Review

Applications, Evolutions, and Challenges of Drones in Maritime Transport

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Abstract: The widespread interest in using drones in maritime transport has rapidly grown alongside the development of unmanned ships and drones. To stimulate growth and address the associated technical challenges, this paper systematically reviews the relevant research progress, classification, applications, technical challenges, and possible solutions related to the use of drones in the maritime sector. The findings provide an overview of the state of the art of the applications of drones in the maritime industry over the past 20 years and identify the existing problems and bottlenecks in this field. A new classification scheme is established based on their flight characteristics to aid in distinguishing drones' applications in maritime transport. Further, this paper discusses the specific use cases and technical aspects of drones in maritime rescue, safety, navigation, environment, communication, and other aspects, providing in-depth guidance on the future development of different mainstream applications. Lastly, the challenges facing drones in these applications are identified, and the corresponding solutions are proposed to address them. This research offers pivotal insights and pertinent knowledge beneficial to various entities such as maritime regulatory bodies, shipping firms, academic institutions, and enterprises engaged in drone production. This paper makes new contributions in terms of the comprehensive analysis and discussion of the application of drones in maritime transport and the provision of guidance and support for promoting their further development and integration with intelligent transport.

Keywords: drones; maritime transport; maritime applications; development trends; drone applications

1. Introduction

The maritime industry has recently experienced a surge in research and applications of Unmanned Aerial Vehicles (UAVs), supported by advanced technologies, for instance, the Internet of Things, digital technology, autonomous driving, and Artificial Intelligence (AI) technology [1–4]. UAVs, commonly known as drones, are remotely or autonomously controlled aircrafts that operate without a pilot [5,6]. Their development results from the integration of various technologies, including aviation, information, network communication, cloud computing, power, AI, and flight control [7–10]. Drone applications have become increasingly significant in maritime transport, including ship inspections, marine life monitoring, search and rescue operations, and environmental assessments [11–16]. Drones can provide real-time data on ocean currents, water quality, and weather conditions, facilitating accurate and efficient decision-making. This information is essential for improving navigational safety, optimising shipping routes, and reducing environmental impact.

Currently, the use of UAVs in maritime transport has evolved into a multi-functional and diversified direction. To enhance their capabilities, specialised sensors (e.g., inertial and image sensors) have been designed and developed to be mounted on UAVs [17–19], leading to the emergence of various applications. Firstly, target detection algorithms such as Region-Convolutional Neural Networks (R-CNN) and You Only Look Once (YOLO) have been used to detect sea violations and mitigate risks [20–24]. The existing object detection algorithms for UAVs can be classified into two-stage and single-stage networks. While two-stage detection algorithms possess high accuracy, they operate slowly. In contrast, single-stage detection algorithms run faster but have a higher rate of false positives. Secondly, drones have been used for exhaust gas monitoring [18,25,26], resulting in more efficient regulatory enforcement. Conventional approaches, such as direct onboard inspections, suffer from low monitoring efficiency, low sampling ratios, and operational complexity. Thirdly, drone technology has been integrated into marine rescue platforms, successfully locating and planning paths to rescue targets [27–29]. The three main types of UAVs used in marine rescue are maritime search and rescue UAVs, high-endurance UAVs, and ground-effect UAVs. Finally, drones have also been utilised in evaluating marine pollution and obtaining evidence of damage to the marine environment [16,30–32]. Traditional satellite remote sensing monitoring has limitations regarding the high-frequency and rapid acquisition of sea area information. In summary, the integration of drone technology in maritime transport has shown strengths in ship operational efficiency, safety, and sustainability.

The primary motivation for exploring the applications, evolutions, and challenges of drones in maritime transport stems from the intersection of technological advancement and the maritime industry's operational needs. Drones offer the potential for enhanced operational efficiency, heightened safety measures, and robust environmental monitoring in maritime operations. Furthermore, they could usher in significant economic benefits through cost savings and increased efficiency. However, it is essential to address the integration challenges to maintain regulatory compliance and ensure that the maritime sector remains forward-thinking and prepared for the future. This research aims to explain how drones can revolutionise maritime transport, bringing together technological advantages and addressing inherent challenges.

To enhance the integration of drones into maritime transport, the following research questions are investigated in this paper:

(1) How can a novel taxonomical framework of drones be formulated to optimise the prospective utilisation of drones in the maritime realm?

(2) What is the current status of drone development and research progress in the maritime industry?

(3) In the scenarios where drones are the most applied within the context of maritime transport, how do these applications impact the operational efficiency of the maritime industry?

(4) What challenges hinder the broader adoption of drones in the maritime field, and what potential solutions or strategies can be proposed to address these challenges?

Despite the considerable potential drones present for the maritime industry, a notable gap persists in the systematic review of their application, evolution, and inherent challenges. The contributions of this study include the following:

(1) Conduct a systematic literature review of drones' current development and research progress of drone applications in the maritime industry.

(2) Establish a new classification scheme for drone research to facilitate their future applications in maritime transport.

(3) Conduct an in-depth analysis of the applications of drones in maritime transport.

(4) Identify the challenges facing the broader use of drones in maritime transport and proposing potential solutions.

The flowchart of this paper is presented in Figure 1. Section 2 describes a systematic review of the recent advancement of UAV research in maritime transport and explores the definitions and classifications of UAVs, providing readers with up-to-date information. Section 3 provides an overview of drone applications in maritime transport, categorising them and listing the technologies employed for each category. Section 4 discusses the technical challenges that drones encounter, including the future challenges in maritime transport. Section 5 concludes this paper and outlines the future trajectory of drones.
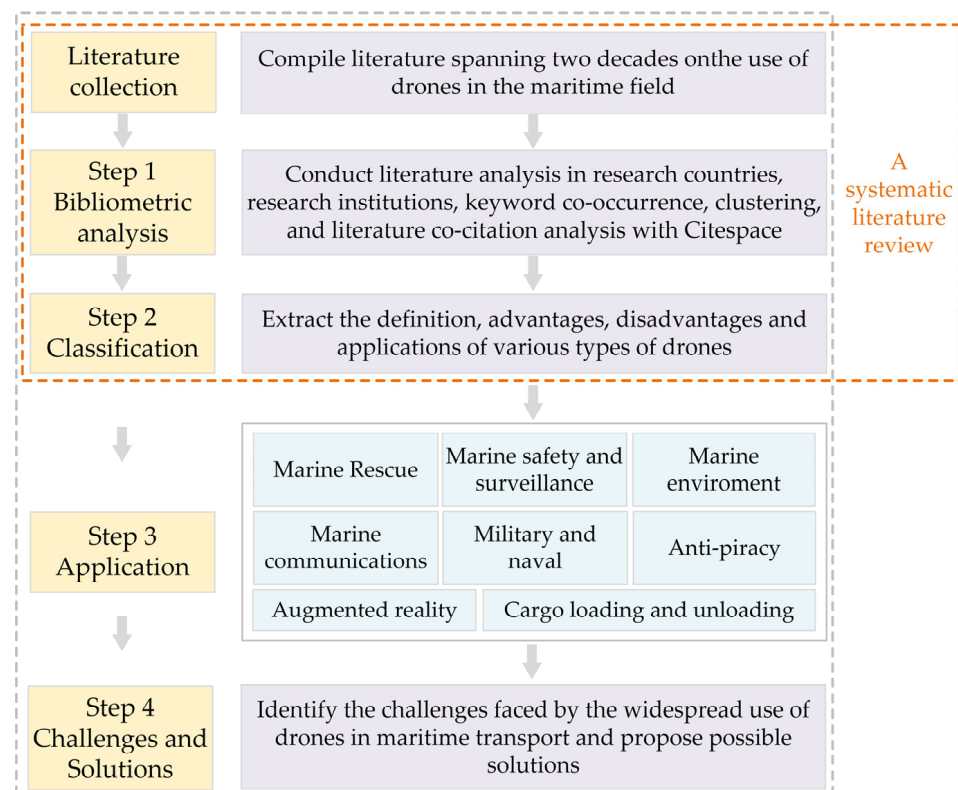
Literature collection	Compile literature spanning two decades onthe use of drones in the maritime field	
Step 1 Bibliometric analysis	Conduct literature analysis in research countries, research institutions, keyword co-occurrence, clustering, and literature co-citation analysis with Citespace	A systematic literature review
Step 2 Classification	Extract the definition, advantages, disadvantages and applications of various types of drones	
Step 3 Application	Marine Rescue / Marine safety and surveillance / Marine enviroment / Marine communications / Military and naval / Anti-piracy / Augmented reality / Cargo loading and unloading	
Step 4 Challenges and Solutions	Identify the challenges faced by the widespread use of drones in maritime transport and propose possible solutions	

Figure 1. The flowchart of this paper.

2. A Systematic Literature Review

2.1. Definition and Categories of Drones

Drones do not require a pilot and are often operated remotely. They are therefore rapidly evolving and used for both military and civilian purposes. Drones can be categorised according to their flight modes, as shown in Table 1. Fixed-wing drones offer advantages such as higher flight speeds, long flight times, and the ability to accommodate larger sensors and cameras, making them well-suited for marine patrols and tasks like marine violation identification. Rotary-wing drones have vertical take-off and landing capabilities, allowing for precise image capture and data collection, and are suitable for marine monitoring and rescue operations. Unmanned airships have long endurance and can function as command centres for port and rescue operations, while para-wing drones offer reduced weight for increased flight times and are ideal for extended missions. Fluttering drones mimic the flight patterns of birds or insects, providing covert reconnaissance capabilities and the potential for communication relays and monitoring of the marine environment.

Table 1. The details and features of different categories of drones.

Categories	References	Characteristics	Advantages	Disadvantages	Applications
Fixed-wing drones	[33–38]	Fixed-wing positions, swept-back angles, and simplified maintenance.	1. Higher flight speeds; 2. Longer flight times; 3. Ability to accommodate larger sensors and cameras; 4. Expanded range of applications.	1. Require larger take-off and landing sites; 2. Lack of hovering capabilities, limiting continuous image capture.	1. Marine patrols; 2. Marine violation identification; 3. Real-time reporting to ground control stations; 4. Ship escorting.
Rotary-wing drones	[18,39–41]	1. Feature rotor shafts for lift generation; 2. Obtain lift from continuously rotating blades; 3. Similar to helicopters in their lift-off principle.	1. Vertical take-off and landing capabilities; 2. Ability to hover for precise image capture and data collection in specific areas	1. More complex maintenance compared to fixed-wing drones; 2. Limited endurance, resulting in slower flight speed and reduced range.	1. Marine monitoring; 2. Marine rescue operations; 3. Pollution forensics.
Unmanned airships	[42–45]	1. Utilise internal gas lighter than air; 2. Consist of a hull, tail surface, pod, and propulsion unit; 3. Use the same lift-off principle as balloons but capable of powered flight and manoeuvring.	1. Long endurance due to reliance on lift principles, not limited by fuel; 2. Convenient departure and docking without requiring take-off or landing.	1. Vulnerable to high winds due to lighter-than-air nature; 2. Crosswinds can deplete their fuel; 3. Slower flight speeds due to larger size and greater air resistance.	1. Extended missions such as port and maritime patrols; 2. Functioning as command centres for port and rescue operations; 3. Overseeing ships arriving in port from the air; 4. Scanning entire accident sites during significant maritime disasters.
Para-wing drones	[46–48]	1. Employ a flexible air-foil made of a stamped wing parachute; 2. Use a propeller engine for propulsion; 3. Reduced weight for longer flight times.	1. Longer flight times due to reduced weight; 2. Ability to glide effortlessly in complex air currents at low altitudes; 3. Versatile launch methods; 4. Capability to take off and land on challenging runways.	1. Limited flight altitude due to lower lift provided by the stamped wing parachute.	1. Transportation of marine rescue supplies.
Fluttering drones	[49–53]	1. Mimic flight patterns of birds or insects; 2. Can be classified into insect-like or bird-like designs.	1. High mobility and integration with corresponding sensors; 2. Potential to be communication relays and monitor the marine environment.	1. Bird-like drones require consideration of range and lift.	1. Maritime military field, especially for long-range observation and night surveillance; 2. Protection of the marine environment; 3. Ensuring maritime security.

2.2. Documentary Scientometric Analysis and Knowledge Visualisation

This study conducts a systematic literature review of drones' applications in maritime transport based on the Web of Science (WOS) database to provide insights into their

historical development and current research hotspots. The retrieval work was carried out in Dec. 2022, and the used searching strings are shown below.

'UAV* AND maritime',

'drone* AND maritime',

'UAV* AND marine',

'drone* AND marine'.

After conducting an initial search on the WOS, a total of 916 results were obtained. Subsequently, journal articles published over a 20-year period from 2003 to 2022 were selected for further analysis, resulting in a refined list of 549 articles. To ensure high quality, the abstracts and keywords of these articles were further screened to ensure their relevance to the research topic, with only those pertaining to specific maritime drone applications being retained. Further, each article's introduction, methodology, and conclusion were thoroughly reviewed to ensure their applicability, resulting in a final selection of 225 papers. For the analysis of the retrieved literature, the Citespace software (v.6.1.R3) is utilised as a research tool to identify the core research countries and research institutions, as well as to conduct the keyword co-occurrence, clustering, and literature co-citation analysis.

The result of the core research countries analysis is visualised in Figure 2, depicting the development trend over the past two decades. The analysis reveals that China, the USA, England, Australia, Korea, Canada, and Spain are the leading countries for publishing research papers on the diverse applications of drones. Furthermore, China and England have demonstrated strong collaborations with other countries in this research domain. Using node centrality as a metric, China, USA, England, and Spain have emerged as pivotal players in this research area, as shown in Table 2. Notably, the majority of the core authors are from China and England, and they have established more collaborations with authors from China than those from other countries.
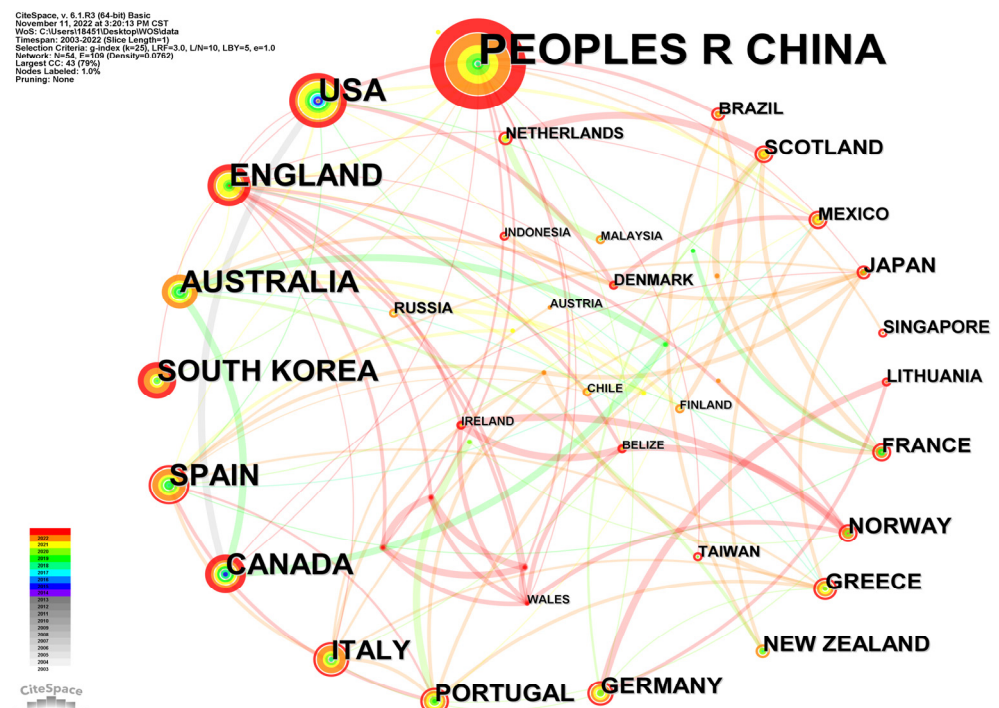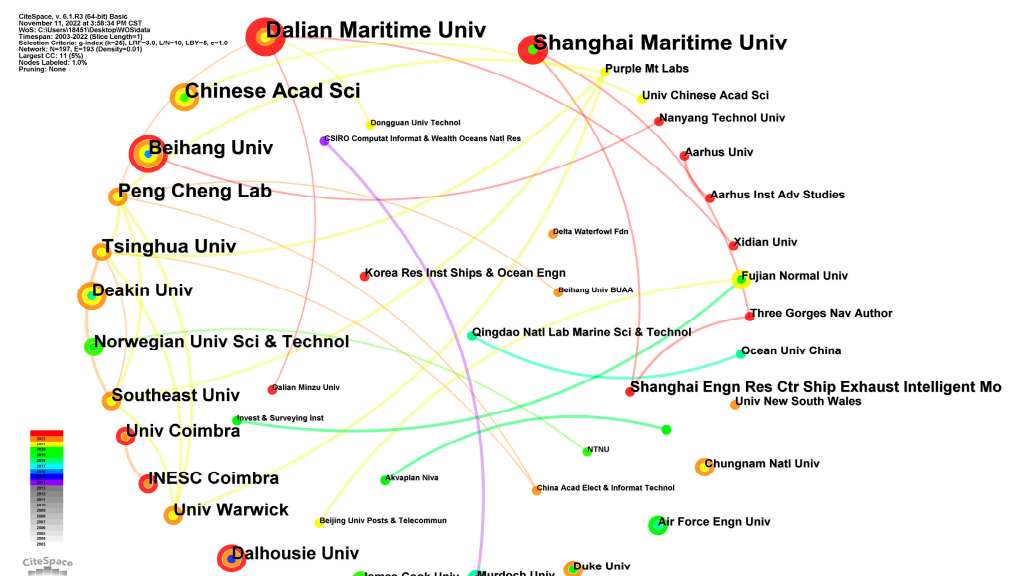

Figure 2. Visualisation of the main research countries.

Table 2. Top 10 countries in unmanned maritime drone research.

Number of the Papers	Country	Centrality
68	China	0.25
20	USA	0.26
17	England	0.23
16	Australia	0.09
15	South Korea	0.01
14	Spain	0.25
14	Canada	0.02
12	Italy	0.11
9	Portugal	0.11
8	Germany	0.08

The finding of the core research institutions is illustrated in Figure 3, demonstrating that most nodes are not isolated and suggesting their close collaboration. The Dalian Maritime University, Beihang University, Tsinghua University, and Pengcheng Laboratory have made significant contributions in terms of the number of publications. Additionally, these institutions have collaborated extensively with foreign countries.

Figure 3. Visualisation of the network of core research institutions.

The co-occurrence analysis of the keywords provides valuable insight into the latest research trends and cutting-edge areas of study. The keywords with a higher citation frequency indicate a more significant impact in the field. In this investigation, a total of 263 keywords were extracted. As depicted in Figure 4, the most frequently cited keywords include 'UAVs', 'remote sensing', 'computer vision', 'marine litter', and 'maritime communication', highlighting the growing importance of drone applications in the maritime industry. Table 3 presents the high-frequency keywords for each year according to Figure 4. The analysis reveals that research on UAVs in the maritime field commenced in 2008. In recent years, keywords such as 'deep learning' and 'maritime communication' have demonstrated relatively high occurrence frequency and centrality, indicating they are currently the research hotspots.
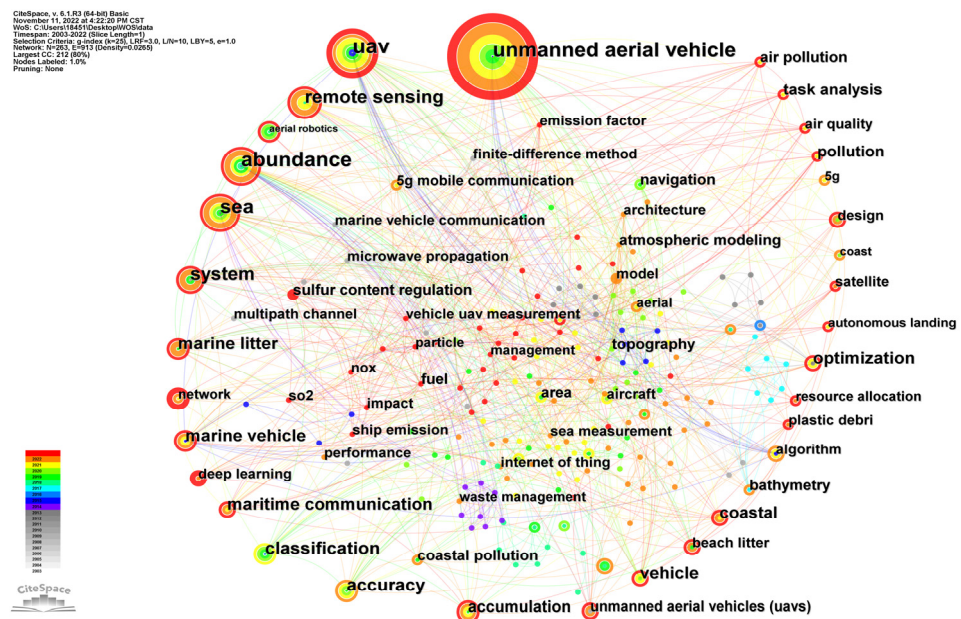
Figure 4. Visualisation of keyword co-occurrence analysis.

Table 3. Keywords with high frequency in maritime drone research.

Year	Frequent	Centrality	Keyword
2009	12	0.23	System
2012	73	0.61	Unmanned aerial vehicle
2012	6	0.04	Optimization
2014	8	0.04	Marine vehicle
2015	7	0.10	Classification
2017	19	0.14	Remote sensing
2018	10	0.09	Marine litter
2019	6	0.05	Vehicle
2019	6	0.02	Design
2020	9	0.02	Network
2020	7	0.04	Maritime communication
2020	6	0.04	Coastal
2021	8	0.03	Deep learning
2021	6	0.03	Model

The clustering function in the Citespace is used to identify nine keyword clusters, as illustrated in Figure 5. The top five clusters are presented in detail in Table 4. The primary phase in the Citespace tallies up the keyword frequencies and their associations. Subsequently, the Log-Likelihood Ratio (LLR) test algorithm within the Citespace groups the related keywords. According to the LLR algorithm, the keywords in the same cluster are given a value. The keywords with the peak value stand as the emblematic category for that cluster. As illustrated in Figure 5, the foremost five clusters are the following: cluster #0 marine vehicles, cluster #2 marine robotics, cluster #3 atmospheric modelling, cluster #4 unmanned aerial vehicles, and cluster #5 central Tyrrhenian sea. This underscores that over the past 20 years, maritime UAV research has concentrated on the aforementioned areas. Based on Figure 5, it is apparent that cluster #0 marine vehicles is immediately associated with cluster #1 remote sensing, cluster #2 marine robotics, and cluster #4 unmanned aerial vehicles. Additionally, the research direction in this field is primarily focused on marine vehicles. Moreover, the UAV maritime field is being shifted towards cluster #1 remote sensing, cluster #2 marine robotics, cluster #3 atmospheric modelling, cluster #4 unmanned aerial vehicles, and cluster #7 unmanned aerial systems.
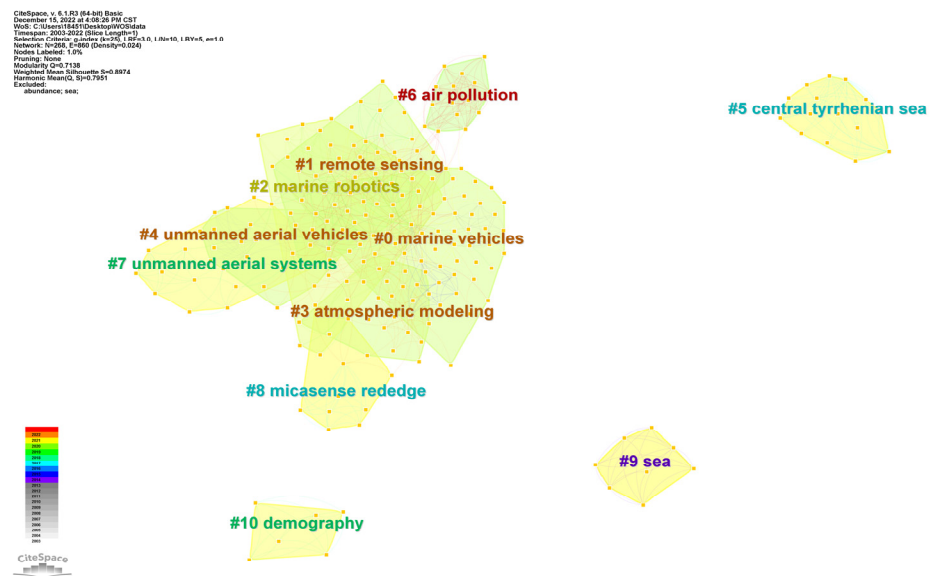
Figure 5. Visualisation of keyword clustering.

Table 4. Top 5 keyword clusters for drone research in the maritime industry.

Cluster	Size	Silhouette Coefficient	Year	Top Terms (LLR)
#0	51	0.909	2018	Marine vehicles
#1	42	0.813	2019	Remote sensing
#2	23	0.867	2019	Marine robotics
#3	21	0.943	2020	Atmospheric modelling
#4	19	0.921	2013	UAVs

The co-citation analysis is a valuable technique for identifying common themes and evolutionary dynamics in a specific field. Figure 6 illustrates that the investigation into drones in the maritime sector commenced between 2016 and 2020, initially concentrating on floating litter and intertidal macroalgae. Subsequently, drone-based studies employing multispectral cameras have proved to be an effective method for monitoring beach litter. Table 5 provides detailed information on the referenced documents. The cited literature indicates that the early applications of drones in the maritime industry were centred around marine litter monitoring. Furthermore, the academic community exhibits a keen interest in collaboration in marine litter detection. However, the number of researchers in other fields seems relatively limited.

2.3. Research Gaps and Solutions

In the current maritime research field, there are several research gaps related to the study and implementation of drones.

(1) The absence of comprehensive research and reviews on drones in the maritime sector.

There is a lack of specialised reviews on drone applications, particularly in areas such as ship inspection (e.g., ships' hulls and hard-to-reach regions), ocean monitoring, and disaster relief. This scarcity hinders a comprehensive understanding of the current state of drone applications in maritime operations. To bridge this gap, this paper undertakes a systematic review of research progress and the relevant literature to provide insights into the existing drone applications in the maritime sector.

(2) The lack of a complete application system for UAVs in the maritime field.

The applications of UAVs in areas such as route exploration, ocean monitoring, and search and rescue currently lack coherence and are scattered. There is a need for further improvement and enhancement of UAV applications in order to promote coordinated

development. To address this, a comprehensive overview of UAV applications in different maritime fields is necessary. This study aims to provide a review and analysis of UAV applications, contributing to a better understanding of their potential and facilitating their effective utilisation in the maritime domain.

(3) The technical difficulties, challenges, and possible solutions encountered by UAVs in maritime applications.

The complex maritime environment, harsh weather conditions, and strong electromagnetic interference present significant challenges to the application of UAVs in the maritime sector. Moreover, technical limitations, particularly in obstacle avoidance capabilities, further restrict their usage. To address these gaps, Sections 3 and 4 of the paper focus on the evolution of drone applications in maritime transport and the challenges associated with using drones in this context. These sections aim to provide insights and potential solutions to overcome the obstacles faced by UAVs in maritime applications.
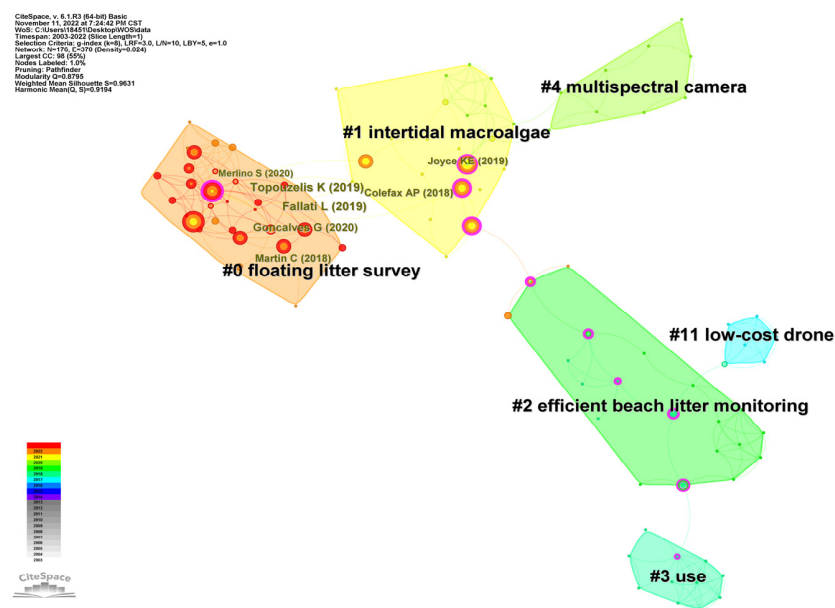

Figure 6. Visualisation of the co-citation clustering of literature (the corresponding seven references in the figure are [54–60]).

Table 5. Top 5 most cited papers with their co-citation frequency.

Citation Count	Reference	Title
15	Gonçalves et al. (2020) [57]	Mapping marine litter using Unmanned Aircraft System (UAS) on a beach-dune system: A multidisciplinary approach
15	Fallati et al. (2019) [56]	Anthropogenic Marine Debris assessment with Unmanned Aerial Vehicle imagery and deep learning: A case study along the beaches of the Republic of Maldives
15	Topouzelis et al. (2019) [55]	Detection of floating plastics from satellite and unmanned aerial systems (Plastic Litter Project 2018)
12	Colefax et al. (2018) [59]	The potential for UAVs to conduct marine fauna surveys in place of manned aircraft
12	Martin et al. (2018) [58]	Use of UAVs for efficient beach litter monitoring

3. Development and Different Applications of Drones in Maritime Transport

Drones possess exceptional mobility, robust monitoring capabilities, and extensive coverage, enabling them to be highly suitable for deployment in the marine sector. This section first highlights the development trends of drones and relevant regulations over time.

Then, it introduces the different applications of drones in the sectors of fast-growing interest, including maritime rescue (i.e., Section 3.2), marine safety and surveillance (i.e., Section 3.3), marine environment (i.e., Section 3.4), marine communications (i.e., Section 3.5), military and naval (i.e., Section 3.6), anti-piracy (i.e., Section 3.7), augmented reality (i.e., Section 3.8), and cargo loading and uploading (i.e., Section 3.9), as well as the associated methods.

3.1. The Development Trends of Drones over Time

A timeline diagram showcasing the progression of regulations and application development of drones is depicted in Figure 7. The timeline diagram reveals the evolving trend of drone applications. Initially, drones were primarily utilised for marine rescue operations and quickly expanded to encompass various other areas, including marine environmental monitoring, marine communications, and marine navigation.

Starting from the conceptual proposal of the 'Queen Bee' drone in 1934 and leading up to the introduction of the 'European Union Unmanned Aircraft Systems Regulations' in 2019, the drone industry has experienced significant growth over a long period of time. Throughout this development, relevant regulations have been established at both the national and international levels to govern drone operations and ensure safety and responsibility.

In summary, the regulations that have been put in place over the past century have played a vital role in promoting safe and responsible drone operations on a global scale.
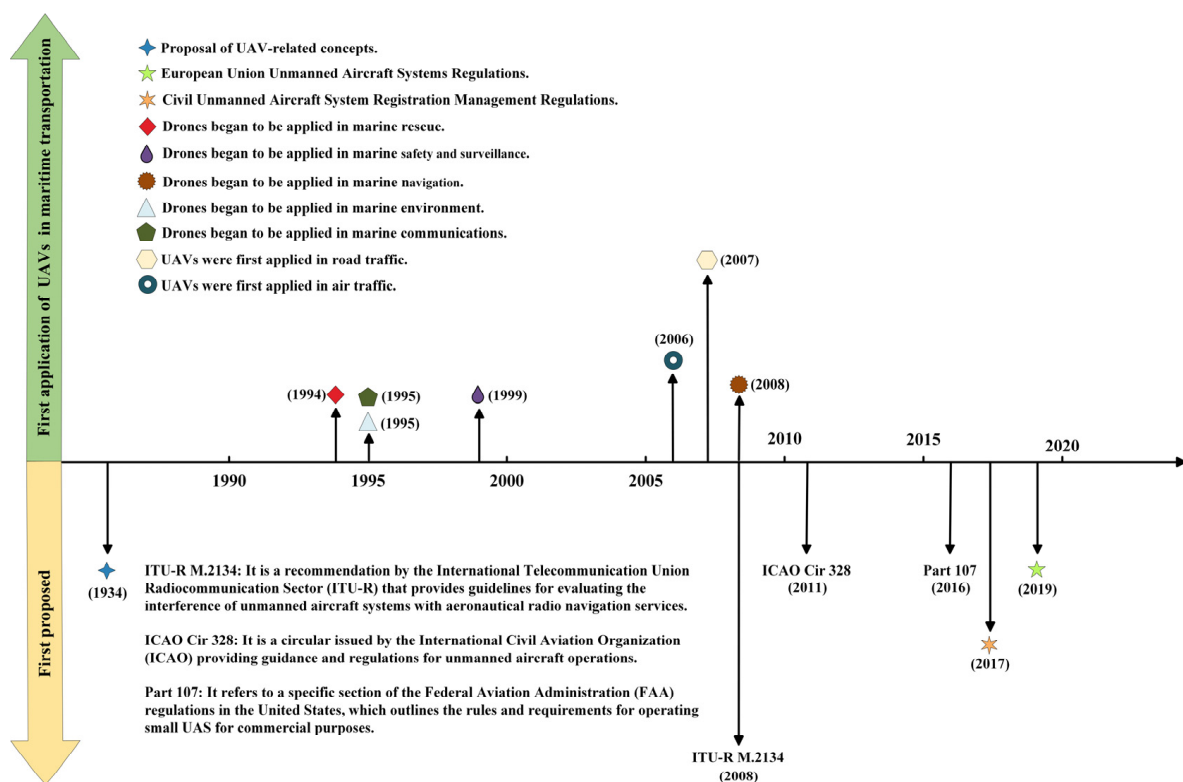

Figure 7. The flowchart of the proposed methodology.

3.2. Marine Rescue

3.2.1. Delivery of Relief Supplies

Recent statistics from the International Maritime Organization (IMO) database reveal that between 2014 and 2019, the global marine casualties and incidents were counted as 2664 incidents annually on average. However, the advent of the coronavirus in 2020 resulted in a decrease in marine casualties and incidents, with the number dropping to 2547. Nevertheless, in 2021, the number rebounded to 2637. Such data highlight the ongoing high frequency of maritime accidents worldwide [61–63]. In such a circumstance, the prompt delivery of relief supplies to inaccessible accident sites becomes paramount for saving

lives. Drones have proven to be an effective tool for delivering these supplies to disaster sites, ensuring their timely arrival and alleviating the burden on rescue workers [64]. By facilitating the transportation of food, medical supplies, and other emergency resources, drones play a vital role in providing relief assistance in the maritime sector [65].

3.2.2. Locating Rescue Targets

In the event of a marine accident, the primary focus is on rescuing survivors [66]. Extensive research has demonstrated that drones can play a crucial role in this regard by swiftly identifying and relaying the precise locations of survivors to command centres and rescue teams [67,68]. This utilisation of drones significantly enhances the efficiency of rescue operations. Moreover, employing drones can enhance safety for both the survivors and rescue personnel as it reduces the necessity for them to enter the water [39]. Although it is still necessary to address the associated legal concerns, the use of drones for maritime rescue missions emerges as an efficient and cost-effective solution, offering substantial potential for improving the likelihood of successful outcomes.

3.2.3. Search Path Planning

Efficient search and rescue are critical when dealing with maritime accidents. However, the current use of large search and rescue equipment in maritime Synthetic Aperture Radar (SAR) sometimes proves to be inefficient [39,69]. To improve search efficiency, the integration of drones into large rescue equipment has been proposed, allowing for the collaborative modelling of the accident area and the optimisation of search paths for both equipment and rescuers [70].

As an example, the integration of advanced sensors and cameras onto drones can facilitate the rapid scanning of expansive open water areas, enabling the identification of potential targets or points of interest [27]. The data gathered by the drones can subsequently be employed to generate a digital map of the accident site, which in turn can be leveraged to optimise the search paths for other equipment and rescuers [68,71]. The integration of drones and path planning algorithms in conjunction with traditional SAR equipment holds significant potential for improving SAR operations at sea.

3.3. Marine Safety and Surveillance

3.3.1. Port Supervision and Facilities Maintenance

Efficient port management is essential for ensuring a port's capacity to handle cargo effectively. However, the challenging environments in which many port facilities are situated often make inspection and maintenance a daunting task. To address this challenge, drones are employed to actively monitor ports and maintain facilities, streamlining the port supervision and maintenance processes [72].

Drones have proven to be highly effective in monitoring the perimeter of ports, swiftly detecting any unauthorised access attempts or suspicious activities. This enables security personnel to respond promptly to potential threats, preventing incidents before they occur and bolstering overall port security [73,74].

In addition, drones can be employed for asset management and inventory control in ports [72,75]. Equipped with high-quality imaging capabilities, drones assist in monitoring the flow of goods in and out of port, mitigating the likelihood of lost or misplaced shipments. Moreover, drones can swiftly and accurately perform inventory checks, identifying any discrepancies between physical inventory and records.

Furthermore, the use of drones for port supervision and maintenance can enhance safety by minimising the need for workers to operate at heights or in hazardous environments. Drones can aid in inspecting and surveying hard-to-reach areas, such as crane arms, cargo stacks, and roofs, identifying potential safety hazards such as cracks or corrosion [76,77]. This proactive approach allows port operators to address safety issues before they escalate, preventing accidents and equipment failures.

In summary, drones offer a promising solution to enhance safety, efficiency and cost-effectiveness in port management and maintenance. By actively monitoring ports, assisting with inventory control, and conducting inspections in hazardous areas, drones contribute significantly to the smooth operation and security of port facilities.

3.3.2. Marine Patrol

With the continuous growth of global trade, ships play a vital role in maritime transport [78]. However, the inherent risks associated with this industry cannot be overlooked. To tackle these challenges, drones offer a valuable solution by providing real-time data on ships and maritime activities [79]. These data are analysed to identify various types of vessels and monitor their movements, enabling law enforcement agencies to intervene and prevent illegal activities such as smuggling, piracy, and illegal fishing [80].

Moreover, drones excel at covering vast areas of water efficiently, making them a valuable asset for monitoring the health of marine ecosystems [20]. By gathering valuable information, drones contribute to ongoing conservation efforts and aid in promoting sustainable resource management [81,82]. This enhanced capability provided by drones allows maritime law enforcement agencies to protect the oceans effectively and ensure their long-term sustainability [83].

As a result, drones play a crucial role in addressing the risks associated with maritime transport. By providing real-time data and enabling the efficient monitoring of ships and maritime activities, drones empower law enforcement agencies to combat illegal activities [84]. Additionally, their ability to survey large areas of water contributes to the preservation of marine ecosystems, fostering sustainable practices in resource management [85].

3.3.3. Vessel Inspections

Vessel inspections are crucial to ensure their safety and seaworthiness [72]. However, traditional methods involving close-range inspections by surveyors when ships are docked often entail high costs, time, and potential risks. Scaffolding is commonly employed to access hard-to-reach areas, further complicating the process [21]. In contrast, drones present a safer and more efficient solution.

By utilising drones, ultra-high-definition images of a vessel's structural condition can be transmitted in real-time to ground monitoring stations, enabling surveyors to remotely assess the vessel [86]. This remote assessment eliminates the need for any physical assessment and exposure to danger, thereby reducing costs and enhancing safety.

Additionally, drones offer the advantage of conducting inspections even in challenging weather conditions. Traditional inspection methods can be time-consuming as surveyors need to manually inspect every area of a whole vessel. Conversely, drones can swiftly cover large areas of the vessel, providing high-quality data for analysis [87,88]. This significantly improves the efficiency of the inspection process.

Drones can revolutionise vessel inspections by providing a safer and more efficient alternative to traditional methods. Through the real-time transmission of high-definition images, remote assessments can be conducted, eliminating the need for scaffolding and reducing costs. Furthermore, drones' ability to operate in difficult weather conditions and cover large areas expedites the inspection process, enhancing overall efficiency.

3.4. Marine Environment

3.4.1. Ship Port Exhaust Monitoring Forensics

The maritime transport industry is facing increasing pressure to mitigate ship emissions for the Net Zero goal by the IMO [25]. However, conventional methods involving ship exhaust sniffing sensors often suffer from drawbacks such as bulkiness, heaviness, and high costs. Drones have emerged as a viable and cost-effective alternative for screening vessel exhausts to ensure compliance with emission regulations [31].

By leveraging drones, the cost and complexity associated with traditional monitoring methods can be significantly reduced [30]. Drones equipped with high-resolution cameras

and gas sensors can provide real-time data on ship emissions, enabling the identification of pollution sources and instances of non-compliance [89,90]. This information can then be utilised to enforce regulations and minimise the impact of shipping activities on the marine environment. Moreover, drones possess the capability to cover expansive areas swiftly and effortlessly, offering a cost-effective solution to exhaust monitoring without the necessity for expensive equipment or infrastructure [91,92]. As a result, the utilisation of drones for ship exhaust monitoring presents an efficient and effective approach to mitigating marine pollution caused by ships.

3.4.2. Coastal Zone Ecological Monitoring

The global population's growing concentration in coastal areas has placed significant pressure on the environment and coastal ecosystems [30]. The situation is further exacerbated by the impacts of climate change, which disrupts natural organisms and ecosystems in these regions [93]. In response to the challenges faced by Marine Protected Areas (MPAs) in conserving and safeguarding marine biodiversity and ecosystems, the use of drones has emerged as a promising solution to improving the required and relevant monitoring operations and management [32].

Drones have numerous advantages when it comes to MPA management. Equipped with high-resolution cameras and sensors, drones can gather detailed data on marine habitats, species distributions, and ecosystem dynamics [94]. This wealth of information provides valuable insights into the condition and status of protected areas, enabling informed decision-making and proactive measures to protect vulnerable ecosystems.

One of the key benefits of using drones in MPA management is their ability to conduct real-time monitoring of MPA boundaries [95]. Drones can cover large areas and capture aerial imagery, facilitating the detection of encroachments or illegal activities within the protected zones. This capability allows for swift response and enforcement actions, serving as a deterrent against illegal fishing, poaching, and unauthorised activities.

Additionally, drones can access and survey challenging marine areas that are typically inaccessible or hazardous for humans [96,97]. This enables data collection from remote or neglected locations, providing a comprehensive understanding of species populations, habitat conditions, and environmental changes.

Therefore, the use of drones in monitoring and managing MPAs offers great potential for conserving and protecting marine biodiversity and ecosystems. Drones can help address resource limitations, enhance surveillance efforts, and provide critical data for informed decision-making. By harnessing these technological advancements, MPAs can effectively tackle the growing pressures from the concentration of the global population in coastal areas and the impacts of climate change. Ultimately, this promotes the sustainable management and long-term preservation of our coastal and marine environments.

3.5. Marine Communications

While the existing marine infrastructure generally meets the communication needs of the shipping industry, there are occasions where shore-based wireless communication facilities may fall short, particularly during emergencies. In such cases, drones offer an effective solution to enhancing the quality of wireless communication [98]. By being operated at high altitudes, drones can provide extended coverage and establish a reliable communication network between ships and between ships and the shore. This capability ensures that communication remains uninterrupted, even in remote or challenging environments. Additionally, drones have the ability to transmit real-time video and audio data during emergencies, equipping rescue teams with critical information to make prompt and well-informed decisions [99]. Furthermore, drones are equipped with a diverse range of communication equipment, including radios, antennas, and satellite links. This enables them to offer various communication services to ships at sea, ensuring reliable connectivity and facilitating effective communication between vessels and onshore facilities [100].

The continuous technological advancements in the field of drones have further enhanced their appeal as communication nodes in the maritime industry. With improved capabilities and features, drones have become an increasingly viable option for fulfilling communication requirements in challenging situations and emergencies.

While shore-based wireless communication facilities in the maritime industry generally suffice, drones play a crucial role in augmenting communication quality during emergencies. Their ability to provide extended coverage, transmit real-time data, and offer diverse communication services makes them an effective and appealing solution for enhancing wireless communication in the maritime sector.

3.6. Military and Naval Applications

Drones have become an integral part of military and naval operations. They are used for surveillance, reconnaissance, and intelligence gathering purposes. Military drones, such as UAVs, provide real-time aerial imagery, video footage, and sensor data, helping armed forces monitor enemy activities, identify targets, and assess battlefield conditions. They can also be equipped with weapons for offensive operations. Surveillance is a fundamental aspect of military strategies, and drones excel in this domain. Due to their flexibility, low-fuel drones and high-fuel drones alternate missions. In addition, adding refuelling drones to military missions aims to allow drones to continue to perform missions [101].

In terms of military reconnaissance, the sensors installed on drones are airborne mobile sensors. They carry out the cooperation of static ground sensors and airborne mobilesensors to effectively expand the detection area of drones [102]. The aerial perspective offered by drones enables military commanders to gain a comprehensive understanding of the battlefield, identify potential threats, and develop appropriate response strategies [103].

In addition to surveillance and reconnaissance, drones play a crucial role in intelligence gathering. Military intelligence gathering has relied on human-controlled aerial vehicles in the past, but with the advent of more and more autonomous systems, it is increasingly important to use the situational awareness capabilities of drones for intelligence gathering [104]. This intelligence is essential for understanding enemy tactics, identifying vulnerabilities, and formulating effective countermeasures.

Moreover, the integration of weapon systems with military drones has transformed the nature of warfare. Armed drones, commonly known as unmanned combat aerial vehicles (UCAVs), possess the capability to launch precision strikes on enemy targets. This offensive capability enables armed forces to engage enemy forces, disrupt their operations, and neutralise threats while minimising collateral damage and reducing the risk to friendly forces [105]. Drones have become indispensable assets in military and naval applications. Their contributions to surveillance, reconnaissance, intelligence gathering, and offensive operations have significantly enhanced the capabilities of armed forces.

3.7. Anti-Piracy Applications

Drones are increasingly employed in maritime security to combat piracy. They can be used to patrol coastlines and shipping routes, monitor suspicious activities, and provide early warning systems to prevent pirate attacks.

Currently, piracy surveillance at sea is conducted using a combination of Automatic Identification Systems (AISs), Coastal Radar Systems (CRSs) and Long Range Cameras (LRCs). The above monitoring methods are not enough in terms of adaptability to dynamic events or simple and effective path coordination ability. UAV swarm monitoring is emerging as an attractive countermeasure that increases the flexibility of traditional methods and improves mission success [106]. Therefore, the integration of drones into maritime security strategies has revolutionised the fight against piracy. Their ability to patrol extensive areas, monitor suspicious activities, and provide early warnings has proven instrumental in preventing and deterring pirate attacks.

3.8. Augmented Reality Applications

Drones can enhance augmented reality experiences by acting as aerial platforms for Augmented Reality (AR) applications in maritime. By integrating drones with AR technology, users can view real-time augmented views of their surroundings from an aerial perspective. This will be particularly helpful in the remote control of autonomous ships.

A significant advantage of using drones with AR is witnessed as it provides a unique perspective that cannot be obtained easily using other means from the ground. These drones, equipped with advanced cameras and sensors, can collect data that are used to generate AR models. For example, the combination of GIS, AR, and drones generates an AR model of coastal terrain, through which key factors of terrain changes can be judged [107].

Additionally, drones equipped with specialised sensors, such as thermal or multispectral cameras, can provide valuable data for specific maritime applications. In combination with AR, these sensors enable users to visualise and analyse critical information that would otherwise be invisible to the naked eye. For instance, thermal cameras on drones can detect temperature variations in water, helping to identify potential hazards or anomalies [108]. By integrating these data with AR overlays, users can gain a deeper understanding of the maritime environment and make more informed decisions.

It is evident from the existing literature that the integration of drones with AR technology opens up a world of possibilities in maritime applications. From providing aerial perspectives and overlaying real-time information to capturing specialised data, drones significantly enhance AR experiences in the maritime domain. This synergy between drones and AR holds tremendous potential for exploration, safety, and environmental monitoring in coastal and marine areas.

3.9. Cargo Loading and Unloading

Drones are being explored for cargo operations in maritime settings. They can assist in the efficient loading and unloading of goods on ships or between ships and shores. Drones equipped with lifting mechanisms or cargo pods can transport small packages or supplies, reducing the need for manual labour and optimising logistics processes. This technology has the potential to streamline operations in ports, offshore platforms, and logistics centres.

The utilisation of drones in cargo operations brings numerous benefits to the maritime industry. Firstly, drones offer increased flexibility and adaptability compared to traditional methods. They can swiftly navigate through congested port areas and tight spaces, reaching locations that may be challenging for conventional machinery or vehicles. As a result, the loading and unloading process becomes more agile and less time-consuming [72].

Moreover, the introduction of drones in cargo operations has the potential to streamline activities in various maritime settings. Ports, offshore platforms, and logistics centres can greatly benefit from the implementation of this technology. Drones enable the quick and precise delivery of goods, eliminating bottlenecks and reducing waiting times. For example, drones drag goods along the sea surface to complete deliveries between coasts, which is called the Side-Pull Manoeuvre (SPM) [109]. Therefore, the integration of drones in cargo loading and unloading operations in maritime settings represents a significant advancement in the field of logistics. By leveraging their lifting capabilities and manoeuvrability, drones offer a promising solution to optimise processes and improve efficiency.

4. Challenges and Solutions of Using Drones in Maritime Transport

4.1. Technical Challenges of Using Drones and the Associated Solutions in Maritime Transport

The technical challenges of drones in the maritime transport domain are delineated, encompassing the difficulties in flight control, navigation, power, communication, and vision systems.

4.1.1. Flight Control System

The prevailing trend in flight control technology is flight intelligence, which has already gained widespread adoption. However, there are still several issues that have important theoretical implications that are unaddressed and hence require further investigation. Firstly, the existing fault-tolerant technology primarily revolves around fault-tolerant control laws for two types of actuator deviations: actuator deviation and actuator failure faults. Nonetheless, the physical limitations of the actuator motor and other factors can restrict the actuator control input, leading to errors stemming from these limitations. Hence, it is necessary to develop new fault-tolerant control algorithms that can effectively handle restricted control inputs [110,111]. Secondly, the insufficient infrastructure at sea poses a challenge to drone recharge. One potential solution is to integrate UAV landings with ships or offshore wind farms [112]. Although the current research primarily focuses on visual landings, future studies should take into account weather conditions and ship movements. Exploring autonomous ship landing technology is crucial to broadening the scope of drone applications in the maritime sector [113].

Overall, while flight control technology has embraced the predominant trend of flight intelligence, there are still unresolved issues that warrant further investigation. Enhancing fault-tolerant control algorithms with restricted control inputs and exploring autonomous ship landing technology are vital steps to address the challenges faced in this domain.

4.1.2. Navigation System

The current state of UAV navigation technology primarily involves the utilisation of single and combined navigation methods. However, the future directions in UAV navigation technology encompass several important aspects. Firstly, inertial guidance technology plays a significant role in UAV navigation. As advancements continue in different types of inertial guidance technology and computer systems, future research will concentrate on developing smaller, lower-power consumption inertial guidance systems that are well-suited for UAV payloads [114]. Additionally, efforts will be made to enhance the accuracy of the technology to achieve higher levels of precision. Secondly, it is imperative to conduct thorough and detailed analyses of the stability and reliability of UAV navigation technologies. Instead of relying solely on one or two technologies, the combination of multiple navigation technologies can improve the overall performance of the navigation system, even in the event of failures in one particular technology [115,116].

The future of UAV navigation technology involves advancing inertial guidance systems to be more suitable for UAV payloads, improving accuracy levels, and conducting comprehensive analyses of stability and reliability. By combining multiple navigation technologies, the performance and reliability of UAV navigation systems can be enhanced.

4.1.3. Power System

The recent patent distribution in powertrain branch technologies indicates that fuel engines have obtained the highest number of patents, followed by hybrids, propellers, and electric motors. Each technology faces unique development challenges. Firstly, fuel engines remain the primary focus of research, especially for large-scale cargo drones with long ranges and heavy payloads. Future challenges in this area include retrofitting and implementing automatic onboard starting for conventional engines [117]. Secondly, hybrid power technology necessitates the development of coupling and integrated control technologies for gasoline–electric power generation. This will be crucial for future advancements in hybrid drone technology [118]. Thirdly, propeller technology should give priority to the development of pitch and locking technologies [119]. Improving these aspects will enhance the efficiency and performance of propellers in drone applications. Lastly, motor technology should concentrate on fault-tolerant motor control and the exploration of new energy sources [120,121]. These advancements will increase the range and enhance the flight control performance of drones using electric motors.

It is evident that the development challenges vary for different powertrain technologies in the drone industry. These challenges include retrofitting and automatic starting for fuel engines, coupling and integrated control for hybrid power, pitch and locking for propeller technology, and fault-tolerant motor control with new energy sources for electric motors. Addressing these challenges will contribute to the overall advancement of drone powertrain technologies.

4.1.4. Communication System

UAV-assisted mobile communications hold significant promise, but the technology is still at its nascent stages, and numerous challenges need to be thoroughly addressed. Firstly, achieving seamless coverage over a wide area necessitates high-speed and low-latency data interaction between drones and other heterogeneous networks in an airspace network [122,123]. This presents a pressing technical challenge that requires further research and development to enable efficient and reliable communication between drones and existing networks. Secondly, the broadcast nature of wireless communications raises concerns regarding the potential exposure of user information over the air. UAV communications are particularly vulnerable to eavesdropping and channel estimation attacks, which can lead to interception and unauthorised access to private information [124,125]. Ensuring the security of communication transmissions and developing robust countermeasures against active jamming attacks are critical areas that require significant attention and future research efforts.

To sum up, the field of UAV-assisted mobile communications shows immense potential, but there are significant challenges that need to be addressed. Achieving high-speed and low-latency data interaction, ensuring the security and privacy of communication transmissions, and developing robust defences against active jamming attacks are key areas that require further exploration and innovation to unlock the full capabilities of this technology.

4.1.5. Vision System

The utilisation of vision sensors in drone applications is increasingly widespread; however, researchers have to address various challenges associated with this technology. Firstly, while researchers primarily concentrate on enhancing the performance of vision sensors, security concerns are often overlooked. The negligence of security issues will generate serious consequences, such as disrupting UAV hovering and filming. To mitigate these risks, it is necessary to conduct further research to address security aspects, specifically those relating to vision sensors [126]. Secondly, the processors carried by drones are typically small in size and possess limited computing power. Therefore, it is crucial to develop lightweight vision algorithms that can operate efficiently on these processors without compromising detection quality or speed [127,128]. The focus should be on optimising algorithms to ensure optimal performance with limited computing resources.

Ultimately, as the use of vision sensors in drones becomes more prevalent, it is essential to address key issues. These include enhancing security measures related to vision sensors and developing lightweight vision algorithms that can efficiently run on the limited computing power available on drone processors. By tackling these challenges, the full potential of vision sensors in drone applications can be realised.

Based on the above analysis in Section 4.1, the technical challenges of using drones in maritime transport and the relevant solutions are listed in Table 6. It can provide references for different stakeholders.

Table 6. Technical challenges and solutions associated with the use of drones in maritime transport.

System	Challenges	Solutions
Flight control system	1. Limitations of fault-tolerant control laws with restricted control inputs 2. Inadequate infrastructure at sea for UAV recovery	1. Develop control algorithms that can effectively deal with the physical properties of the actuator motor. 2. Investigating drone autonomous ship landing technology.
Navigation system	1. The accuracy, size, and power consumption of inertial guidance systems are not suitable for drones. 2. The unreliability of single guidance technology.	1. Research on miniaturised and low-power inertial guidance technology for drones. 2. Investigate the performance of combining multiple navigation technologies.
Power system	1. Fuel Engines: Retrofitting and automatic onboard starting of conventional engines in UAV applications	1-1 Install an electric starter motor. 1-2 Installing an engine monitoring system.
	2. Hybrid Power: Coupling and integrated control technology of gasoline-electric power generation	2-1 Integrate software and hardware. 2-2 Optimised Design Powertrain.
	3. Propellers: Focus on the pitch and locking technology	3-1 Develop locking mechanisms 3-2 Integrate with flight control systems
	4. Electric Motors: Fault-tolerant motor control	4-1 Use redundant components to improve fault tolerance.
Communication system	1. Achieving high-speed and low-latency data interaction between drones and other networks 2. Security concerns for UAV communications	1. Research on technical solutions to improve data interaction. 2. Research on secure communication transmission and overcoming active jamming attacks.
Vision system	1. Security concerns with vision sensors 2. Limitations of computing power for lightweight vision algorithms	1. Study encryption techniques for drone communications. 2. Development of lightweight vision algorithms without sacrificing quality or speed.

4.2. Challenges and Solutions Associated with the Use of Drones in Future Maritime Transport

In recent years, the utilisation of drones in maritime traffic has undergone significant advancements. However, there remains ample room for further improvement. These challenges prompt endeavours to investigate the future development of drones in five essential domains of maritime transport: marine rescue, marine safety and surveillance, marine navigation, marine environment, and marine communications.

4.2.1. Marine Rescue

The existing applications of drones in marine rescue encompass searching for rescue targets, delivering supplies, and path planning for search operations. However, to simulate the future development of this technology, it is essential to address the following urgent challenges:

(1) Transportation of injuries from the sea: When an incident occurs at sea, it is a challenging task to transport injured individuals from sea to somewhere safe, such as shore or nearby safe ships, particularly during undersea rescue operations. Conventional transportation methods are often time-consuming and not conducive to prompt treatment. Employing medical drones for transportation purposes can serve as an efficient alternative to traditional ship transport. However, the current research on this technology primarily focuses on feasibility, and further development on real-word demonstration is necessary to address this critical issue [129].

(2) Visual technology plays a primary role in drones' involvement in rescue operations by locating injured individuals. Nevertheless, maritime environments are frequently affected by adverse weather conditions such as rain and fog, which can impede visual detection efforts [127]. To overcome this challenge, there is a need for radar-equipped drones capable of penetrating clouds and rain to swiftly identify the location of targets [130]. Additionally, long-endurance drones can serve as command centres, transmitting real-time

visual data from disaster sites [71]. It is vital to do further research in this area to improve the effectiveness of rescue operations.

4.2.2. Marine Safety and Surveillance

Specific challenges in terms of deep learning-based methods and data transmission capabilities affect the significance of using drones for marine surveillance. They include.

(1) Data transmission: Real-time monitoring data collected by drones need to be efficiently transmitted to shore-based mobile monitoring vehicles or ground-based base stations via a control data chain. In medium to long-range sea monitoring, the collected data can be transmitted to unmanned vessels or maritime law enforcement vessels, which can establish communication with the rear using shipboard satellite equipment [131]. Within this context, new solutions to improving data transmission during UAV surveillance are wanted to ensure the reliability and security of the transmitted data, especially in adverse weather conditions and remote areas [132].

(2) Data processing and data fusion for maritime supervision: It is crucial to develop effective techniques for data processing and fusion to enhance the overall effectiveness of maritime drone surveillance [133]. The integration of vessel behaviour monitored by drones with vessel information obtained using the AIS can help detect potential violations and improve monitoring capabilities [134,135].

(3) Cooperation between drones and existing maritime supervision equipment: It is promising to develop a 3D maritime supervision system with Vessel Traffic Service (VTS) as the central monitoring point and foster cooperation between drones and patrol vessels [136,137]. The development can ensure seamless coordination and collaboration between different surveillance assets.

4.2.3. Marine Navigation

Drones have the potential to enhance vessel inspection by providing stable hovering, autonomous obstacle avoidance, and real-time transmission of ultra-high definition photos in environments without satellite communication, light, and sufficient electromagnetic interference. However, several challenges remain in marine navigation that require attention:

(1) Utilising drones for measuring hull structure thickness: Using drones for measuring hull structure thickness during inspections can significantly improve inspection efficiency. However, current technologies rely mainly on manual handheld ultrasonic thickness gauges, lacking automation. Further research and development are needed to automate this process and enhance measurement accuracy [86].

(2) Automatic image recognition, measurement and real-time alerting of structural defects in hulls: Vision technology can play a crucial role in scanning the hull structure and accurately identifying locations of deformation, thereby improving the effectiveness of online inspection [88,138]. It is beneficial to develop advanced algorithms for automatic image recognition, precise measurements, and real-time alerting to enhance the efficiency and accuracy of detecting structural defects.

(3) Autonomous tracking flight of drones inside cabins: Vision technology can facilitate smooth and practical tracking tasks within ship cabins, which remains challenging when searching for targets in confined areas. A future research agenda should be set to develop autonomous tracking capabilities of drones within cabins, as they can aid in significantly improving inspection efficiency and enable effective monitoring of specific areas [88].

4.2.4. Marine Environment

Although showing some attractiveness in coastal ecological monitoring, UAV technology has still revealed some application problems in practice.

(1) Data fusion: The sensing data acquisition from a single UAV could arguably be insufficient to meet the actual needs of coastal environmental monitoring. A possible solution approach is to combine multiple payloads, such as visible loads, infrared loads, and light detection and ranging (LiDAR), to acquire remote sensing data [139]. By fusing

data from different sources with varying characteristics in the same area, the reliability of remote sensing information can be better assured.

(2) Limited coverage area: When monitoring missions span across a large area, a single UAV may need to make multiple trips to cover the entire region, resulting in a time-consuming and inefficient result. The implementation of self-organising network technology can enable multiple drones to work collectively, optimising the monitoring mission and completing it in a more efficient and timely manner [140]. Furthermore, drone carriers (e.g., ships carrying drones) can be deployed to enlarge the coverage area [91].

4.2.5. Marine Communications

In marine communications, drones are mainly applied as communication relay nodes. While research has been conducted on the static 3D deployment and dynamic trajectory planning of drones, there are still unresolved issues that need to be addressed, taking into account the static and dynamic characteristics of drones.

(1) Interference management: Deploying drones effectively in the presence of interference is a significant challenge. Addressing interference-related issues will be critical to optimise the performance of drone-based communication systems [141,142].

(2) Trajectory planning in three dimensions: Current studies often assume that all drones fly at the same fixed altitude when planning their trajectory. However, to maximise performance and coverage, it is necessary to enable UAVs to travel along any path in three dimensions [143,144]. Research efforts are required to develop trajectory-planning algorithms that allow drones to navigate dynamically while considering obstacles, communication range, and other factors.

According to the above-mentioned content in Section 4.2, Table 7 presents an overview of the challenges and corresponding solutions related to the application of drones in maritime transport in the future. It serves as a reference guide for various stakeholders involved in the maritime industry.

Table 7. Challenges of and solutions to the use of drones in the future maritime transport.

Application	Challenges	Solutions
Marine rescue	1. Difficulties in transferring injured individuals at sea during rescue operations. 2. Cloud and rain interfere with target recognition.	1. Research on medical drones for transportation purposes. 2. Develop radar-forming equipment that can penetrate clouds and rain.
Marine safety and surveillance	1. Data transfer capability for maritime surveillance during drone surveillance is limited by distance. 2. Developing data processing and data fusion techniques for maritime drone surveillance. 3. Practical cooperation between drones and existing maritime supervision equipment.	1. Further research to improve the security and reliability of UAV data transmission. 2. Integrate vessel behaviour monitored by drones with vessel information obtained using the AIS. 3. Establish a 3D maritime supervision system with VTS as the centre of supervision.
Marine navigation	1. Inefficient process for measuring hull structures. 2. Errors in using drones to inspect hull structural flaws. 3. A high probability of errors in the manual control of drones to inspect the cabin.	1. Develop automated technologies for measuring hull structure thickness using drones. 2. Integrate multiple vision technologies such as automatic image recognition and measurement. 3. Utilise computer vision techniques to facilitate smooth and practical autonomous tracking flight of drones inside the cabin.
Marine environment	1. Remote sensing data acquisition of a single UAV is no longer sufficient to meet the actual needs of coastal environmental monitoring. 2. The limited coverage area of a single drone.	1. Combine multiple loads to acquire remote sensing data. 2. The self-organising network technology can be used to enable multiple drones to work together.
Marine communications	1. Effectively deploying drones in the presence of interference. 2. All drones fly at the same fixed altitude when planning their trajectory.	1. Find ways to eliminate interference between drones. 2. Investigate how drones can explore arbitrary routes in three dimensions.

4.3. Implications from the Challenges and Solutions

By taking into account the challenges and solutions of the use of drones in the current and future maritime transport from Figures 6 and 7, the following departments can make informed decisions, develop appropriate strategies, and drive innovation in this evolving field.

(1) Maritime regulatory authorities can utilise the information on technical challenges and solutions to develop or update regulations and guidelines regarding the use of drones in maritime transport. This can help ensure safety, security, and compliance with regulatory requirements.

(2) Shipping companies and port operators can gain insights into the technical challenges and corresponding solutions to integrate drones effectively into their operations. They can explore the implementation of drone technologies for tasks such as surveillance, cargo delivery, and maintenance operations.

(3) Companies involved in drone manufacturing and technology development can benefit from the identified technical challenges and solutions. This information can guide them in improving drone designs, enhancing performance, and addressing specific requirements for maritime applications.

(4) Academic institutions and research organisations can leverage the challenges and solutions to identify further research and development areas. They can focus on refining existing drone technologies, exploring new applications, and addressing emerging technical challenges in the maritime transport sector.

5. Conclusions

This paper presents a systematic review of research on drone applications in the maritime industry, encompassing marine safety and surveillance, marine rescue, marine environment, marine communications, military and naval applications, anti-piracy applications, augmented reality applications, and cargo loading and unloading applications. It proposes a new classification scheme based on drone flight characteristics to aid in selecting the most suitable drone for different situations. Furthermore, it provides detailed descriptions of the evolution trends, different applications, and technical points for drones in maritime transport to promote the systematic application and holistic development of drones in the maritime industry. This paper not only discovers the promising application prospects of drones in the maritime industry, but also highlights the challenges facing its future developments, such as safety, stability, and reliability. It analyses the technical bottlenecks of drones in the maritime environment and proposes technological innovations and solutions to ensure safe and sustainable development. In summary, this paper provides valuable support and guidance for the application and development of drones in the maritime industry.

Future work will focus on the optimisation of maritime rescue by drones and the seamless cooperation of drones and ships in ensuring maritime safety. Such collaborations could lead to the development of integrated systems where drones act as the eyes in the sky, providing ships with real-time information, early warnings, and strategic insights, ensuring a safer and more efficient maritime environment. It will also incorporate new data from 2023 and onwards, when they become available, to continue the relevant evolution analysis.

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