocean engineering and computer science. It is worthwhile to point out that the developing countries had a limited global impact in the field of new technology in USVs in terms of publications and citations, as only two developing countries ranked within the top 15 productive countries, suggesting that new technology in USVs is well embraced and propelled in developed countries under most circumstances.

The information is likely to assist Chinese students with an inclination towards USVs in identifying appropriate educational institutions for advanced studies and suitable academic mentors for pursuing research degrees. Furthermore, the findings may serve as a valuable resource for international scholars or institutions seeking to identify high-performing establishments for collaborative endeavors. Additionally, they can facilitate partnerships between industry and academia for concerted efforts in the domain of USVs.

4.3. Citation and Co-Citation Network Summary

The citation analysis shows that, though China has the highest of citations, with reference to Table 6, the average citation rate of Chinese scholars in the USV field is comparatively low in the top five most cited countries, with nearly a third of the articles never having been cited. The USA has a total number of citations close to China, whereas it only has about the half of publications of China's, showing that the USA's new technology in USV research currently has a relatively powerful international impact, and that China should make efforts to enhance the quality of its articles.

Table 6. The top five countries with highest number of citations.

Rank	Country	TP	TC	AC	H-Index
1	China	172	1455	8.46	19
2	USA	68	1320	19.41	18
3	South Korea	20	704	35.2	8
4	England	29	605	20.86	10
5	Poland	19	334	17.58	8

Notes: TP = total publications; TC = times cited; AC = average number of citations per publication.

According to co-citation analysis, the new technology in USV research primarily focused on four aspects: control system, navigation technology, robot automation and visual remote sensing, as well as autonomous visual perception, such as path planning and object detection.

The primary journals that witnessed substantial contributions from international scholars and exhibited significant impact citations included *Journals of Ocean Engineering, Journal of Marine Science and Engineering, Sensors, IFAC-PapersOnLine* and *Applied Sciences-Basel.*

A co-citation analysis of these referenced journals reveals four principal thematic clusters where scholars, engaged in the field of USV, actively contribute: (i) models, algorithms and systems; (ii) navigation, sensing and safety; and (iii) automation and robots; (iv) AI, deep learning and intelligent machines.

4.4. Future Directions

The analysis of prevalent themes in new technology in USV research reveals a pronounced emphasis on path-planning algorithms, marine navigation, the design of systems and collision avoidance, marine robots, sensor fusion, e-Navigation, multi-agent systems and simulation. However, throughout the period from 2014 to 2018, the discernible observation shows the limited emergence of novel topics, always focused on simulation and navigation. The heated keywords featured with the latest version are centered on machine learning, AI and deep learning, which were actually initiated 10 years ago. Hence, the application of AI in USVs is a little hysteretic, and there is still a long way for us to go. While scholars have made substantial contributions to the new technology of USVs, evident in the extensive publication of English-language articles across diverse subjects, the scarcity of groundbreaking methodologies or research focus during this period is conspicuous, despite tremendous efforts put into planning algorithms. This suggests a potential gap in impact or innovation. Consequently, there exists considerable scope for enhancement within specific subdomains of the research field in USVs, necessitating efforts to align with and potentially surpass advancements achieved at the current time.

In light of these considerations, the prospect of shaping future research directions in the realm of USV is explored, drawing inspiration from the most recent advancements in global USV research. It is recommended that scholars should in future give further attention to the following research topics to achieve shipping safety, energy saving and emission reduction, and reducing operating costs.

4.4.1. Enhanced Intelligence and Autonomy

The intelligent waterway has been increasingly heated in recent years, spurring the technology of intelligence and autonomy. As the development of the Yangtze River's smart waterway infrastructure progresses, the deployment of USVs in its inland channels has seen a significant rise. For the autonomous navigation of the "Jinghai-I" USV within these inland waterways, a composite route determination technique has been formulated. This technique merges an enhanced A* algorithm with a refined model predictive control algorithm, demonstrating proficient autonomy and intelligent navigational capabilities [72]. To improve the autonomy level, a method combining the use of sparse random neighborhood graphs and constrained nonlinear Model Predictive Control (MPC), while implementing a feedback strategy that navigates through sparsely connected areas free of obstacles using a sequence of MPC policies, was proposed by Atasoy Simay [73]. New technology with intelligence was also used in the health management of USVs, exemplified by a hybrid neural network (HNN) prediction model, which integrates Convolutional Neural Networks (CNN), Bidirectional Long Short-Term Memory (BiLSTM) and Attention mechanisms, designed specifically for the prediction of Exhaust Gas Temperature (EGT) in marine diesel engines. This approach provides a new way of thinking for the research of fault early warning and the health management of marine diesel engines [74]. To speed up autonomy, the Unmanned Maritime Systems Program Office (PMS 406) is enhancing autonomy in unmanned maritime vehicles through the Unmanned Maritime Autonomy Architecture (UMAA) for software standards and the Rapid Autonomy Integration Lab (RAIL) for developing new capabilities [75]. Intelligence and autonomy likewise show their advantage in risk analysis [76].

In the future, it is predicted that USVs will become more intelligent and autonomous through the integration of AI, deep learning and machine learning technologies [77]. This will enable them to better perceive their environment, make autonomous decisions, and execute tasks. This advancement will encompass state-of-the-art sensing and obstacle avoidance systems, as well as robust decision support systems. Additionally, the level of autonomy in USVs will continue to rise, including autonomous path planning, autonomous cruising and autonomous maintenance. This will alleviate the burden on operators, enhance efficiency and reduce costs.

4.4.2. Highly Integrated Sensor Systems and Multi-Modal Task Execution

Recent advances in robotic design, autonomy and sensor integration create solutions for the exploration of deep-sea environments [78]. As marine exploration and exploitation continue to advance, coupled with the strides made in mechanical intelligence, there is a notable emphasis on the utilization of USVs and the intricate design of their guidance systems. A newly developed module in 2021, designated as the Three-Dimensional Perception Module (PMTD), employs a combination of camera and LiDAR technology to assimilate multi-dimensional environmental data. This module attains centimeter-level localization accuracy through the integration of Global Positioning System (GPS) and Inertial Measurement Unit (IMU) technologies [79]. A new integrated USV and unmanned underwater vehicle (UUV) platform connected via underwater cables capable of acquiring real-time underwater data and long-time operation was developed to gather more sensory data for decision making [80].

Additionally, new technology was presented in a novel recovery system: one a piece of hardware that ensures the attainment of unique attitude requirements and improves the effectiveness of stern chute recovery [81]. A new controller for dynamic positioning was then developed, combining model predictive control with predictions of short-term wave movements. This approach effectively compensated for wave effects, thereby significantly enhancing the operational capabilities of the vessel [82]. With more and more adjuncts devised, USVs will be expected to be equipped with a greater variety of and higher resolution sensors, such as high-resolution cameras, LiDAR, sonar, radar and more, to enhance their environmental perception capabilities [83]. This will contribute to a broader range of applications, including ocean surveys, marine conservation, military operations and emergency response.

In the meanwhile, USVs will be capable of executing a variety of tasks, including underwater exploration, subsea operations, cargo transportation, search and rescue, etc. This will necessitate advanced adaptive control systems and task-planning algorithms.

4.4.3. Extended Endurance and Resilience

For intelligent systems, the endurance and resilience are important in case of fatal failure. Effective human-AI interaction design is predicated on increased cross-disciplinary efforts, requiring reconciling productivity with resilience [84]. To investigate the fragile problems of the controller, a new non-fragile fault-tolerant scheme was provided against multiplicative and additive controller gain perturbations [85]. An adaptive error constraint line-of-sight guidance law was originally proposed with better transient and steady-state performance, and simplified the design of the controller by not relying on interference observers [86]. A new approach is suggested for the high-level processing of received data to evaluate their consistency, which is agnostic to the underlying technology of the individual sensory input [87]. This approach [87] demonstrates the feasibility of identifying anomalies in nominal operations when the navigation sensor is subjected to adversarial attacks or experiences malfunctions.

Furthermore, it is concluded that deploying multiple USVs as a formation fleet benefits great fault-tolerant resilience [88]. A new algorithm named the 'angle-guidance fast marching square' (AFMS) was presented, and a novel priority scheme based upon the distance to the closest point of approaching (DCPA) has been proposed and developed to efficiently and effectively navigate the USV formation [88]. A comprehensive training framework encompassing multiple tasks has been formulated for the management of formation control, tailored to the dynamic behavior of Unmanned Surface Vehicles and employing the leader–follower approach. Within this framework, the Soft Actor-Critic (SAC) reinforcement learning algorithm has been modified to facilitate the development of agent constructs [89].

Last but not least, the development of more efficient battery technology and the integration of renewable energy sources and power systems will also incessantly enable USVs to achieve extended endurance. This will allow them to carry out longer-duration missions, such as ocean monitoring and research [90]. A hybrid power system [91] comprising a solar array, an ocean wave energy converter, a fuel cell system, a diesel generator and a lithium ion battery pack was designed. The results show that optimization has been achieved with a 19.6% contribution from solar power during daylight hours and a 5.53% contribution of the wave energy harvester to meet the load demands [91]. And, an AutoNaut uncrewed surface vehicle powered entirely by renewable energy has been invented as the first USV to regularly run scientific missions off the coast of the UK [92].

Therefore, research related to fault-tolerant schemes and resilience amelioration by means of the USV formation has always been a heated discussion in the topic of USVs. And, in a more practical perspective, the industry will call for an increasing innovation of power systems in the future.

4.4.4. Satellite Communication and Interconnectivity

Nowadays, the majority of navigation systems employed by USVs utilize integrated approaches combining the global positioning system (GPS) and inertial navigation system(INS) methods to enhance overall navigation accuracy. To enhance and keep the performance in case of outages, interference and weakness, a continuous and accurate navigation solution was put forward via integrated GPS with micro-electro-mechanical (MEMS)-INS smartphone sensors and reduced-aided visual odometry (RAVO) using centralized Kalman filter (CKF) data fusion [93]. In case of insufficient satellites, the loose and tight integrated models of the USV navigation system were established with effective performance in a certain time range with relatively lower position errors [94]. A framework, comprised of an execution module and a multi-layered planner, was designed to enable the AUV to avoid collisions, maintain communication with the USV, and increase the sum of the rewards by reaching many of the discovered goals and demonstrate the efficiency of the approach to solve dynamic multi-goal motion-planning problems with communication constraints [7]. At the same time, some communication quality evaluation models were researched in this part, including the mobile communication quality evaluation model based on the multi-path effect, the Doppler effect and the ray beam method [95].

Hence, it is presumed that USVs will make wider use of satellite communication technology for remote telemetry and remote control. Additionally, they will be better equipped to engage in real-time communication and collaborative operations with other USV, vessels and terrestrial stations. It is hoped that the 6G communication [46] will be a recipe for the ground-breaking progress of USVs.

4.4.5. Eco-Friendly and Sustainable Practices

Climate change has become one of the top worldwide concerns and issues an urgent call for more sustainable developments in the near future [96]. A novel Remote Hyperspectral Imaging System (RHIS) was integrated into an Unmanned Aquatic Drone (UAD) for the purpose of detecting and identifying plastic debris in both coastal and freshwater ecosystems. The findings indicate that this newly implemented RHIS, in conjunction with the UAD, constitutes an environmentally friendly and effective method for the identification of plastic pollution in aquatic settings [97]. In the case that mobile sensors could not be deployed, the USV was taken to identify pollution sources, map the environmental impact and be an analysis tool for the further research of these ecosystems, promoting the green development of ecology [98].

The path-planning sector can also expedite the sustainable practices of USV, since an innovative path-planning algorithm, grounded in AI methodologies, was proposed to calculate viable navigation routes adhering to the Convention on the International Regulations for Preventing Collisions at Sea (COLREG). This algorithm uniquely incorporated considerations of energy efficiency, factoring in wind and sea current data to optimize energy consumption during maritime voyages [99]. Additionally, the USV was utilized in water quality monitoring [100,101], Arctic exploration [102] and persistent ocean observation [103], and was considered a catalyst for energy revolution [91], since some USVs are equipped with sustainable natural energy sources using solar arrays and ocean wave energy converters. An improved differential evolution particle swarm optimization algorithm (DePSO) was proposed, and demonstrates that it can effectively reduce the path intersection points, and thus greatly shorten the overall path length to reach sustainable development [104]. The integration of the chaotic quantum-behaved particle swarm algorithm (cQPSO) with the multi-population genetic algorithm (mGA) led to the development of a novel hybrid algorithm, termed cQPSO-mGA. This advanced algorithmic fusion demonstrated the effective resolution of the two-level scheduling model, as substantiated by empirical data. The results highlighted its proficiency in facilitating cost-effective transportation solutions and ensuring reliable path tracking [105].

Consequently, USV development will place greater emphasis on environmental sustainability, including emissions reduction, the adoption of renewable energy sources, and mitigating marine pollution through technological innovations, but the relevant research is blank at the moment.

4.4.6. Navigation Safety and Military Defense

The future of USVs holds great promise in enhancing security and defense capabilities, particularly in the military domain. This emphasis on safety and self-defense features underscores the growing importance of USVs in modern maritime operations.

In terms of navigation safety, object detection comes forth and trajectory planning follows in tune. The incorporation of a multi-scale feature extraction layer, encompassing dilation convolution and group convolution, into the baseline model of the Faster Region-based Convolutional Neural Network (Faster-RCNN), accompanied by modifications to the classification algorithm, was suggested. This enhancement aimed at augmenting the model's capability for obstacle detection, with a specific focus on bolstering its robustness and precision [106]. A fusion framework of field theoretical planning and a model predictive control (MPC) algorithm were proposed to obtain a realizable collision-free tracking trajectory to enhance safety, where the trajectory smoothness and collision avoidance constraints under a complex environment needed to be considered [107]. A new process of dynamic collision avoidance, combined with new attractive and repulsive potential field functions, was constructed to ensure the safety of USVs [108]. An innovative collision avoidance algorithm, predicated on Approximate Representation Reinforcement Learning (AR-RL), was developed to facilitate the collision avoidance capabilities of Maritime Autonomous Surface Ships (MASS) within a continuum state space. This algorithm was characterized by an interactive learning feature, mirroring the decision-making process of a human crew in navigational contexts. Its effectiveness has been established in significantly enhancing maritime safety, particularly in scenarios where mixed traffic consists of both manned vessels and MASS, promising substantial improvements in nautical safety in the foreseeable future [109]. In response to the critical requirement for assessing human error probability in terms of autonomous cargo ships with human–autonomy collaboration, a probabilistic model mixed with the Shore Control Centre (SCC), Technique for Human Error Rate Prediction (THERP)and Bayesian Networks was proposed, and was employed to evaluate the likelihood of human errors, specifically concentrating on the interaction between human operators and autonomous systems [110].

From the point of defense, the new technology of USVs mainly casts light on derivative techniques, combat theories and methods of arrangement in military scenarios. Multiple object tracking (MOT) in USV videos has many application scenarios in the military and civilian fields [111]. By projecting military power in a more affordable way, through the use of USVs, the exposure of human life to military risks should be significantly reduced [112]. A new attack strategy, USV combat based on wolves' attacks with weight, was testified to have conspicuous advantages in USV combat. In the future naval deployment of USVs, it is also proposed that, for the initial stages of exploration and investigation, the application of a queuing network theory was deemed more advantageous than relying on simulation-based analysis [112].

As is listed above, there are several hot research directions in this prediction, such as Enhanced Safety, Anti-Jamming Communication, Automatic Missile Defense Systems, Surveillance and Reconnaissance, Autonomous Swarming and Cost-Effective Alternatives.

4.4.7. Brief Summary

In summary, one of the primary areas of development will be the enhancement of intelligence and autonomy for USVs. This evolution is expected to be fueled by the integration of sophisticated AI, deep learning and machine learning technologies. These advancements will enable USVs to better perceive their environment, make autonomous decisions and execute complex tasks with greater efficiency and accuracy.

The focus will also be on developing advanced sensing and obstacle avoidance systems, as well as robust decision support systems, which will further enhance their operational capabilities in diverse environments. The progression in autonomy will likely include more sophisticated features such as autonomous path planning, cruising and maintenance, thereby reducing the reliance on human operators and enhancing operational efficiency.

Another significant area of development for USVs will be the integration of highly advanced sensor systems and the ability to execute multi-modal tasks. The advancement in sensor technology, including high-resolution cameras, LiDAR, sonar and radar, will significantly improve the environmental perception capabilities of USVs. This, in turn, will expand their applicability in various fields such as oceanographic research, marine conservation, military operations and emergency responses.

Furthermore, the enhancement in endurance and resilience through innovative power systems and fault-tolerant designs will enable USVs to undertake longer-duration missions and operate effectively in challenging conditions. The integration of renewable energy sources and eco-friendly practices in USV design will also contribute to sustainable maritime operations. In addition, the increasing use of satellite communication and improved interconnectivity will enhance remote operation capabilities, allowing for more coordinated and collaborative efforts in maritime missions.

Table 7 shows a brief and overall summary of this section.

Table 7. The summary of future directions.

Direction	New Trends	Effect
Enhanced Intelligence and Autonomy	Make autonomous decisions and execute tasks like autonomous cruising and autonomous maintenance	Alleviate the burden on operators, enhance efficiency and reduce costs
Highly Integrated Sensor Systems and Multi-Modal Task Execution	Marine conservation, military operations, underwater exploration, subsea operations, cargo transportation, search and rescue	Necessitate advanced adaptive control systems and task-planning algorithms
Extended Endurance and Resilience	More efficient battery technology and the integration of renewable energy sources	Allow them to carry out longer-duration missions
Satellite Communication and Interconnectivity	Real-time communication and collaborative operations with other USVs, vessels and terrestrial stations; 6G	A recipe for the ground-breaking progress for USV
Eco-Friendly and Sustainable Practices	Emissions reduction the adoption of renewable energy sources, mitigating marine pollution; new energy converter Intelligent feeding	More green to the world Cut down the cost
Safety and Defense	Enhanced Safety Anti-Jamming Communication Automatic Missile Defense Systems Surveillance and Reconnaissance Autonomous Swarming Cost-Effective Alternatives	Protect the lives of operators, countries and the sea
Eco-Friendly and Sustainable Practices	Emissions reduction The adoption of renewable energy sources, mitigating marine pollution new energy converter Intelligent feeding	More green to the world Cut down the cost

These developments, combined with the ongoing research in navigation safety and military defense applications, suggest that USVs will play an increasingly vital role in the future of maritime operations, offering both enhanced capabilities and cost-effective solutions.

4.5. Biases and Limitations

Despite the fact that this study has provided some valuable insights, it is essential to acknowledge its limitations, which stem from the publication retrieval process and the chosen analytical methodologies. Firstly, the exclusive utilization of the WoS database was necessitated by its adoption, attributed to variations in data standards. This constrained choice might have led to the inadvertent exclusion of pertinent papers concerning USV globally, potentially introducing biases in the outcomes and impeding a comprehensive elucidation of discernible patterns and developments. Moreover, this paper, based on existing research, primarily utilizes the WoS as the database for data retrieval. Future research could consider incorporating a wider range of databases to enrich the scope of the study and facilitate comparative analysis.

Secondly, to facilitate a broader understanding of the structural dynamics and evolutionary trends in USVs, this study focused exclusively on articles published in the English language, which is the predominant medium of academic discourse. Regrettably, a significant number of USV articles written by researchers from Non-English-speaking maritime powers, including countries like China, South Korea, Japan, Russia, etc., are published in their domestic language journals. Consequently, they are not included in the WoS database. The exclusion of these contributions could impact the comprehensiveness of the results.

Additionally, there are several common limitations that this paper may have encountered. These include potential publication bias, as certain types of articles or journals may be overrepresented or underrepresented in the chosen database, thus impacting the generalizability of the findings. The selected time frame for the analysis may influence the assessment of trends and patterns, as research topics and publication rates can evolve. The choice of bibliometric indicators, such as citation counts, can introduce sources of bias, as they may not capture the full impact or relevance of a paper. Moreover, the design of the search query, such as the confine of keywords and the combination of conjunctions, may also do a disservice to the final result.

Lastly, it is imperative to recognize that the scope of the database itself may not encompass all relevant articles, potentially resulting in the omission of some significant contributions to the field.

5. Conclusions

In this paper, to provide a detailed overview of the key contributions in this research domain, a comprehensive bibliometric analysis of USV research was conducted by utilizing 402 publications sourced from the WoS database. The analysis entailed the exploration of publication trends, the identification of influential authors, institutions, countries, notable articles, journals, disciplines, references and terms. Additionally, deeper insights were demonstrated of the international cooperation in USV research, explaining it from the perspectives of countries, institutions and authors. Furthermore, we used a dual-function word analysis to identify prevalent terms and keywords in USV research, thereby uncovering emerging research topics and trends. The evolution of focus areas in different periods was also analyzed, and future directions for the advancement of USV were put forth.

To facilitate a clearer understanding of the findings, this paper was supplemented with visual representations, including co-authorship networks of authors, countries and institutions, citation networks of publications and countries, co-citation networks of journals and density maps of focus topics, as well as the term networks. These visual aids serve to demonstrate the utility of bibliometric analysis in gaining insights into the development of USV research.

The implications of the results extend to various stakeholders. For scholars, the findings offer insights into the current state of research in the field, highlighting both strengths and weaknesses. Meanwhile, scholars can use the information to identify potential partners for collaborative educational and research endeavors in the realm of USVs. This collaboration has the potential to contribute not only to the sustainable development of sustainable marine development but also to related industrial activities worldwide.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. The iteration of query.

Time	Index Word Input	Number of Papers
1	TS = (unmanned surface vessel) AND TS = (new technology) AND TS = (automation)	1
2	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel) AND TS = (new technology or new science or new technique) AND TS = (automatic control or automation or automatization)	7
3	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel) AND TS = (new technology or new science or new technique or advanced technology) AND TS = (automatic control or automation or automatization or robotization or automate)	30
4	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship) AND TS = (new technology or new science or new technique or advanced technology) AND TS = (automatic control or automation or automatization or robotization or automate)	30
5	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships driverless surface ships or unmanned surface marines or driverless surface marines) AND TS = (new technology or new science or new technique or advanced technology) AND TS = (automatic control or automation or automatization or robotization or automate)	32
6	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles) AND TS = (new technology or new science or new technique or advanced technology) AND TS = (automatic control or automation or automatization or robotization or automate)	91
7	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles) AND TS = (new technology or new science or new technique or advanced technology) AND TS = (automatic control or automation or automatization or robotization or automate or marine navigation)	108

Table A1. *Cont.*

Time	Index Word Input	Number of Papers
8	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles) AND TS = (new technology or new science or new technique or advanced technology or new technologies or new technological or new processes) AND TS = (automatic control or automation or automatization or robotization or automate or marine navigation)	145
9	TS = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and TS = (new technology or new science or new technique or advanced technology or new technologies or new technological or new processes or new methods or new method or new model or new approach) and TS = (automatic control or automation or automatization or robotization or automate or marine navigation or automatic operation or automated or automations) OR TI = (driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles unmanned surface vessels or automatic surface vessels or driverless surface vessels) and TI = (new technology or new science or new technique or advanced technology or new technologies or new technological or new processes or new methods) and TI = (automatic control or automation or automatization or robotization or automate or marine navigation or automatic operation or automated or automations)	216
10	TS = (USV or unmanned surface vehicle or driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or marine navigation or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and TS = (new technology or new science or new technique or advanced technology new technologies or new technological or new processes or new methods or new model or new approach) and TS = (automatic control or automation or automatization or automate or robotization or automatic operation or automated or automations) OR TI = (USV or unmanned surface vehicle or driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or marine navigation or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and TI = (new technology or new science or new technique or advanced technology new technologies or new technological or new processes or new methods or new model or new approach) OR AB = (USV or unmanned surface vehicle or driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or marine navigation or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and AB = (new technology or new science or new technique or advanced technology new technologies or new technological or new processes or new methods or new model or new approach)	1025

Notes: TS = Topic; TI = Title; AB = Abstract.

The final search strings in this article.

TS = (USV or unmanned surface vehicle or driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or marine navigation or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and TS = (new technology or new science or new technique or advanced technology new technologies or new technological or new processes or new methods or new model or new approach) and TS = (automatic control or automation or automatization or automate or robotization or automatic operation or automated or automations)

OR

TI = (USV or unmanned surface vehicle or driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or marine navigation or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and TI = (new technology or new science or new technique or advanced technology new technologies or new technological or new processes or new methods or new model or new approach)

OR

AB = (USV or unmanned surface vehicle or driverless surface vessel or unmanned surface vessel or manless surface vessel or unattended surface vessel or automatic surface vessel or unmanned surface ship or driverless surface ship or unmanned surface ships or driverless surface ships or unmanned surface marines or driverless surface marines or unmanned surface vehicles or driverless surface vehicles or automatic surface vehicles or marine navigation or unmanned surface vessels or automatic surface vessels or driverless surface vessels) and AB = (new technology or new science or new technique or advanced technology new technologies or new technological or new processes or new methods or new model or new approach)

Table A2. Parameter setting of mapping.

Figure	Resolution	Min. Cluster Size	Attraction	Repulsion	Threshold
Figure 5	1	1	2	−3	2
Figure 6	1	1	2	−2	2
Figure 8	1	4	2	−2	2
Figure 9	1	4	2	−2	2
Figure 11	10	8	2	0	7
Figure 12	1	5	0	−1	60
Figure 13	10	6	2	−1	5
Figure 14	1	1	3	−1	10

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