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Meet the editors

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Contents

Preface

In recent years, the world has witnessed incredible advancements in the field of autonomous vehicles, changing industries, logistics, transportation, defense, and other applications. The journey towards fully autonomous systems has been both exciting and challenging, with researchers and engineers pushing the boundaries of technological innovation. This book, *Autonomous Vehicles – Applications and Perspectives*, includes eight chapters that discuss autonomous vehicles.

The book is divided into four sections: "Introduction", "Autonomous Vehicles Enabling Technologies", "Autonomous Vehicles Applications and Potentials" and "Challenges and Perspectives". Section 1 includes two chapters: "Autonomous Systems for Defense Applications" and "Autonomy in UAV Civilian Applications". Section 2 includes two chapters: "Communication and Network for Autonomous Vehicles" and "Mobile Industrial Robotic Vehicles: Navigation with Visual SLAM Methodologies". Section 3 includes two chapters: "How the Micro ROV Class Will Change the Maritime Sector: An Introductory Analysis on ROV, Big Data and AI" and "Unmanned Ground Vehicle as a Docking Element of a Ground-Aerial Robotic System". Section 4 includes two chapters: "Sharing the Road: Challenges and Strategies" and "Perspective Chapter: Training Autonomous Ships for Safe Navigation".

This book is a comprehensive and informative resource for researchers, students, and professionals interested in the dynamic world of autonomous vehicles. We hope that the diverse perspectives presented in these chapters will inspire further advancements and discussions, propelling the field of autonomous vehicles to new heights.

The editors give special thanks to the staff at IntechOpen, including Publishing Process Manager Ms. Zrinka Tomicic and Commissioning Editor Ms. Iva Simcic Mance for their contributions to the editorial process.

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Section 1

Introduction

Chapter 1

Autonomous Systems for Defense Applications

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Abstract

The numerous advantages of using UAV platforms, alongside with recent scientific developments in the field of autonomous vehicles in general and the lower production costs for such platforms, have increased interest in their usage in a variety of defense applications. This work investigates swarming in defense applications and provides information about the crucial modules needed for a swarm to operate and the main missions in defense applications that the swarms can be used to enhance the situational awareness.

Keywords: UAV, military applications, guidance, autonomy, swarm, unmanned vehicles

1. Introduction

Swarming technology is a disruptive and game-changing technology that can change the way militaries conduct operations. Swarms can be employed in surveillance and reconnaissance to autonomous attack operations in defense, – and are the two potential applications of Unmanned Vehicles (UV) swarms that gaining significant interest in the last decade. UV swarms can be used to capture important information, and intelligence by monitoring certain areas for adversary positions, movements, and activities and behaviors.

Swarms, due to their collaborative nature, can cover large regions of an area, providing real-time situational awareness and decreasing the risk to human soldiers. Target Detection UV swarms can detect and track high-value targets like hostile vehicles, weapons systems, or troops, using advanced sensors, artificial intelligence, and machine learning to detect, identify, and track prospective targets, enabling more precise targeting and engagement in a faster and more accurate manner. Moreover, UV swarms can be used in offensive operations like air attacks or naval battles and overwhelm enemy defenses by coordinating their movements and assaults, improving the chances of mission success.

UV swarms are also capable of carrying out coordinated electronic warfare strikes, such as jamming enemy communications or damaging radar systems. Additionally, utilizing advanced decision-making algorithms, UV swarms may safeguard military assets by establishing a protective perimeter around high-value targets such as ships or stations. They can identify, track, and confront prospective threats, making successful strikes more difficult for opponents. UV swarms can be used to restock and sustain frontline soldiers by delivering critical resources like gasoline, ammo, and medical supplies. This reduces the need for risky convoys and human engagement in dangerous places.

One of the key advantages of swarms is their ability to operate autonomously, with minimal human supervision. This allows them to adapt to changing situations in real time and respond to threats quickly and effectively. Swarms can also operate in a coordinated manner, allowing them to perform complex tasks that would be difficult or impossible for a single vehicle.

Another advantage of swarms is their low cost and scalability. Small, low-cost unmanned vehicles can be produced in large quantities, allowing military forces to deploy swarms in large numbers. This can help to offset the numerical advantage of an enemy force and increase the effectiveness of military operations. Overall, swarming technology has the potential to be a game-changing technology on the battlefield.

This work investigates swarming in defense applications and provides information about the crucial modules needed for a swarm to operate and the main missions in defense applications that the swarms can be used to enhance the situational awareness.

2. Swarming technology

In defense applications, swarming technology refers to the coordinated behavior of multiple UVs working together to achieve a common goal. This technology provides numerous benefits by leveraging UV swarms' collective intelligence, adaptability, and resilience.

Individual vehicles can work together as a cohesive unit thanks to effective communication and coordination algorithms, while advanced autonomy and artificial intelligence (AI) capabilities allow the swarm to make decisions and execute tasks without constant human intervention. UV swarms are also scalable and modular, making them appropriate for a wide range of defense applications.

Furthermore, they provide greater redundancy and resilience than single-platform systems, ensuring that the loss of one or more vehicles does not have a significant impact on overall mission effectiveness. UV swarms can operate in a variety of domains, including air, land, sea, and space, making them adaptable to a wide range of defense applications, including surveillance, reconnaissance, electronic warfare, logistics, and combat operations.

This section examines three key characteristics of swarms for defense applications: the most important capabilities and technologies that enable the development of efficient swarms, the primary architecture schemas used when designing a swarm, and some of the operation types that are frequently combined to describe a swarm's mission for defense applications.

For defense applications, three major technology modules must be considered: perception, task allocation & decision-making and path planning & deconfliction [1] as illustrated in **Figure 1**. From perception capabilities to swarm communication protocols [2] and routing [3], each module plays an important role in swarm performance and robustness.

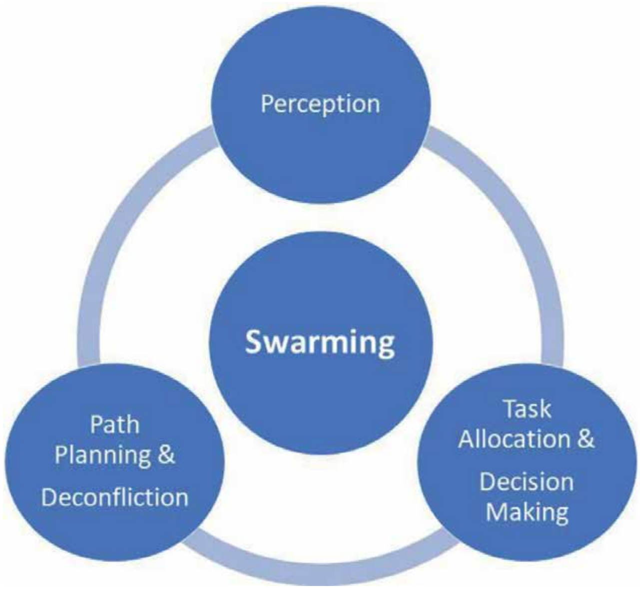

Figure 1.
The overview of the main characteristics.

2.1 Perception

The ability to perceive is critical for the success of swarms of unmanned vehicles. Perception allows the swarm to observe and comprehend its environment, recognize obstacles and desired targets, and retain situational awareness. The swarm's effective perceptual abilities allow it to operate in complex and dynamic missions and complete a wide range of complex tasks with high efficiency. Effective perception ensures that the swarm can navigate through the environment, communicate, and accomplish tasks efficiently and precisely. Machine learning (ML) and AI methods, as well as sensor fusion, allow a swarm to acquire situational awareness at a previously unattainable level. UV swarms can benefit from ML and AI by processing and analyzing big data from many sources, allowing them to identify patterns, make predictions, and adapt to changing situations. These approaches can assist swarms in distinguishing desirable targets, detecting obstacles and determining the optimal course of action, and adjusting their behavior in real-time.

The technique of merging and combining data from several sensors to provide a more accurate and comprehensive picture of the environment is known as sensor fusion. Data from cameras, LiDAR, radar, sonar, and other sensors may be included and so UV swarms can gain a more detailed and reliable situational awareness by fusing input from several sensors, which is critical for navigation, communication, and task execution.

Several works address the topic of efficiently merging and combining data from different types of sensors [4]. In the work presented in [5], the authors introduce a system including static sensor network design, mobile sensor tasking, and information and algorithms for use in commercially available unmanned vehicles with low computational power requirements, flexibility, and reconfigurability. A practical demonstration of swarm technologies in a scaled outdoor environment aimed to test and validate the effectiveness of various algorithms and techniques for persistent monitoring in military and law enforcement applications. The swarm technologies addressed several critical aspects, including task allocation, situational awareness, target detection and tracking, and cooperative guidance. The greedily excluding technique was used for task allocation, which ensures near-optimal allocation in real-time and allowed the swarm to adapt and respond effectively to rapidly changing environments. Enhanced situational awareness was achieved through Unmanned Aerial Vehicle (UAV) aerial sensing, a general framework for autonomous behavior monitoring, and trajectory analysis tools. Sensor fusion technology and decentralized tracking algorithms supported automatic target detection and tracking. A reactive and distributed cooperative guidance law was designed for mobile vehicles, addressing mission and safety objectives, as well as interactions between the vehicles and the static sensor network.

2.2 Task allocation and decision-making

Task allocation aims to analyze existing tasks that need to be performed and distribute them to the available agents. More specifically, it assigns tasks to an agent or a group of agents intending to find an optimal or near-optimal mapping between agents and tasks. Effective task allocation guarantees that each agent is allocated a task that matches its capabilities, maximizing the utilization of available resources. Swarms can compensate for the failure of one or more agents, and task allocation aids in the distribution of decision-making, allowing the swarm to quickly adjust to changing conditions. In general task allocation also improves adaptability, scalability, and decision-making speed, allowing swarms to be more successful in dynamic and uncertain environments and providing efficient resource utilization, increased resilience, and fault tolerance.

Under multi-constrained conditions, multiple UAV task allocation models were established [6]. This work used the Multi-Agent Systems (MAS's) abilities of environmental perception, collaboration, and self-learning to establish a distributed immune multi-agent algorithm (DIMAA) by using a high-performance artificial immune system for solving complex problems. The following operators are proposed: immune memory, neighborhood clonal, neighborhood suppression, neighborhood crossover, and self-learning. Simulation experiments validate the proposed algorithm's performance under three dynamic conditions task allocation, new targets, damaged UAVs, and pop-up weather threats. The simulation results revealed that the proposed algorithm has a fast solution speed, a high optimization capability, and the ability to balance the missions of the UAVs and reduce communication loss. Furthermore, in a changing task environment, it can still obtain good task allocation results. All these results mean that the proposed algorithm has better global optimization capability, dynamism quality, and robustness.

In [7], the paper analyzes a described scenario to answer the question "Should the robots compete, or should they cooperate?". There are two game-theoretical algorithms developed. The competitive algorithm plays games with each drone and its neighbors while looking for the Nash Equilibrium. The cooperative one defines electoral systems that allow drones to vote on the task allocations they prefer for their neighbors. Both algorithms are extensively tested in multiple scenarios with different features. After the experiments, the question can be answered: "The robots should cooperate!".

The work presented in [8] describes a probabilistic strategy for assigning specialized individual agents within a robotic swarm to match limited tasks. The proposed approach evaluates the probabilistic fitting of the available robot individuals based on the requirements imposed by the current task, which takes the form of a recognized target object in a specific environment, on the assumption that each agent possesses specialized capabilities. To evaluate a task-agent fitting score among all accessible agents, a formal matching scheme is devised. As the best responder, it assigns the most qualified and available specialized robotic agent to do the recognized task. A simulation study is presented to validate the efficiency and robustness of the proposed approach.

The work presented in [9] illustrates the Bird Swarm Algorithm (BSA), a new bio-inspired method for tackling optimization problems. BSA is based on swarm intelligence collected from bird swarm social behaviors and interactions. Birds primarily engage in three types of behaviors: foraging, alertness, and flight. Birds can seek food and avoid predators through social interactions, giving them a high probability of survival. BSA develops four search techniques connected with five simplified rules by modeling these social behaviors, social interactions, and related swarm intelligence. Simulations and comparisons based on eighteen benchmark problems demonstrate the effectiveness, superiority, and stability of BSA.

2.3 Path planning and deconfliction

Swarms are expected to contain a high number of robots. Path planning and deconfliction procedures are therefore critical for efficient and safe swarm operations. Path planning in swarms seeks to discover the best way for each agent to take to its destination while avoiding obstacles and consuming the least amount of time and energy. Deconfliction prevents robots from colliding, enabling each agent to fulfill its duty properly. Path planning, for example, can optimize the trajectories of the agents in a surveillance mission to reduce overlap and enhance coverage area. A range of methodologies, including centralized and decentralized ones, can be used to achieve path planning and deconfliction. Centralized techniques entail a single entity planning and coordinating the activities. Decentralized approaches, on the other hand, involve each robot making its own path-planning decisions based on available information.

This paper [10] investigates collision avoidance algorithms for many UAVs based on geometry. By extending the collision-cone technique to UAV formation, the suggested strategies allow a group of UAVs to avoid obstacles and split if required, using a simple algorithm with cheap processing. The geometric technique incorporates dynamic limitations into the construction by using line-of-sight vectors and relative velocity vectors. Each UAV may choose the plane and direction to use for collision avoidance. An analysis is undertaken to design an envelope for collision avoidance, considering angular rate constraints and object detection range limits. Each UAV in a formation decides if the formation can be maintained while avoiding obstacles based on the collision avoidance envelope. Numerical simulations are performed to demonstrate the performance of the proposed strategies and the results indicate good performance for coordinated collision avoidance by multiple UAVs. The work presented in [11], describes a method for collision-free trajectory planning with several UAVs that detect conflicts automatically. When problems between UAVs are detected, the system collaboratively resolves them using a collision-free trajectory planning method based on a stochastic optimization approach known as Particle Swarm Optimization (PSO). The novel Maneuver Selection Particle Swarm Optimization (MS-PSO) implementation of the PSO method outperforms prior implementations. Because the scale of the problem is decreased, the execution time is lowered, and other types of maneuvers can be used to resolve discovered conflicts: course/heading, speed, or altitude modifications. The MS-PSO has been validated with simulations in scenarios with multiple UAVs in a common air space.

3. Applications

Unmanned vehicle swarms communicate information through communication protocols, which are established by the mission's unique requirements as well as the swarm's features [12]. An efficient architecture is required for exchanging information among a swarm of unmanned vehicles, allowing them to operate safely and accomplish their missions.

To ensure efficient information exchange in a swarm, it is crucial to choose the appropriate architecture and communication protocols that are scalable, reliable, adaptable, and interoperable. The architecture and protocols should be scalable to handle the increasing number of vehicles in the swarm without affecting performance. The communication system should be reliable, ensuring accurate, timely, and consistent information exchange, while also being resilient to adversarial forces.

Furthermore, the architecture and protocols must be adaptable to changing mission requirements and swarm compositions, allowing the swarm to respond to unexpected events or challenges effectively. Interoperability between various types of vehicles, sensors, and systems is critical for seamless cooperation among heterogeneous swarm members and the incorporation of new technologies. Finally, low latency and scalable bandwidth are critical for time-critical missions that require quick decision-making and response times.

The three primary architectural strategies for developing swarms of unmanned vehicles for defense purposes include Centralized, Decentralized, and Hybrid architectures.

Hybrid architecture is appropriate for larger swarms and complex missions requiring a high level of coordination and autonomy between vehicles. The centralized component can provide higher-level decision-making and overall mission objectives, whereas the decentralized component can provide local decision-making based on real-time data. This approach ensures the swarm's ability to adapt to changing mission requirements, maintain a robust and resilient communication network, and remain effective in dynamic and uncertain environments. Finally, the architecture chosen will be determined by the specific mission requirements, the number of vehicles in the swarm, and the level of coordination and autonomy required for mission success.

Swarms of unmanned vehicles present a plethora of military applications and can conduct various missions. Some key examples of operation types of autonomous swarms are identified here. The presented operation can be combined to create a series of missions. In **Figure 2**, the main applications of the swarms of UVs are illustrated.

3.1 Full and persistent area coverage

For low-level automated coordination of a swarm of robotic agents, the authors in [13] suggest using a straightforward force law that draws inspiration from both

Figure 2.
The overview of the main applications.

swarm intelligence and classical physics. Authors show how the coverage issue can be solved by using this control law to build a lattice of sensors for an airborne surveillance application.

They aim to find the correct separation distance R to maximize overall coverage and the constant G that affects the rate at which the swarm converges to a stable configuration using a genetic algorithm for optimizing the control law for a relatively simple scenario with a limited search space having a simulation of 7 robot agents in a hexagonal lattice formation which can control their velocity and sense the range and bearing of neighboring agents. They found that this approach is a viable option for learning parameter settings within the control-law framework and application/problem setting considered in this paper.

3.2 Area search

Swarm capabilities present a great benefit to area search operations due to the easiness of distributing the work. The task of area search differs from the previously mentioned operations since target specificity can be applied. Moreover, optimizing swarm performance means identifying the target in as little time as possible, hence it is unnecessary to search the whole area of interest. Area search algorithms play an important role in the effectiveness of the swarm, the authors in [14] studied data fusion to enhance swarm control and decision-making. To do so the search region was discretized by turning it into cells and a probability map is built on each UAV. A distributed fusion scheme was developed which showed that all probability maps converged to the same one that reflected the true environment. In [15], the authors propose three cooperative search algorithms for military applications using a heterogeneous swarm. A decentralized task allocation has been developed, and the tradeoff between prediction-based and search-based approaches is examined. The results indicate an intelligent use of prediction can be helpful. Lastly, the authors in [16] have developed an efficient cooperative search that takes into account potential intelligence being present on the target of interest in the form of evasion tactics. The two search algorithms proposed to enable the swarm to perform decentralized area search for one or more targets. Both algorithms provided exceptional results and it is worth noting that one of them also can search in areas of undefined shape and size.

3.3 Area surveillance

In [17] the authors present a project called "ASIMUT", a distributed decentralized surveillance system that utilizes UAV swarms to collect information and generate data of higher quality. The system is composed of a Command and Control (C2) system and a set of heterogeneous UAVs that constitute swarms. The UAVs are equipped with various onboard sensors including long-range radar and electro-optical/infrared cameras to monitor the movements of ground vehicles. The system has a basic layered model structure consisting of three layers, each serving specific purposes: Collaboration of UAVs, Detection by UAVs, and Exploitation of Data. The ASIMUT system is designed to perform automatic detection of targets in a full motion video, and the process has been divided into several steps, including work on optical flow, detection of points of interest, projective image transformation, compensation for camera movement, and motion detection.

Work in [18] proposes an adaptive recommender-based system for swarm guidance and control for aerial surveillance tasks that can adapt the level of swarm autonomy in real time according to the needs of human operators. The system uses a sheepdog shepherding control method for the swarm, which provides a single point of control for a large swarm of autonomous UAVs. A recommender system powers the suggested system, giving the human operator optimized recommendations in real time for maximizing work performance. The frequency with which the system provides those recommendations to the operator is controlled by variable adaptation, which adjusts according to their cognitive load in real time. A particle swarm optimization algorithm is used to find the best strategies for shepherding the swarm of UAVs, and its effectiveness and efficiency were evaluated through simulation experiments. However, the study was limited to simulation-based experiments, and the authors plan to investigate the performance of the proposed approach in an adaptive human-swarm interaction context in the future.

3.4 Target tracking

Target tracking: Commonly a target tracking operation involves one target and one vehicle. The scope of the vehicle is to online plan its path based on its sensory data and its estimation of the target's location and in some cases the predicted behavior or future location of the target [19]. The vehicle must guide itself to constantly follow the target. With the introduction of swarming capabilities, the target tracking problem can be augmented into a multi-vehicle problem, tracking a single [20] or multiple targets [21]. Moreover, the concept of target tracking has been extended from the ground to aerial targets where a swarm of autonomous UAVs are tasked with tracking another malicious UAV [22]. In this work, the authors explore different methods of UAV formation to effectively tackle the tracking of a UAV with superior flight capabilities. Lastly, multi-agent target tracking using Fixed-Wing UAVs has been researched extensively along with formation control and performance outcomes in [23] alongside a proposed architecture for the above in [24]. Overall, the design of swarms for defense applications requires careful consideration of several factors, including mission requirements, swarm size, communication capabilities, and computational resources.

4. Conclusions

In conclusion, unmanned vehicle swarms have the potential to transform military operations. However, in order to ensure efficient information exchange in a swarm, it is critical to select scalable, reliable, adaptable, and interoperable architecture and communication protocols. Centralized, decentralized, and hybrid architectures are the three primary architectural strategies for developing swarms of unmanned vehicles for defense purposes. The architecture selected will be determined by the mission requirements, the number of vehicles in the swarm, and the level of coordination and autonomy required for mission success. The main modules needed for a swarm to operate efficiently are task allocation, path planning, object detection and tracking and deconfliction. The combination of these modules can provide the necessary swarm intelligence for military applications for missions like full and persistent area coverage, area search, area surveillance, and target tracking.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 2

Autonomy in UAV Civilian Applications

Niki Patrinopoulou, Vaios Lappas, Ioannis Daramouskas, Dimitrios Meimetis and Vassilis Kostopoulos

Abstract

The multiple advantages of the use of Unmanned Aerial Vehicle (UAV) platforms in combination with the recent research advancements in the field and the reduction of production cost for such platforms have caused an increasing interest for their use in multiple civilian applications. As the number of UAV operations in a common airspace increases, Unmanned Traffic Management (UTM) plays a crucial role in accommodating flights in a safe and systematic manner. This work looks into six categories of those applications and the relevant guidance and decision-making algorithms and methodologies to enable autonomy in their execution, as well as traffic management systems required to support them.

Keywords: UAV, civilian applications, unmanned traffic management, guidance, autonomy

1. Introduction

Research on the use of UAVs for civilian applications has gathered a lot of interest in the last decades, as UAVs prove to be a highly useful tool for a plethora of use cases. UAVs were initially employed for military applications, responsible for a variety of missions. Their decreasing cost, high aerial mobility, and the advancements in battery technologies made UAVs highly attractive options for civilian applications as well [1]. Proposed civilian applications include agriculture, photography, shipping and delivery, disaster management, rescue operations, archeological surveys, geographic mapping, human health, livestock surveillance, safety inspection, wild-life observance, weather forecasting, emergency response, telecommunication, and border surveillance [2, 3].

UAVs present a wide variety from micro-UAVs weighing some 100 g to large UAVs weighing over 100 kg. They also differentiate by their control configuration. Some examples of UAVs with different kinematics models are presented in **Figure 1**. Their size and control configuration are factors that should be considered while selecting a UAV for a specific application and while designing the guidance methodology to apply.

UAVs are expected to decrease the financial cost, improve performance in terms of range and completion time, and minimize human fatigue and safety risk in the operations they are involved in. Systems consisting of multiple UAVs capable of

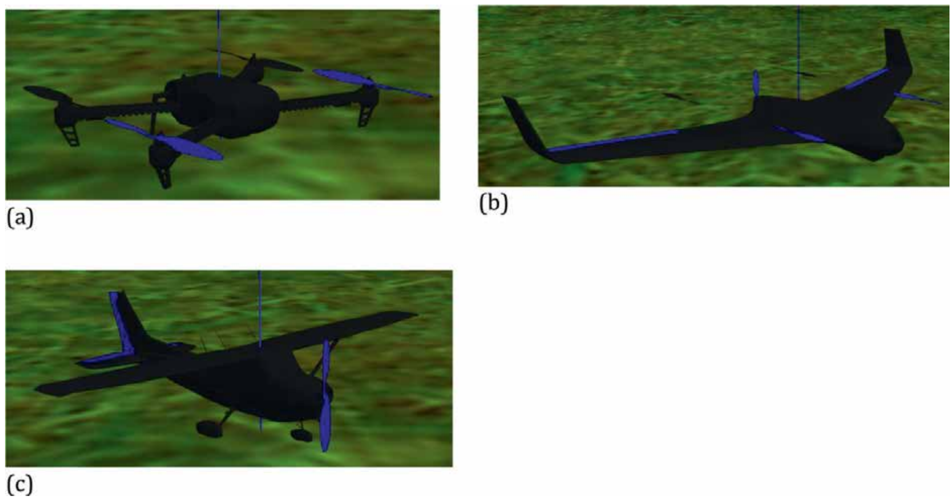

Figure 1.
Examples of UAVs in the Gazebo simulator. (a) A multirotor quadcopter, (b) A vertical take-off (VTOL), (c) A fixed-wing.

collaborating to reach a user-defined goal reduce the response time for time critical operations (e.g., search and rescue missions). Autonomy capabilities reduce the operator's workload and enable operations with multiple UAVs. In addition, UAVs with autonomy features should lower the risks related to the performance of the human operator [4]. Fully autonomous UAVs make decisions on their missions and planning with no human intervention [1].

Four levels of autonomy for UAVs are identified in [5], from remote control to fully autonomous:

- Fully autonomous: The UAV is capable of achieving its given scope and completing its mission with no human intervention while considering operational and environmental conditions.

- Semi-autonomous: The UAV is capable of autonomous operation between human interactions. The mission is planned and executed by the human operator and/or the UAV.

- Teleoperation: The UAV receives actuator commands or continuously updated goals by the human operator, who accesses sensory data from the vehicle.

- Remote control: The UAV is continuously controlled by a human operator and only conducts Line of Sight missions.

The significant advantages and multiple applications of UAVs are expected to cause an outstanding increase in the number of UAV operations over urban and rural areas. The need for methods to manage and control increasing UAV traffic is becoming more urgent. A UTM system is responsible for supporting, monitoring, and regulating the safe and smooth incorporation of UAVs into civilian airspace. UTM systems are seen to be a part of or an addition to Air Traffic Management (ATM), which has been employed for manned aviation for decades. Research on UTM has boosted in the latest decade, with several research programs focusing on defining its requirements, describing its operations, and designing and testing its implementations.

In this chapter, a short literature review of different civilian applications of UAVs is presented, focusing on guidance algorithms designed to increase the vehicles' autonomy capabilities in decision-making and planning to support fully autonomous operations. Recent work with guidance methods designed for specific civilian applications is presented. Additionally, an overview of proposed traffic management systems and concepts for UAVs is presented, describing their safe incorporation into civilian airspace.

2. Civilian applications

In this section guidance and decision-making paradigms based on the intended use case are described. Although different UAV applications and use cases could be formulated as well-known guidance problems (e.g., traveling salesman problem (TSP), vehicle routing problem (VRP), coverage path planning problem, etc.), each application type introduces specific constrains and optimization parameters for the guidance system. Six main civilian applications are presented: cinematography, payload delivery and shipping, agriculture, surveillance, search and rescue, and disaster and environmental monitoring.

UAV operations in [1] are separated into six categories: area coverage, search, routing for a set of locations, data gathering and recharging in wireless sensors network, allocating communication links and computing power to mobile devices, and operational aspects of a self-organizing network of drones. Most of the applications considered in this work fall into the first three categories. **Figure 2** shows the relation between those three operation categories and the UAV applications studied in this work.

In area coverage operations, the UAVs must scan a specific area. In the coverage path planning problem, the UAV must design a path to cover all points of the area with its sensors. In case full area coverage is not possible, the designed path must maximize the collected information while obeying to the imposed constraints. If the area is decomposed to a grid of cells, the problem can be transformed into a traveling salesman or a vehicle routing problem. Coverage operations are applied in agriculture, surveillance, and disaster and environmental monitoring.

In search operations, the UAVs are tasked to explore an area and locate specific targets of interest with unknown locations. The operation or search area is usually partitioned into a grid of cells and cells are associated with probabilities to create a belief map on the existence of targets. The applied approach is usually optimized to minimize the time to detect the targets. Search operations include applications in search and rescue, surveillance, and disaster and environmental monitoring.

In routing operations, a set of waypoints of interest are given by the end-user or generated from another system and the UAV must design paths to visit them all while minimizing time or energy criteria. Routing operations are generally formulated as TSP or VRP problems, with multiple variations of them identified in literature. If the kinematic model of UAVs is considered the problems may be converted into Dubins-TSP or Dubins-VRP. Similarly, if multiple UAVs are cooperating to visit all locations, multi-vehicle TSP or VRP problems are defined. Additional constraints are included depending on the intended application. For example, waypoints might be coupled with specific visitation time windows, or some waypoints might need to be visited in a specified sequence. Routing operations are commonly encountered in cinematography and payload delivery.

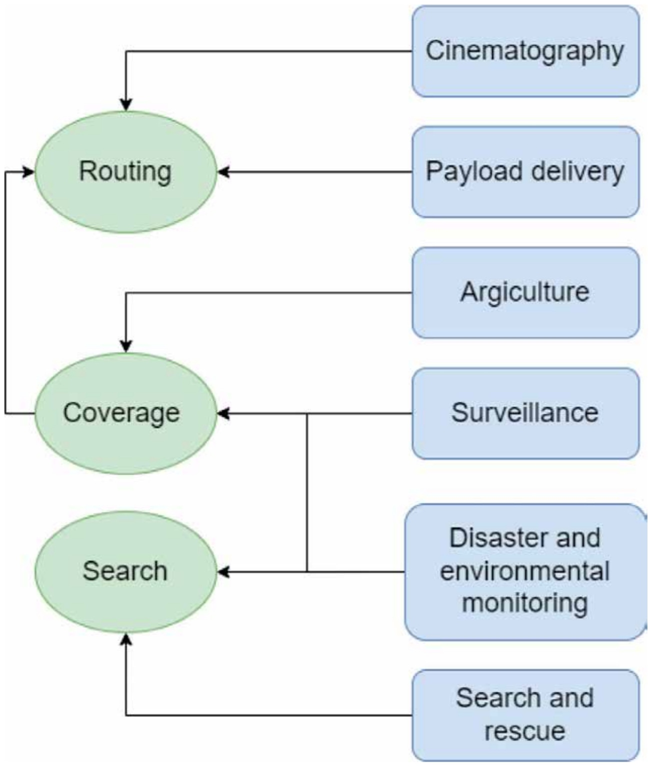

Figure 2.
Civilian application of UAVs and their relations to three common operations (routing, coverage, and search).

2.1 Cinematography

Autonomous UAV cinematography offers the capture of aerial video footage from previously hard-to-reach areas, innovative visual effects and shot types, large area and multiple targets coverage, capturing a scene from multiple view angles, and cost reduction in comparison to manual shooting [6, 7]. The UAV cinematography concepts are described by the desired camera motion shot type and the desired framing shot type given by the director or human end user. The camera motion shot types define the UAV's trajectory and are categorized into static, dynamic, target tracking, and dynamic target, depending on if the UAV is moving and if its motion directly depends on the target's trajectory [6]. The framing shot type describes the percentage of the camera image covered by the target.

An autonomous system for cinematography including multiple UAVs consists of [8]:

- A high-level planner, responsible for generating and allocating specific tasks to the system's UAVs while considering time and resources constraints.

- A path planner, responsible for generating a list of waypoints for the involved UAVs, including specification for the camera's attitude while considering the vehicles' safety.

- A trajectory follower, responsible for guiding each UAV to execute the generated path while controlling its camera to provide the desired shot angle.

- A scheduler, responsible for synchronizing the action of the above three modules.

The autonomous cinematography UAV system uses as input a high-level mission description provided by the director/human end-user. The mission description contains a set of artistic instructions including shot types, starting time and duration, positions and targets, etc.

Trajectories for cinematography UAVs must meet esthetic quality criteria in addition to constraints imposed from the UAV's dynamics. The attitude of the UAV and camera must be planned to obtain the desired result. The trajectory planning of the UAV and the attitude control of the camera can be approached as one optimization problem or be decoupled and solved separately. A proposed method of trajectory planning for flying cameras is presented in [9]. The problem is formulated in a non-linear model predictive contouring control manner, and it is solved online in a receding horizon fashion. The formulated optimization problem includes dynamic planning and collision avoidance to smoothly guide the UAV to follow virtual rails, the desired 3D path.

By decoupling the two problems, the headings of the UAV and the camera are examined independently. A covariant gradient descent is proposed in [10] to compute the UAV's trajectory while minimizing the cost function. The cost function includes smoothness, shot quality, occlusion, and safety metrics. A desired trajectory can be computed by formulating the problem as a constrained nonlinear optimization problem, solved in a receding horizon manner [11, 12]. This allows to minimize the required camera changes for smooth camera movement, the vehicle's acceleration for smooth and efficient trajectory, and the distance to target to guide the vehicle towards the desired location. The UAV's kinematic constrains and collision avoidance constrains must be added to ensure the generated trajectory is feasible and safe.

2.2 Payload delivery and shipping

Employing UAVs for package and food delivery missions is expected to minimize the delivery time and reduce the delivery costs [13]. In addition, it has the potential to decrease energy consumption and CO2 emissions [14]. A UAV based system for food delivery is presented in [15]. The buildings of the area are described in a 3D map and the A* algorithm is used to compute the shortest path from the origin to the desired delivery point.

While the path planning problem for deliveries is relatively simple to solve, this is not the case for delivery using multiple UAVs. The problem is changed into a vehicle routing problem, in which the optimal assignment of UAVs to deliveries must be computed while minimizing criteria like delivery time and energy consumption. A genetic algorithm for assigning delivery tasks to UAVs is presented in [16]. Authors in [17] approach the problem using a Mixed-Integer Linear Programming (MILP) model fitted to optimize several objectives in order to minimize delivery time and energy consumption. The UAVs collaborate to collect and deliver packages. After the routing problem has been formulated, a matheuristic method is applied to generate solutions in restricted computational time. A mixed integer programming model is presented in [18], which integrates constrains sets generated by the business logic of food delivery.

2.3 Agriculture

State-of-the-art UAV farming technologies include planting methods based on UAVs, which decreases the planting cost by up to 85% [19]. Potential UAV agriculture application include planting, crop and spot (i.e., targeted on weeds) spraying, crop monitoring, irrigation monitoring (i.e., identify areas with low soil moisture, dehydrated crops, water-logged areas), soil and environment conditions monitoring, cattle monitoring, and mustering (i.e., locating and gathering livestock animals in a large area) [20–22]. Aerial vehicles are not impacted from difficult terrain condition, frequently met in agricultural application, and they can offer high-level observing overview of the field or detailed level information over a target of interest by adjusting their flight path and altitude [23]. Research in the integration of UAV and multi-UAV systems with autonomy capabilities has boomed, due to the multiple potential applications identified and the benefits of UAVs.

A UAV system for remote sensing and multi-spectral data collection from a field is proposed in [24]. The system must plan a flight for area coverage. The waypoints of the trajectory are computed in relation to the area covered by one image collected of the UAV. The UAV moves forward and laterally and hovers over the generated waypoints to cover the area of interest in its entirety. The IDeAL system, presented in [25], uses UAVs to support Agricultural IoT. The Strip Division along Resultant Wind Flow approach is proposed as a path planning technique for area coverage over the field to minimize information loss, coverage time, path deviation due to wind, and energy consumption. The method is initialized by computing the convex hull of the field's boundary and then a path to cover the area of the field is generated. The path computation considers optimization parameters, like travel distance, overlaps in coverage, energy consumption, the number of sharp turns, and deviation from the planned path. The area of interest is scanned by a sweeping motion of the UAV. The field is separated into strips, so that the forward UAV motion along a strip is parallel to the wind's direction to minimize the deviation of the path due to wind.

A UAV system, capable of autonomously finding livestock in freely moving herds is presented in [21]. The UAV must search a given field and locate the animals who have unknown locations. The problem is formulated as dynamic TSP, in which the waypoints to be visited are not given preflight and the route is updated online. The problem is solved with a dual-stream deep network architecture to compute navigation commands on the grid-based flight area. Their method uses current sensory data and historic map data of the areas already explored.

A route optimization method for UAV spraying in precision agriculture is proposed in [26]. The route planning algorithm receives stressed areas, requiring spraying and generates a UAV flight plan to cover those regions. The given regions may be of irregular shapes and sizes. Their method uses the convex hull of the stressed areas and creates Voronoi diagrams to compute the optimal spray waypoints, depending on the radius of the spray. After the set of waypoints to be visited has been identified, the problem can be formulated as TSP to compute the shortest path visiting all the waypoints. A variation of TSP is used, called clustered TSP. Clustered TSP is defined for optimizing a route visiting waypoints clustered into different groups based on their location. This solution fits well the described spraying problem, as the computed waypoints are clustered based on their corresponding stress region. Specific constraints are added to the obstacle avoidance problem for agricultural spraying UAVs. Sprayer UAVs have a heavier payload, as they must carry the spraying liquid. The spraying process must cover the desired area and coverage optimization should be considered in the selection of an obstacle avoidance approach. An overview of obstacle detection and avoidance methods for this application is provided in [27]. Six families of real-time collision avoidance algorithms are considered for agricultural spraying UAVs: bug algorithms, Artificial Potential Field (APF), collision cone, fuzzy logic, Vector Filed Histogram (VFH), and Neural Networks (NN). Bug, APF and collision cone algorithms are simple to implement and do not create a heavy computational load pre-flight or during flight. Fuzzy logic and NN systems require training or learning with large computational cost and their performance and capability of generalization depends on the training data. VFH algorithms have high computational needs and do not consider the vehicle's dynamics.

Using multi-UAV systems to cooperatively execute agriculture tasks increases the accuracy and efficiency of the system. A distributed swarm control algorithm for agriculture operation is introduced in [28]. Each UAV of the swarm is controlled by three control inputs: (1) the UAV control, guiding the vehicle to the desired position, (2) the formation control, responsible for maintaining the desired inter-vehicle distances in order to maintain their communication's connectivity while preventing inter-vehicle collisions, and (3) the obstacle avoidance control, responsible for avoiding collisions with static obstacles. The formation and obstacle avoidance control inputs are computed using artificial potential functions to generate repulsive and attractive actions for the formation control and solely repulsive actions for the obstacle avoidance control. A multi-UAV system for farmland inspections is presented in [29]. They use an on-the-fly autonomous path planning algorithm able to consider information on the strategic, tactical, and operational level. On the strategic level the algorithm considers the end-user specific mission description. On the tactical level the UAV is capable of deciding to modify its path based on new information, collected by its sensors or received from another cooperating vehicle, during the mission execution. The local path is computed at the operational level, to generate safe, feasible and efficient control commands.

2.4 Surveillance

Surveillance applications require repeated coverage of the area of interest, as the monitored phenomenon is dynamic. The full area should be monitored, and the selected methods should minimize the maximum time between visits in the same region [30]. A single- and a multi-UAV method for surveillance and modification suggestions to integrate dynamic and endurance constraints are presented in [31]. The area is decomposed into a grid and each cell is assigned an age value, corresponding to the time elapsed from its most recent scanning. The next cell to be visited is selected using a control policy based on the ages of all the cells.

Surveillance procedures in urban environments impose specific constraints, as the increased density of high buildings creates multiple occlusion cases for the UAV's sensors. An occlusion-aware approach for UAV surveillance in cities is proposed in [32]. The surveillance task is formulated as a 3D Art Gallery Problem and solved with an approximation approach to define a set of waypoints that must be visited for full coverage. The path planning problem, to connect all computed waypoints is defined as a Dubins-TSP and the spiral and alternating algorithms are used to compute an optimal solution. Another approach of computing the set of waypoints for full coverage is to discretize the target area and use a genetic algorithm to select the required waypoints [33]. The UAVs' paths are computed using the Ant Colony System (ACS) method, fitted with piecewise cubic Bezier curves to generate smooth and feasible paths.

A cooperative surveillance strategy, with connectivity constraints, for a heterogenous team of UAVs is presented in [34]. The decentralized algorithm implements area partitioning for irregular, urban areas by creating sub-areas each assigned to one UAV. The coverage paths are computed to minimize the maximum time between two sequential visits of an area and the maximum time to disseminate collected data within the system.

A distributed multi-agent deep reinforcement learning-based algorithm for surveillance of a set of known targets is introduced in [35]. Energy consumption in addition to surveillance performance optimizations are considered.

2.5 Search and rescue

Search and rescue (SAR) missions are highly time critical [36], as the survivability of the victims decreases with time. For this reason, multi-UAV, collaborative search operations are proposed.

A centralized planning algorithm for multi-UAV collaboration for search and rescue missions, called layered search and rescue (LSAR) algorithm, is described in [37]. LSAR is based on the assumption that the survivors' distribution is denser closer to the center of a disaster and survivors closer to the disaster have a higher rescue priority. The disaster area is divided into regions with different sizes, regions closer to the disaster center have smaller areas than regions more distant to the center. UAVs are assigned to regions prioritizing regions closer to the center, while covering the maximum number of regions.

The search area is described in a grid representation for most SAR implementations, and each cell of the grid corresponds to one single-UAV task. That allows to reformulate the search problem as a multi-UAV task allocation (MUTA) problem. A bio-inspired algorithm, based on the foraging behavior of fish when searching for food, for multi-UAV search and rescue missions is proposed in [38]. The UAVs are divided into groups, representing schools of fish, where each group has one UAV leader. The group's leader selects the next search region for its group. Follower UAVs search grid cells in the region indicated by their leader. Follower UAVs have a forgetfulness feature, allowing them to abandon their leader and join another UAV group or create a new group, if the UAV's performance on discovering survivors is low.

Another example of bio-inspired algorithms for SAR is shown in [39]. A multi-UAV system, based on the locust behavior when searching for food sources is proposed. In the search phase of the mission, during which there is no a-priori information on the location of the survivors, UAVs act as locusts in their solitary phase and spread on the disaster area, selecting area regions not assigned to another UAV. UAVs in the search phase are distinguished into scout UAVs, who are greatly repelled by each other and only select regions unassigned to other scouts, and eagle UAVs, who explore unassigned grid cells in the average locations of other UAVs. In the rescue phase, designed for more detailed exploration of areas, UAVs act as locusts in their gregarious phase and are attracted to regions depending on the number of detected survivors in each region. A similar idea, for assigning social and antisocial behaviors to UAVs for SAR mission is explored in [40]. Antisocial searcher UAVs are guided far away from each other, spreading the swarm in the search area. On the other hand, social search UAVs are responsible for exhaustive local area search in the locations of discovered survivors.

Search paths in [41] are planned for multiple UAVs in a centralized manner using a genetic algorithm to optimize the coverage and the connectivity of the system to the base station, minimizing the sum of time to detect a victim and the time to inform the base station. Authors in [42] used a hexagonal decomposition to generate a grid map and a graph in the search area. A centralized and pre-flight mixed-integer linear programming model is proposed to solve the multi-UAV coverage path planning and achieve full coverage of the graph in minimum time.

A grid-based representation for the area can also be used to create a belief map, containing the probability of finding a survivor in each cell of the grid. A variety of approaches have been found suitable for solving the MUTA problem for SAR operations with belief map, like methods in the family of greedy heuristics, potential fields, and partially Observable Markov Decision Processes [43]. An adaptive memetic algorithm is proposed in [44] for solving the single-UAV search problem with a belief map. The algorithm adaptively selects from six different local search procedures, which are utilized to narrowly modify the solutions in an attempt to improve their fitness and diversity, based on the procedure's performance in previous generations. A coordinated Monte Carlo tree search algorithm is presented in [45]. Their implementation is decentralized and factors belief data into the decision-making process.

2.6 Disaster and environmental monitoring

Disaster and environmental monitoring applications provide a variety of solutions depending on the phenomenon they are designed to investigate. For highly dynamic situations, time is critical and obtaining a good estimation of the location and magnitude of the phenomenon in a short time is preferred over acquiring a complete image of the area in a longer time.

In time-sensitive disasters like oil spillage and wildfires, UAVs must explore the area to identify the location and borders of the disaster in minimum time and a complete area scan is not required. A decentralized methodology for mapping off-shore oil spill using a team of UAVs, called PSOil, is introduced in [46]. The search area is discretized into a grid of cells and a belief map is constructed, representing the likelihood of discovering oil in a cell. The PSOil algorithm uses the swarm dynamics of the Particle Swarm Optimization (PSO) algorithm. Three mapping phases are proposed; a scouting phase for randomly exploring the area to discover oil, an aggressive oil spill mapping phase in which the agents select their next target cell using local and global data, and a boundary tracking phase to define the exact oil spill boundaries using the Moore Neighborhood tracing algorithm.

A bio-inspired and decentralized algorithm based on the Oxyrrhis Marina behavior for locating food sources has been proposed for identifying forest fire locations [47]. The method includes two phases: an exploring phase during which the UAV executes a Levy flight, and a mapping phase during which the UAV uses Brownian search based on the temperature change it senses. The proposed system is enhanced by a dynamic formation control for guiding the firefighting UAVs to a non-overlapping formation. A leader-follower coalition formation approach for wildfire monitoring using a heterogenous swarm of UAVs is proposed in [48]. Coalition leaders decompose their assigned observance regions into single-UAV tasks and the tasks are assigned to UAVs as coalition followers using a distributed, bid-response negotiation process. Firefighting UAVs utilizing a modified PSO algorithm and the temperature readings of their sensors in a decentralized swarm are shown in [49]. PSO was adapted to handle dynamic environments.

Full area coverage is used for static or slow-changing phenomena. Commonly, coverage paths are designed by decomposing the monitored area into cells with techniques like the vertical cell, trapezoidal or boustrophedon decomposition and sequentially sweeping all created cells [50]. A major concern for mapping missions is the mission duration, as the areas of interest may be extensive and full coverage paths may be longer than the UAV's endurance. One proposed solution to this problem is to separate the area into regions, each corresponding to a single-UAV task. Authors in [51] created regions sized to the energy autonomy of one vehicle by discretizing the area, to be scanned, into a grid of cells and clustering obstacle-free cells using the k-means clustering algorithm. The coverage path is computed using a depth-first search algorithm on the cells of the assigned region. Their solution assumed multiple UAVs or recharging breaks between tasks.

If the power autonomy of a UAV is not sufficient for full area coverage, sub-optimal trajectories to cover the maximum area, while obeying to the energy constraint, must be designed. A Voronoi-based path generation (VPG) algorithm is used in [52] to plan coverage paths under energy constraints for environmental monitoring applications. The VPG algorithm is described as a repetitive process to generate the path's waypoints, satisfy energy consumption limitations and are optimized to provide the maximum and more spread coverage of the area. The path's waypoints are initialized randomly, a Voronoi diagram is created based on their positions, and the centroids of the Voronoi polygons are computed. Then, the path is modeled as a chained mass-spring-damper system, with the waypoints representing masses and springs connecting waypoints to the centroids, in order to compute the updated waypoint positions at each repetition of the algorithm.

3. Unmanned traffic management architectures

The multiple identified UAV applications in civilian use cases create the need for the definition of management systems to enable the safe conduction of various autonomous operations in common airspace. Safety, security, and economic factors must be considered when designing a concept for large scale UAV operations [53].

The design of traffic management systems for UAVs takes inspiration from the years-long experience and knowledge in ATM systems, used for manned aviation. However, it is important to identify the different requirements and characteristics of manned and unmanned missions. UAV missions will be shorter and more numerous in comparison to manned flights. In addition, UAVs will have to navigate in more congested environments and integrate a higher level of autonomy. The co-existence of manned and unmanned flights must be taken into heavy consideration, as it is crucial to ensure that manned aviation will not be impacted by the introduction of a high number of UAVs in the airspace.

In 2013, NASA initiated the Unmanned Aerial System (UAS) Traffic Management research initiative to support safe and efficient low-altitude airspace operations for unmanned vehicles [54]. The FAA has published two Concepts of Operations (ConOps) for UTM, a first version in 2018 [55] and a second one in 2020 [56], based on which UTM should include a set of federated services to support UAS operations and ensure that are authorized, safe, secure, and equitable in terms of airspace access. Those ConOps focus on UTM operations below 400 feet above ground level.

The proposed services include flight planning, communications, separation, weather, registration, authorization, and mapping services. Performance and airspace authorizations shall be conducted to assess the operators and equipment's capabilities, and inform ATM stakeholders of UTM operations. UAVs and operators shall be identified. The safety of the operations is ensured through multiple layers of separation: strategic traffic management during pre-flight planning, separation provision using conflict alerts and deconfliction services in a tactical level, contingency management to respond to flight anomalies, real-time collision avoidance using ground-based or onboard equipment, and near real-time notifications and advisories based on airspace constraints.

In 2018, the EU's SESAR Joint Undertaking (SJU) published a blueprint [57], describing its vision for U-space. U-space encompasses a wide range of services to ensure the smooth operation of drones for all types of missions in all operating environments, focusing on very low level airspace. U-space services will be enhanced as the autonomy capabilities of UAVs evolve. Three foundation services are proposed for U-space: electronic registration (e-registration), electronic identification (e-identification), and geofencing (i.e. defined zones in which UAV operations are not allowed). ConOps for UAV operation in U-space have been developed from the CORUS project [58].

ConOps envisioned both in the USA and EU highlight the necessity for integrating unmanned air traffic into ATM. It is crucial that the developed concepts for UAV operations do not impact manned aviation operations. Furthermore, both concepts signify the safety aspects of the airspace, describing separation methods, like strategic and tactical deconfliction and collision avoidance [59]. **Figure 3** depicts the logic commonly followed to safely plan and conduct UAV flights in a UTM system. In the pre-flight stage the system receives the desired flight information and generates a flight plan. The flight is deconflicted with other known flights registered and generated in the system. If conflicts are detected during flight, they are resolved in a tactical manner. The imposed airspace structure and rules are consolidated through all stages.

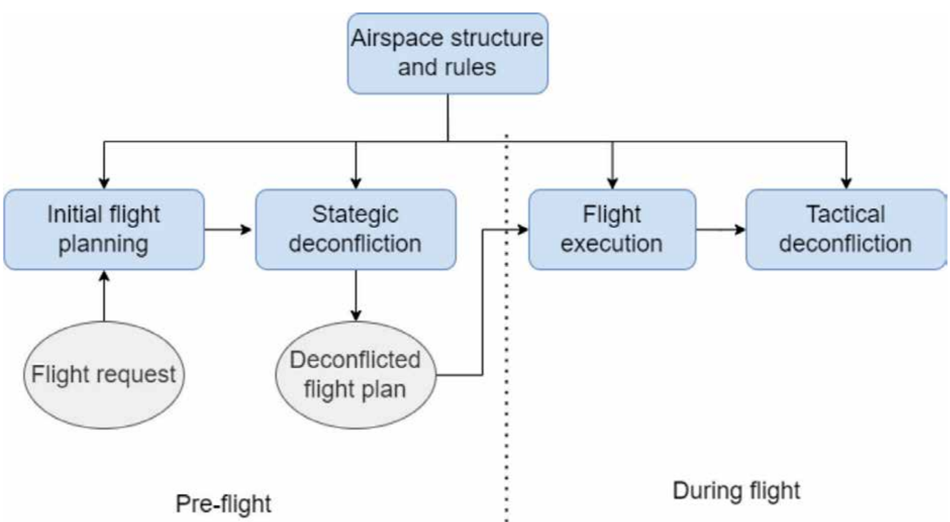

Figure 3.
Flight planning and deconfliction logic.

As the number of UAV operations will increase, so will the traffic density and complexity in the airspace. To safely support high numbers of flights, the airspace shall be structured including a set of local airspace rules. Urban topography, like buildings, shall be considered when designing a UTM network [60]. Layer concepts have been proposed to integrate different flight rules depending on the flight's altitude [61]. The layers, zones and tubes concepts were proposed in the Metropolis project to separate and organize UAV traffic [62]. The layers concept vertically separates traffic based on heading. In the zones concept, circular and radial zones are designed in the horizontal plane inspired by ring roads around cities. The tubes concept structures traffic in both the horizontal and vertical planes, generating a 3D directional graph.

Strategic conflict management is linked to flight planning, as it acts pre-flight to detect and resolve possible conflicts for the requested flights. Flight plans are usually described as 4D trajectories. Flight planning consists of two steps; a path planning phase designs the initial UAV's trajectory, and a strategic deconfliction phase modifies the trajectory in space and/or in time to ensure the safety of the flights. In [63], two flight type operations are considered; area operations are repetitive, while linear operations are point-to-point missions and are executed once. Flights are assumed to retain a static altitude. The airspace is discretized into a 3D grid. Routes for linear flights are generated using the A* algorithm and timestamps are added based on the UAV's velocity, while the area operations occupy regions. A First-Come, First-Served (FCFS) approach is used for flight deconfliction and for each added planned flight, cells of the grid appear occupied for specific timestamps to the ones planned after. The FCFS approach is augmented by an optimization model with mixed integer linear programming to minimize flight delays. Authors in [60] approach the strategic deconfliction problem differently. Flights are planned as no other traffic exists in the airspace and are deconflicted by adjusting their departure time or rejecting flights if an appropriate departure time cannot be found. A genetic evolutionary algorithm is used to compute the scheduling of the flights to minimize conflicts and their delay.

Tactical conflict management is responsible for detecting and resolving conflicts during the flight. Airspace services are used to communicate the positions and velocities of nearby UAVs, to act as input to the tactical conflict management system. An iterative geometric approach is used in [64] for tactical deconfliction by separating the multi-conflict problem into simpler sub-problems in a 4D grid. Potential conflicts are detected using the well-known velocity obstacle geometric method in [65] and conflicts are resolved by adjusting the heading of the UAVs. A MILP technique is proposed to compute the new headings for UAVs with the same speed, and a stochastic parallel gradient descent based method is used for UAVs with unequal speeds. Intent information, describing the designed trajectory of each UAV, can be incorporated into the velocity obstacle representation to make conflict detection in earlier time [66].

Not all missions in the airspace are expected to have the same priority. Some missions, like medical aid or security applications, might be defined as emergency and their arrival delay is more critical than others. Even for normal (i.e., not emergency) missions time constraints may vary. For example, the arrival delay of a food delivery mission is more impactful than the one of a generic package delivery. In addition to time constraints, some missions are coupled with area constraints. For example, a surveillance mission must not deviate from a specific path, or its scope will not be met. Priority should be taken into account when planning flights [67]. Priority information can be integrated in conflict resolution by forcing lower priority flights to resolve potential conflicts [68]. Allocating the responsibility of deconfliction to lower priority flights increases the efficiency of higher priority flights in comparison to the systems where the deconfliction responsibility is shared.

4. Conclusions

Six types of civilian application of UAVs are presented in this work. Proposed guidance and decision-making methods to enhance UAV autonomy in each of those applications are presented. While each application type does not globally correspond to one type of problem, operations in the same application area share restrictions and limitations imposed by the main objective of their application. The civilian applications are followed by an overview of unmanned traffic management systems, required to enable those operations.

Cinematography applications create specific restrictions on the UAV's trajectory planning, as the camera model inserts additional constraints to take into account the viewpoint and potential occlusions of the target. UAVs are equipped with high-end optical cameras and must generate smooth trajectories for visually appealing results. Payload delivery missions shall be cost efficient, be capable of carrying payloads of varying weights and be designed to heavily consider battery constraints. Shipping systems are designed to serve multiple orders and the multi-UAV system should have efficient coordination. UAV applications in agriculture require the full coverage of fields for a variety of tasks. For some specific tasks (e.g., spraying) the UAVs must carry heavy payloads, which add constraints to the planning. Surveillance missions are often applied in environments with dynamic targets, requiring repetitive area monitoring. The potential operational environment shows a wide range from urban congested environments to rural. Grid-based area partitioning is a common approach for surveillance applications, since it allows to easily monitor the age (i.e., time elapsed from last visit) of the grid's cells. Search and rescue operations are the most time-critical missions, so that the survivability of the victims is increased. Disaster and environmental mapping missions may have to cover quite large areas and the desired full coverage is not always possible. The UAVs must conduct feasible trajectories that maximize the amount of useful coverage data. Grid maps are often implemented in search and rescue and disaster and environmental monitoring missions to create belief maps and increase the probability of gathering profitable information.

The need for systems to monitor and manage UAV traffic has become clear and numerous programs have been initiated for that purpose. The US and EU have recognized the importance of creating a framework for the integration of UAVs in the airspace in a regulated manner. UTM services must be selected to ensure safe, secure, efficient, and equal access to the airspace. Structuring the airspace allows to manage the density and complexity of traffic. Safe flights are designed with multiple levels of deconfliction to minimize the risk of an intervehicle collision.

Conflict of interest

The authors declare no conflict of interest.

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Section 2

Autonomous Vehicles Enabling Technologies

Chapter 3

Communication and Network for Autonomous Vehicles

Dong Yin

Abstract

Communication and network are the critical issues for autonomous vehicles (AVs). Three main aspects will be illustrated in this chapter, including wireless communication, self-organizing network, and data transmission. As a typical representative of autonomous systems, unmanned aerial vehicles (UAVs) are the most widely used and numerous in military and civil fields, most of this chapter focuses on UAVs as technical research objects. Firstly, basic characteristics of wireless communication such as signal propagation and attenuation in different applications and other mobile communication issues for AVs, especially some new technologies, which are adaptable, will be presented. Secondly, the features of AVs network architecture and how to design it will be discussed, while the issues of self-organizing networks for AVs will be investigated. At last, typical data transmission methods such as DDS for AVs will be presented. Also, the critical factors that should be considered in designing the data transmission will be illustrated.

Keywords: autonomous vehicles, wireless communication, self-organizing network, DDS, message queue

1. Introduction

AVs are unmanned systems that have the ability to autonomously observe, object, decide, and act (OODA loop) in air, ground, sea surface, and underwater environments, including unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned surface vessels (USVs), and unmanned underwater vehicles (UUVs). In practical applications, communication and networks are particularly important for AVs, mainly in two aspects: first, to maintain communication between AVs and mission control stations to ensure that AVs complete various tasks under the supervision of operators; second, to build information transmission channels with other AVs and manned systems, and multi-system collaboration to do operations. In different application scenarios, different structures of networks built by various communication means are used to interact with single or multiple AVs during mission execution, such as fixed structured networks, 4G/5G with star network structure, WiFi, self-organizing network structures without fixed configuration, grid-like grid networks, and mesh networks with multi-layer grid network structure.

In this chapter, the communication network technologies of AVs are described in terms of wireless communication, network architecture, and data transmission.

During the introduction, the specific technology applications, challenges, and considerations will be explained with the examples of AVs such as UAVs, unmanned vehicles, and robots, which are widely used at present.

2. Wireless communication for autonomous vehicles

2.1 Various types of communication means and technologies can be used for AVs

A very large number of mobile communication technologies are currently applied to AVs, gradually realizing remote control of AVs, multi-system collaboration, and clustering of large-scale AVs. According to the basic way of communication networking, it can be divided into centralized communication mode and distributed communication mode. In centralized communication, 3G/4G-LTE/5G mobile network-based clustering communication technology and high-power WiFi networking technology for small-scale community-level applications have been gradually proposed [1, 2] and widely used with the benefit of high-bandwidth, low-latency, fast-access, and high-capacity communication capabilities. Unfortunately, this centralized architecture requires central access devices such as base stations and routers, and the communication range is limited by one central device.

Compared with centralized communication networking methods, distributed communication modes are more suitable for cluster systems, of which self-assembling networks as typically distributed networks have become a hot research topic today. For example, UAV cluster self-assembling network [3], that is, the communication between multiple UAVs does not completely rely on basic communication facilities such as ground control stations or satellites, but uses UAVs as network nodes, and each node is able to forward control commands to each other, exchange data such as situational awareness and intelligence collection, and automatically establish a network. Dynamic networking, wireless relay, and other technologies are used to achieve interconnection and interoperability between autonomous systems, with the advantages of self-organization, self-healing capability, and efficient and fast networking to ensure that the UAV group forms a whole to perform combat missions. Gupta et al. [4] pointed out that wireless self-assembling network is the most suitable communication network architecture for UAVs, however, more factors such as dynamic topology, direction of routing, heterogeneous network switching, energy of each UAV, and so on, should be considered for applications. Liang Yi Xin et al. [5] from Southeast University reviewed the airborne network architecture and network protocol stack, compared for planar and hierarchical network structures, and pointed out that research is needed in network architecture design, mobility model, routing mechanism, and transmission control mechanism. Chen Si et al. [6] proposed a highly dynamic mobile self-assembling network architecture scheme with switchable modes. However, only a few researchers can build a more practical network. Chen Wu et al. [7] implemented a small UAV self-assembling network demonstration and validation system based on 802.11 b/g, optimized routing and transmission protocols, implemented an H.264-based video transmission system, and a secure communication protocol based on offline digital certificates, and the system consisted of only one command terminal and three mobile terminals. The system includes only one command terminal and three mobile terminals and has been verified by real flight. The various network communication technologies applicable to UAV clusters are summarized in **Table 1**.

Networking method	Transmission rate (1Mbps)	Transmission distance (> 1 km)	Communication cost
Satellite	Yes	Yes	High
WiFi	Yes	No	Low
WiMAX	Yes	Yes	Middle
LTE(4G)	Yes	Yes	Middle
Zigbee	No	No	Low
Bluetooth	No	No	Low
UWB	Yes	No	Low
Self-organizing network	Yes	Yes	Middle

Table 1.
Comparison of transmission performance of common communication technologies.

2.2 Key technologies for wireless communication in AVs

AVs usually used in 4D (dangerous, doll, dirty, deep) working environments, geographical environments, weather conditions, and human activities have a greater impact on the wireless communication, therefore, the AVs communication technology of anti-jamming and security is the most important.

2.2.1 Communication anti-jamming

Anti-jamming communication is the general term for various technical and tactical measures to ensure the normal conduct of communications in various interference conditions or complex electromagnetic environments. There are two major types of anti-jamming communication technologies in common use, one is based on the extended-spectrum anti-jamming communication technology, and the other is based on the nonextended spectrum anti-jamming communication technology.

Spread spectrum (SS) is a means of anti-jamming communication that extends the information bandwidth for transmission. Frequency-hopping spread spectrum (FHSS), time hopping spread spectrum (THSS), frequency modulation spread spectrum (Chirp SS), and hybrid spread spectrum. With the development of artificial intelligence technology, anti-interference communication technology based on spectrum awareness, cognitive radio, and other technologies is developing rapidly.

Nonextended spectrum-based anti-jamming communication system is mainly a general term for the technical methods to achieve anti-jamming without extending the spectrum of the signal. At present, the commonly used methods mainly include adaptive filtering, interference cancelation, adaptive frequency selection, automatic power adjustment, adaptive antenna zeroing, smart antenna, signal redundancy, diversity reception, signal interleaving, and signal bursting. Compared with the extended spectrum-based anti-interference communication system, the nonextended spectrum-based anti-interference methods cover a wider range and involve more knowledge. The extended spectrum-based anti-interference communication mainly considers the interference problem in the frequency domain, time domain, and speed domain, while the nonextended spectrum-based anti-interference will focus on the power domain, spatial domain, transform domain, and network domain, in addition to designing the above three areas.

There are more and more anti-interference communication methods when in essence, the goal of all technical methods is to improve the effective signal to noise and interference ratio (SNIR) at the receiver end of the communication system, so as to ensure that the receiver can properly achieve the correct reception of the useful signal.

2.2.2 Communication security

2.2.2.1 Information encryption technology

The data chain uses a uniform bit-oriented defined information standard with a uniform type format, so data encryption is generally used to ensure data security. According to the different ways of plaintext encryption, secret key generation, and management, encryption systems can be divided into three categories: one is group cipher (also known as symmetric encryption), in which the plaintext is first grouped (each group contains multiple characters) and then encrypted group by group; another is public key encryption (also known as asymmetric encryption); and another is single encryption.

A symmetric encryption algorithm is one that uses the same key for encryption and decryption and is reversible (decryptable). The AES encryption algorithm is an advanced encryption standard in cryptography that uses a symmetric packet cipher system with a minimum supported key length of 128. It has been widely analyzed and used worldwide. The advantage of AES is that it is fast, but the disadvantage is that the transfer and storage of the key is a problem, and the key used by both parties involved in encryption and decryption is the same, so the key can be easily leaked.

Asymmetric encryption algorithm means that different keys (public and private) are used for encryption and decryption, so asymmetric encryption, also called public key encryption, is reversible (decryptable). The RSA encryption algorithm is based on a very simple number-theoretic fact: it is easy to multiply two large prime numbers, but extremely difficult to factorize their product, so the product can be made public as the encryption key. Although the security of RSA has never been theoretically proven, it has survived various attacks and has not been completely broken. The advantage of RSA is that the encryption and decryption keys are not the same, and the public key can be made public, so it is only necessary to ensure that the private key is not leaked, which makes the transmission of the key much simpler and reduces the chance of being cracked; the disadvantage is that the encryption speed is slow.

Typical one-way encryption algorithm MD5 full name is message-digest algorithm 5, a one-way algorithm is irreversible (the data encrypted by MD5 cannot be decrypted). The length of the data after MD5 encryption is much smaller than the encrypted data, the length is fixed, and the encrypted string is unique. The algorithm is applicable to scenarios: commonly used in irreversible password storage, information integrity checking, etc. In information integrity checking, a typical application is to generate a message digest for a piece of information to prevent tampering. If there is a third-party certification authority, MD5 can also be used to prevent "repudiation" by the author of the document, which is called a digital signature application.

2.2.2.2 Information authentication technology

Authentication of a message is another important aspect of message security. The purpose of authentication is twofold: first, to verify that the sender of the message is genuine and not an impostor; second, to verify the integrity of the message. That is, to verify that the information has not been tampered with, replayed, or delayed during transmission or storage.

2.2.2.2.1 Digital signature technology

A digital signature algorithm consists of two main algorithms, namely a signature algorithm and a verification algorithm. A signer can sign a message using a (secret) signature algorithm, and the resulting signature can be verified by a public verification algorithm. Given a signature, the verification algorithm makes a "true" or "false" question and answer depending on whether the signature is true or not. There are a large number of digital signature algorithms, such as RSA digital signature algorithm, finite automaton digital signature algorithm, etc.

2.2.2.2.2 Identification technology

The security of communication and data systems often depends on the ability to correctly identify the individual communication user or terminal. There are two main common ways of identification, one is the way of using passwords; the other is the way of using badges. Passwords are the most widely used form of identification. Passwords are generally strings of 5–8 long consisting of numbers, letters, special characters, control characters, etc.

2.3 Relay communications

In the field of autonomous system communication, relay communication is widely used as an effective means to extend the communication range. In this section, we take the most widely used UAV relay communication as an example to explain the relay communication technology.

For UAVs applications in various environments, such as reconnaissance and surveillance [8], assist communication [9, 10], emergency communication [11, 12], search and rescue [13], and so on [14], wireless communication for data transmission between UAVs and GCS often suffers from the undulating terrain, high buildings, and other factors, which block the direct link. In this case, according to the advantages of rapid deployment, mobility, and wide communication range [15], relay UAV is adopted to build up indirect connections by multiple hops, as shown in **Figure 1**.

First of all, the throughput and communication range are the two main issues of relay UAV serving for data transmission. Some researchers propose the optimization for the relay UAV position to maximize the end-to-end throughput [16]. Meanwhile, the communication range for more users, including spectrum resources, energy-efficient and quality-of-service (QoS) are considered in relay applications [17, 18]. Moreover, an iterative and suboptimal algorithm is presented to optimize robust transmit power along with relay UAV speed and acceleration for EE mobile relaying

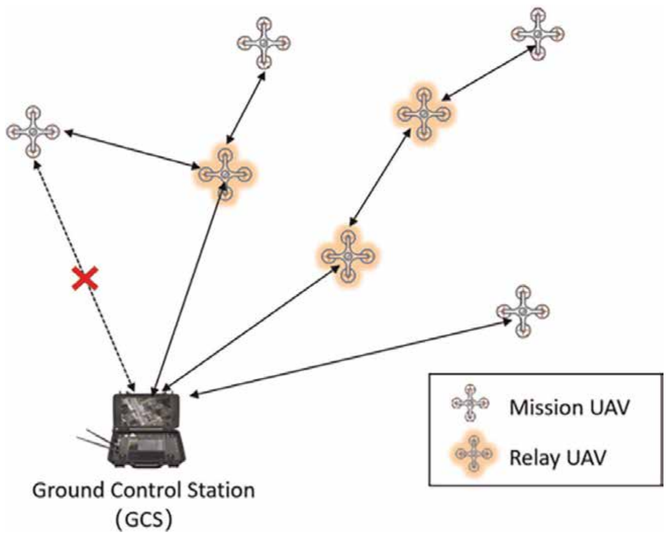

Figure 1.
Relay UAV implementation in UAVs swarm.

networks [19], and a mood-driven online learning approach is illustrated for relay UAVs assignment and channel allocation to maximize total transmission rate of the networks [20]. Multi-rotor UAVs are usually used as relays with limits of endurance, energy, and mobility, and the collaboration scheme with multiple UAVs substitution to maintain a long time relaying is necessary [21].

Except for the multi-rotor UAVs, fixed-wing relay UAVs with the advantages of high mobility is able to provide better service in a wide range. In this case, the trajectory of the relay is more important. Some methods for trajectory planning are studied [22, 23]. A genetic algorithm is proposed for optimizing the amount of data transmitted to users, as well as the access order and motion trajectory of user groups [24]. A path optimization algorithm is described for fixed-wing UAVs' relay assistant communication system based on maximizing the weighted sum of ergodic capacity of each state [25].

In addition, the relay task allocation is a typical optimization problem, which is above trajectory planning, QoS, and other aspects [4]. A heterogeneous UAV task assignment model with distributed online task allocation based on the extended CBBA algorithm is investigated [26], while the deployment strategies with a distributed game-theory-based scheduling method are discussed to maximize the stationary coverage to guarantee the continuity of the service [27]. Also, some advanced optimal solutions are studied such as automatic generation control strategy in Ref. [28, 29], a modular relay positioning and trajectory planning algorithm in Ref. [30], and so on.

With the growing applications of UAV swarms in civil and military currently, swarm network and relay cooperative communication became the popular topic. Trajectory planning for dynamically deploying relay UAVs one by one for continuous communication is the main issue. A joint optimization on multi-hop UAVs trajectories and transmitting power to maximize the end-to-end throughput is proposed with the capability of obstacle avoidance [31]. Meanwhile, energy efficiency is another critical issue. An aerial backbone network scheme with the assistance of relay connecting GCS and core networks is presented [32]. Moreover, multiple relay UAVs cooperate to assist in swarm network. The method for UAV cooperative relay is investigated to improve the capability of communication network [33], and also, a UAV relay selection joint game model and a distributed fast UAV relay cooperative formation algorithm are shown to optimize the EE of UAV swarms [34].

How to design the relay planning framework for AVs' application is a hot topic today [35]. According to UAVs' tasks schedules and task regions in the swarm, we propose a framework for relay UAVs task planning as shown in **Figure 2**. In this framework, two main processes are designed, including initial deployment and optimization of task planning of relay UAVs. It is assumed that both relay UAVs (RUs) and mission UAVs (MUs) in the swarm are the same type of fixed-wing UAV.

Based on the mission planning of swarm, the first process is to analyze the distribution of task points or regions of each MU and determine when and where the relay is required for assisting the data link between mission UAVs and GCS. In this step, MINLP method is adopted for global deployment for relay UAVs, in which the rough number for deployment and approximate accessing locations for service could be solved. In the next process, the CBBA method is applied to optimize the relaying resource allocation [26] for arranging the RUs as few as possible. In the worst cases, all RUs demand relays to connect GCS at the same time.

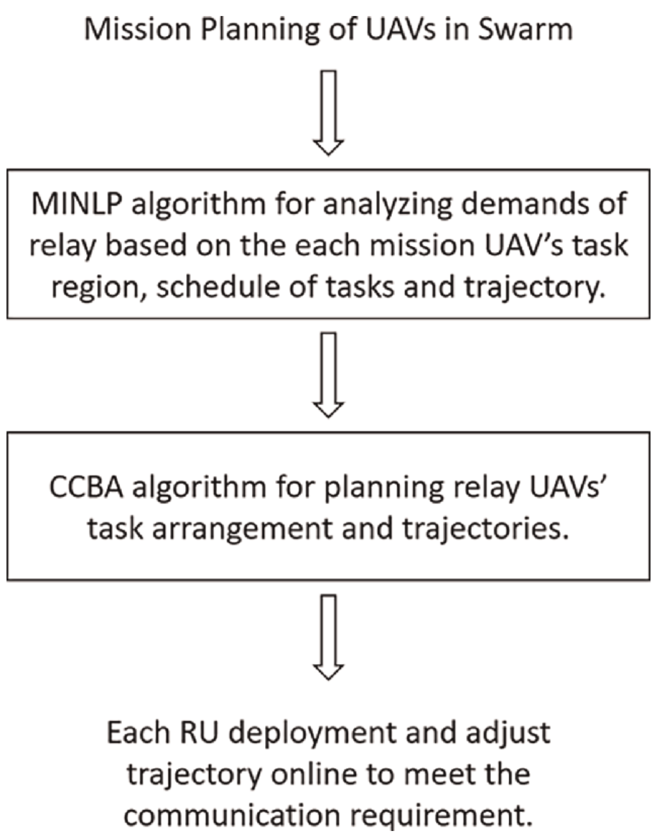

Figure 2.
Relay planning framework for AVs' application.

3. Network architecture for autonomous vehicles

Network communication is an important guarantee for information interaction in the process of AVs cooperating to accomplish their tasks. In this section, we will start with a typical network structure, analyze the characteristics of AVs networking requirements, and put forward some suggestions for designing AVs network architecture design.

3.1 Typical wireless network structure

3.1.1 Star network topology

A star topology, also known as a central radiating topology, uses a central node to connect other nodes in a "one-to-many" fashion, as shown in **Figure 3** below. Unlike bus topologies that simply broadcast transmitted frames to all connected endpoints, star topologies use components with additional built-in levels of intelligence. The central node maintains dynamic media access control and data traffic forwarding for each node in a star topology deployment.

The structural characteristics of the star topology are as follows:

- Simple control: Any one site is only connected to the central node, so the media access control method is simple, resulting in a very simple access protocol. Easy network monitoring and management.

- Easy fault diagnosis and isolation: The central node can isolate the connected lines one by one for fault detection and location, and the fault of a single connection point affects only one device and does not affect the whole network.

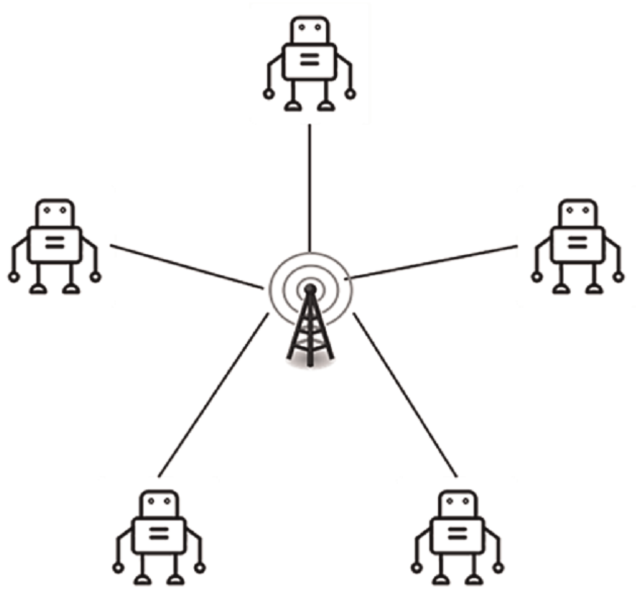

Figure 3.
Star network structure.

- Convenient services: The central node can easily provide services and network reconfiguration to individual sites.

Take the example of a UAV forming a star network. In the star network, each UAV establishes a connection with the central node. There is no direct communication between UAV nodes but rely on the central node for relay and forwarding services. As shown in **Figure 4**, a multi-star network consists of multiple-star networks. One node in each group is connected to a ground station.

3.1.2 Ring network topology

The data in the ring can only be transmitted in one direction, and the delay time of the information on each device is fixed, which is especially suitable for real-time

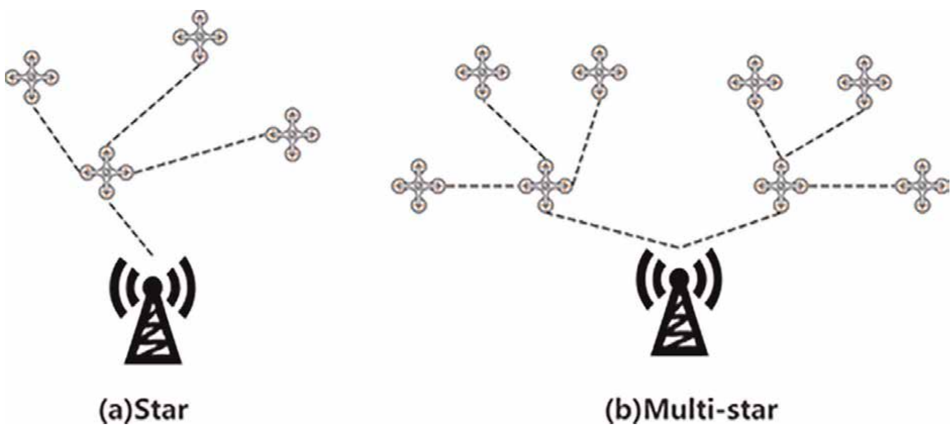

Figure 4.
Multi-star network structure.

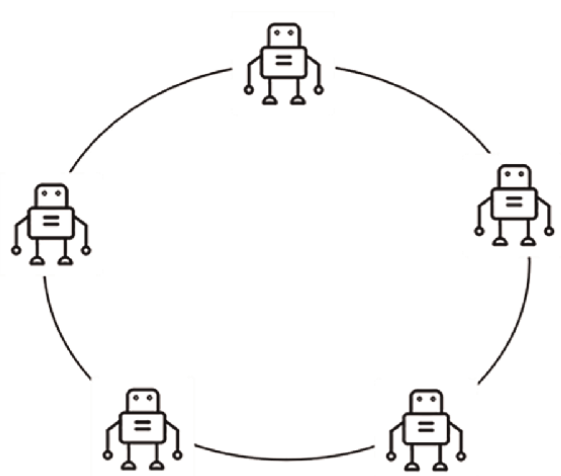

Figure 5.
Ring network structure.

control LAN system. As shown in **Figure 5**, the ring structure is like a string of pearls, and each computer on the ring structure is one of the beads on the necklace.

The network characteristics of the ring topology are as follows:

- This network structure is generally only applicable to the IEEE 802.5 token network (token ring network), and "tokens" are passed sequentially along a fixed direction in a ring-type connection. There is only one path between every two nodes, and path selection is simplified.

- Each node on the loop is bootstrap control.

- Since the information source is serially passed through each node in the loop, it will task a long time for transmission when the number of nodes are large in the loop.

- Loops are closed and not easily expandable.

- When a node failure will cause the whole network to go down.

- It is difficult to locate branch node faults.

3.1.3 Tree network topology

A tree topology is a hierarchical structure where nodes are linked and arranged like a tree, as shown in **Figure 6**. Usually, property topology can be generally divided into three layers: core layer, distribution layer, and access layer. At the top of the tree is core layer, which is the "root" of the tree and also high-speed transmission from current network to another. In the middle of the network is distribution layer, serving transmission for the core, which is also operating the access control and QoS policies. Access layer is at the bottom, where endpoint devices or users connect.

The network characteristics of the tree topology are as follows:

- Simple network structure, easy to manage

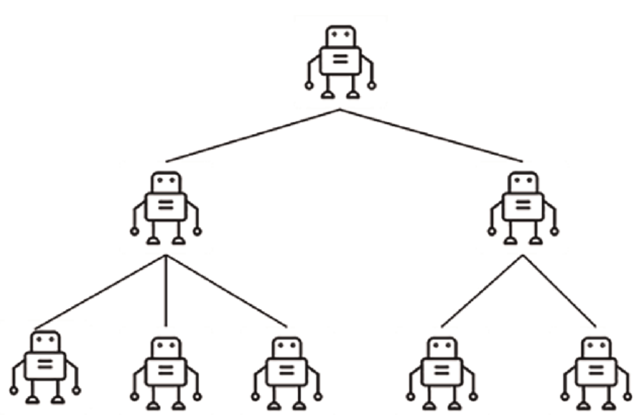

Figure 6.
Tree structure for network.

- Simple control, easy network building, and easy expansion. The tree structure can be extended with many branches and subbranches, and these new nodes and new branches can be easily added to the network.

- Short network latency and low bit error rate

- Fault isolation is easier. If a node or line in a branch fails, it is easy to isolate the failed branch from the entire system.

- Poor network sharing capability

- Underutilization of communication lines

- The root node is too heavily loaded and the individual nodes are too dependent on the root node. If the root fails, the whole network does not work properly.

3.1.4 Mesh network topology

A mesh topology is another nonhierarchical structure in which each network node is directly connected to all other nodes, as shown in **Figure 7** below. A mesh topology ensures great network resilience because if a connection is disconnected, neither disruption nor connection loss occurs. Instead, traffic is simply rerouted along a different path.

The structural characteristics of the mesh network topology are as follows:

- The network is highly reliable, and generally, there are two or more communication paths between any two node switches in the communication subnet, so that when one path fails, information can still be sent to the node switch through the other path.

- Networks can be formed in a variety of shapes, using a variety of communication channels and a variety of transmission rates

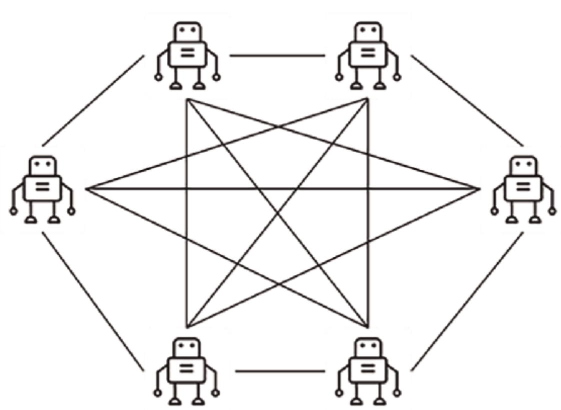

Figure 7.
Mesh network structure.

- Easy to share resources among nodes in the network
- Improved information traffic distribution on the line
- Optimal path selection and low transmission latency

A hierarchical grid network removes the central node and enables all nodes to connect, as shown in **Figure 8**. A hierarchical mesh network has multiple grids, and one node in each group is able to reach other groups. All nodes in the hierarchical grid network are able to self-organize. While one node fails, the remaining nodes are triggered to rebuild the network. For some practical applications, the hierarchical grid network is more suitable for the multi-AVs system.

3.2 Analysis of the demand characteristics of AVs' networking

Large-scale AVs applications are characterized by large numbers, wide range, fast speed, flexible mobility, frequent changes in space-temporal relationships, changeable tasks, and cross-regional scheduling, which pose greater challenges in terms of clarifying the information transfer between systems, network structure, and dynamic optimization. Through the authors' previous studies [1, 2, 35], we analyze and summarize the main challenges and challenges in the current research of AVs' networking, as follows.

3.2.1 Insufficient correlation between network architecture design and AVs cluster tasks

The current network planning and communication studies of large-scale AVs are disconnected from the cluster task requirements and lack the understanding of the intrinsic connection between task behavior and information transfer in the network layer. The cluster network of large-scale AVs is a typical complex network, which

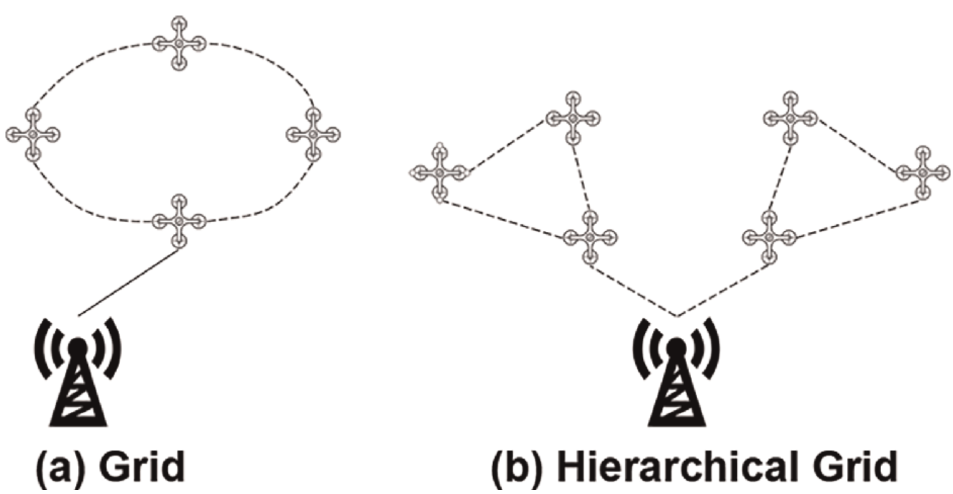

Figure 8.
Hierarchical network structure.

should start from the typical task characteristics of the cluster, establish a model of individual behavior and information transfer between individuals, and thus design the network generation method. Most of the current research abstracts the AVs task process as a model of prime behavior with certain probability distribution characteristics and unifies the various types of information of concurrent interaction between nodes as the value of transmission capacity between nodes, which makes the network architecture theory research detached from the cognition of the cluster task. In the link communication layer, a large amount of research work focuses on communication waveform design, channel design, and access technology, while the type of information service and transmission characteristics in the cluster task process is not considered for problem formulation, difficulty attack to testing process. Therefore, there is an urgent need to explore the associated transfer mapping and characterization methods from the cluster task domain to the information domain and to guide the design and construction of the cluster network architecture from the task process to the information requirements.

3.2.2 The contradiction between loose organizational structure and close communication relationship

The contradiction between the loose cluster organization in the AVs network and the close communication of multiple nodes involved in collaborative tasks within the cluster poses a big challenge to the construction of the cluster network structure. On the one hand, the cluster of autonomous vehicles is "task/sub-task-centric," and each AV can be scheduled and assigned online, resulting in flexible entry and exit of nodes and rapid integration and separation of subnetworks, which make the nodes loosely coupled in terms of organizational structure. On the other hand, in the task process, the information interaction between nodes around the same subtask is frequent, the information transfer between subnets in the collaborative task is close, and each link of the task is closely coupled with the information quality, meanwhile, the movement and state of each node participating in the task will affect the data link stability and transmission quality, thus making the task participants and information transfer tightly coupled together. The loose task organization and behavior of the cluster bring a great challenge to the close information interaction between nodes in task execution. In this regard, it is necessary to deeply analyze the characteristics of AVs' group behavior, explore the coupling mechanism between task behavior and information service, and propose a network generation method with mutual coupling of link layer, network layer, transmission layer, and application layer.

3.2.3 Conflict between task-oriented planning and communication network optimization

In the main system network architecture, each AV node balances mission and communication, and there is a contradiction between mission replanning and network optimization in complex dynamic scenarios, and the network robustness and transmission stability face challenges. In complex mission scenarios, such as low-altitude close-range reconnaissance surveillance, earthquake relief emergency communication, etc., the mission may be replanned with the development of the situation (mission reassignment, route replanning, etc.), and the organizational relationship of the cluster changes accordingly; at the same time, the mission may encounter the loss of a few AVs due to loss of control or destruction, resulting in network topology changes, requiring reconfiguration of links, adjustment of network topology, and optimization of routing, and how to ensure continuous and stable network information delivery during dynamic changes is an optimization problem. However, each AV in the cluster is both a task performer and a network participant, and planning and constraining the behavior of AVs from two different dimensions of network optimization and task execution at the same time is an optimization challenge that cannot be solved. In this regard, the dynamic evolution process of the network needs to be studied in terms of the role assignment and role change of each node in the cluster in the task as well as the time-varying task correlation among the nodes.

3.3 Design thinking of AVs networking for task-oriented process

Based on a comprehensive analysis of the main problems and challenges, this paper proposes a valve idea of small-world network generation for AVs clusters based on task cognition, which mainly solves two problems: firstly, it starts by analyzing the task flow and recognizing the information and communication requirements, and constructs a dynamic diagram of the internal topological association of the group with the development of the task chronology; secondly, it constructs a multi-layer network structure combining "self-organized multi-hop transmission and cooperative relay communication" for the data transfer characteristics of the group subtasks, and establishes a network organization method and mechanism that adapts to the changes of subtask increase/decrease and node loss, so as to achieve better support for the cooperative tasks of AVs clusters.

The main idea of the task-oriented AVs network planning and generation system design is that the AVs have the characteristics of local convergence and global

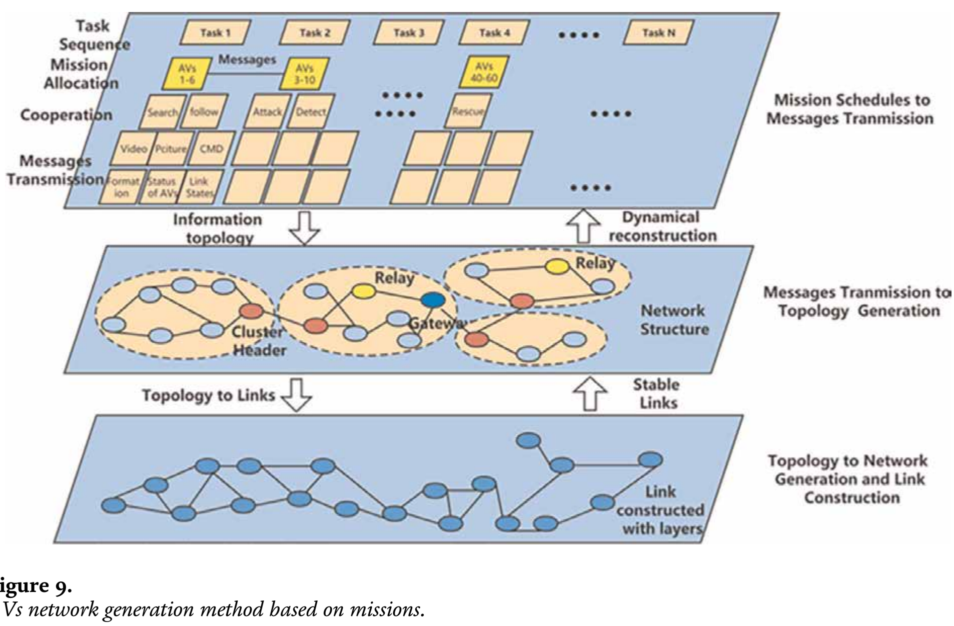

Figure 9.
AVs network generation method based on missions.

dispersion, or global convergence as a whole, with the target or specific task as the center in the actual application process, and the information transfer interaction between individuals within the cluster must meet the timeliness requirements of the task.

As shown in **Figure 9**, the first layer is the application layer, which mainly solves the problem of cognition from cluster task domain to information domain. It can adopt the description method of information flow, establish the characterization method and model from cluster task domain to network information domain, and get the information cross-linking relationship within the cluster, whose difficulties are: there are many types of cluster tasks, single-computer independent tasks and multi-computer collaborative tasks are intertwined and can be executed in parallel, and the information business requirements change with the advancement of task time, yes, the granularity of task decomposition is closely coupled with information flow description, and it is difficult to accurately decompose cluster tasks and establish dynamic information flow model between nodes.

The second layer is the network layer, which mainly solves the problem of network generation and evolution adapted to the cluster task characteristics. Based on the information association relationship of each node in the cluster established in the first layer, the logical topology relationship of the network is constructed and the initial topology diagram of the network is formed.

The third layer is the link layer, considering the physical characteristics of the link, and combining the idea of "multi-hop and relay," proposing a network-structured design and generation method to guide the construction of network links, and establishing a dynamic network link reconfiguration method to cope with sudden changes in network topology in complex environments.

4. Data transmission for autonomous vehicles

Data transmission between multiple autonomous vehicles is a typically distributed information transmission mode. There are two kinds of information transmission in the current distributed system: one is to establish point-to-point direct communication mode; the other is the indirect communication mode in which the information producer and consumer are decoupled.

4.1 Direct communication mode

4.1.1 Inter-process communication

Inter-process communication refers to the relatively low-level communication methods used between processes in distributed systems, including message-passing meta-language, direct access to API provided by network protocols (socket programming), and support for multicast communication.

4.1.2 Remote procedure call, RPC

RPC is the most common communication paradigm in distributed systems and consists of a set of techniques based on bi-directional exchange between communicating entities in a distributed system, including remote operations, procedures, or methods. The most common ways of RPC are request-response mode, remote procedure invocation, and remote method invocation.

4.1.3 Remote method invocation, RMI

RMI is very similar to RPC, but it is applied to the environment of distributed objects. In this method, an object that initiates a call is able to call a method in a remote object. As with RPC, the underlying details are hidden from users. For example, in Java, just a class extends the java.rmi. Remote interface can become a remote object that exists on the server side for the client to access and provide certain services.

4.2 Indirect communication

A characteristic of indirect communication is that these technologies will support the adoption of a third entity, allowing deep decoupling between the sender and the recipient. Kafka, for example, is a typical technique for indirect communication, which is considered a message queue implementation and can also be used as a publish-subscribe system.

Indirect communication will come to be considered to handle two main scenarios:

- Spatial decoupling: senders do not need to know who they are sending to

- Time decoupling: sender and receiver do not need to exist at the same time

The key technologies of indirect communication mainly include: publish-subscribe system, message queue, distributed shared memory (DSM) and tuple space, and group communication, among which publish-subscribe system and message queue are the most widely used indirect communication technologies in ROS and other applications.

4.2.1 DDS (distributed data system, distribution-subscription system)

Data Distribution Service (DDS) is a standard data-centric distributed system publishing and subscription programming model and specification that is compatible with the performance requirements and hard real-time requirements of data-centric distributed applications. DDS can control service behavior through quality of service (QoS) and effectively support complex data communication models [36].

4.2.1.1 DDS specifications

The DDS standard consists of two separate parts: the first part is data-centric publish-subscribe (DCPS), which deals with data-centric publish/subscribe, and applications can use this layer to communicate with each other; the second part is the Data Local Reconstruction Layer (DL-RL), which is located on top of the DCPS layer and can abstract the lower services and establish mapping relationships. It is an optional object-oriented layer.

DDS uses standard software application programming interfaces (APIs) to provide an infrastructure for communication between various applications and can be quickly added to any software application.

4.2.1.2 DCPS communication mechanism

Data is transferred across domains, and there can be publishers, subscribers, or both on a node. The publisher owns and manages the data writers and the subscriber owns and manages the data readers. A data reader and a data writer must be associated through the same subject and compatible QoS policies so that data published by the data writer can be received by the subscribed data reader, as shown in **Figure 10**.

Domain: A domain represents a logically isolated communication network. Applications that use DCPS to exchange data must belong to the same domain, and entities belonging to different domains will never exchange data; Domain Participant: A domain actor is an entry point for an application to interact in a particular domain and a factory for multiple objects to write or read data.

Topic: A topic is a method of publish/subscribe interaction and consists of a topic name and topic type. The topic name is a string that uniquely identifies the topic within the domain. A topic type is a definition of the data that a topic contains. Each topic data type can specify its key to distinguish different instances of the same topic. In the DCPS communication model, a connection can be established only when the topics of the data writer and the data reader match each other.

Data writer: The application passes the value to the DDS by using the data writer. Each data writer must be a specific topic, and the application publishes examples on that topic using an interface of the type specified by the data writer. The data writer is responsible for encoding the data and passing it to the publisher for transmission.

Publisher: The exact mechanism used to capture published data and send it to the relevant subscribers in the domain is determined by the implementation of the service.

Subscriber: Receives a message from the publisher and delivers it to any associated data reader connected to it.

Data reader: Gets the data from the subscriber, decode the topic into the appropriate type, and delivers the sample to the application. Each data reader must be a specific topic. The application uses a specific type of interface to the data reader in order to receive samples easily.

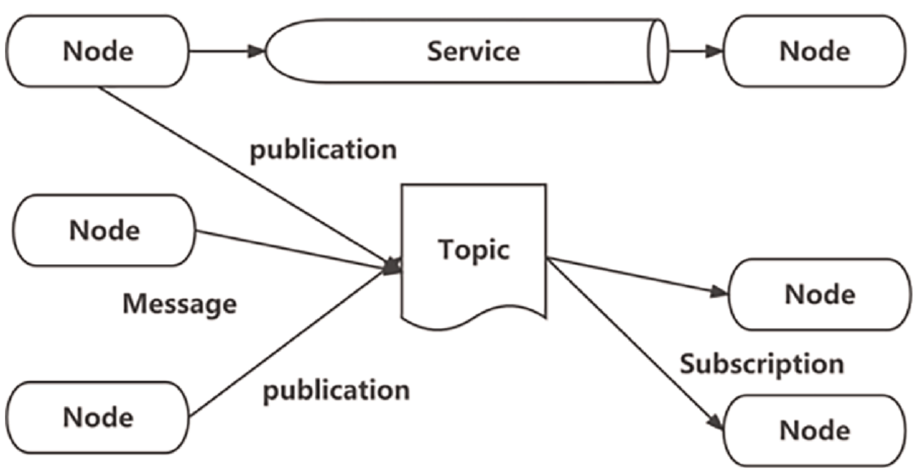

Figure 10.
Publishing and subscription programming model.

4.2.1.3 QoS policy

The fine control of real-time QoS is one of the most important features of DDS. DDS defines multiple QoS policies, including reliability, bandwidth control, send cycle, and resource restriction. Each publisher/subscriber can establish an independent QoS protocol, so DDS designs can support extremely complex and flexible data flow requirements. It should be noted that these policies can be applied to all entities in DCPS, but not all policies will work for every entity type. The match between publisher and subscriber is done using the request-offered (RxO) mode. In this pattern, the publisher "provides" a set of QoS policies, the subscriber "requests" a set of required QoS policies, and the middleware is responsible for determining whether the provided policies match the requested policies, thereby establishing communication or indicating incompatibility errors.

4.2.1.4 Discovery process

In DDS, publishers and subscribers do not need to specify the number and location of each other; the application sends samples of a topic one at a time, and the middleware distributes samples to all applications that want that topic. In addition, new publications and subscriptions for topics may appear at any time, and middleware will automatically interconnect with each other. The mechanism of DDS is realized through list information. The dissemination of list information between applications by DDS is called "discovery" process [40].

4.2.1.5 Features of DDS

The advantages of the system structure of DDS are summarized as follows:

- The concept of global data space is introduced to improve the communication efficiency.
- Take data as the center to reduce network delay.
- QoS is used to control the service behavior, which increases the communication flexibility.
- UDP/IP protocol is adopted to increase the network throughput.
- Dynamic configuration to improve data transmission capability.

4.3 Message queues

Message middleware pass, also known as a message queue server, is a technology often used in today's distributed application architectures as a way to communicate asynchronously from program to program, where the sender of a message does not have to wait all the time for the message to finish processing, but instead sends the message to the message middleware and returns. The designated consumers of the messages subscribe to the messages and process them. The message queue model means that the message producer puts messages into a queue and the message

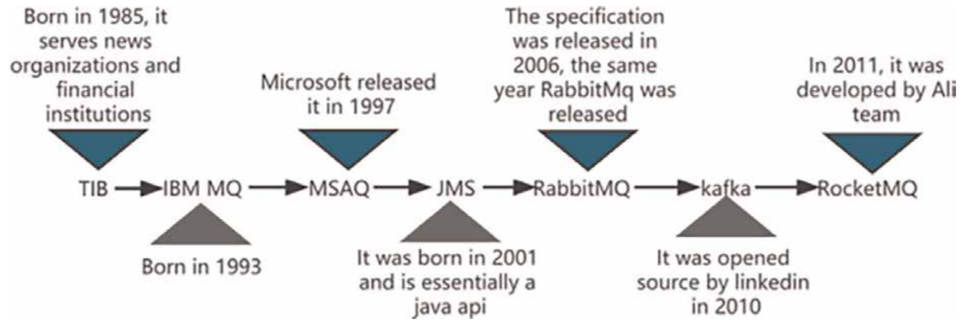

Figure 11.
Development of message queues.

consumer messages from the queue. The publish-subscribe system means that the message producer publishes messages to the queue of a specified topic and the message consumer subscribes to the queue messages of the specified topic. When there is a new message in the subscribed topic, the message consumer can consume the message by pull or the message middleware by push.

As shown in **Figure 11**, the first modern message queue software The Information Bus (TIB) was developed in 1982, and three years later IBM's message queue IBM MQ product family was released, followed by a period of evolution of the MQ family into WebSphere MQ to rule the commercial message queue platform market. The year 2001 saw the birth of Java Message Service (JMS), JMS by providing a public Java API way to hide the implementation interface of separate MQ product vendors, thus spanning different MQ consumption and solving interoperability problems. Later, AMQP (Advanced Message Queuing Protocol) advanced message queuing protocol was created, which uses a standard set of underlying protocols, adding many other features to support interoperability. Currently, there is a proliferation of open-source message queuing middleware, with the more popular ones being ActiveMQ, RabbitMQ, Kafka, and Ali's RocketMQ.

4.3.1 ActiveMQ

ActiveMQ is produced by Apache, the most popular, powerful open-source messaging bus, which is a fully supported JMS1.1 and J2EE 1.4 specification of the JMS provider implementation, designed to provide efficient, scalable, stable, and secure enterprise-class messaging for applications, as shown in **Figure 12**.

The ActiveMQ client uses the ConnectionFactory object to create a connection through which messages are sent to and received from the messaging service. Connection is the active connection between the client and the messaging service. When the connection is created, communication resources are allocated and the client is authenticated. This is a fairly important object, and most clients use a connection for all messaging. A connection is used to create a session, which is a single-threaded context for generating and using messages. It is used to create producers who send and consumers who receive messages and to define the delivery order for the messages sent. Sessions support reliable delivery through a large number of acknowledgment options or through transactions.

The client sends messages to a specified physical target by the MessageProducer, which can specify a default delivery mode, priority, validity value, and other factors

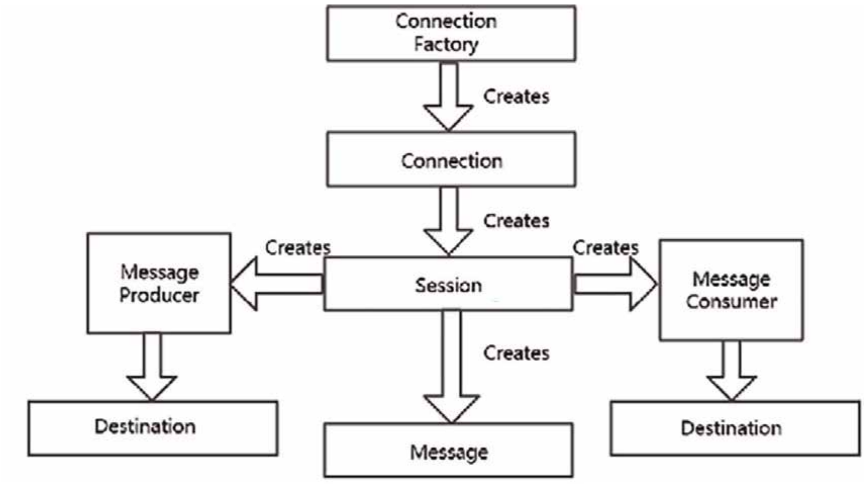

Figure 12.
The process of active message queues.

to control all messages. Meanwhile, the client receives messages from the specified physical target by the MessageConsumer. The consumer can use a message selector designed for consumer, which operates the messaging services and matches the selection criteria. Also, consumer is able to synchronously or asynchronously receipt messages.

4.3.2 RabbitMQ

RabbitMQ is an AMQP (Advanced Message Queued Protocol) messaging middleware implemented in Erlang language, originally originated in financial systems and used in distributed systems for storing and forwarding messages. This is due to its outstanding performance in terms of ease of use, scalability, reliability, and high availability.

The basic components of RabbitMQ and its workflow are shown in **Figure 13**:

Broker: The entity server of RabbitMQ. It provides a transport service that maintains a transport line from the producer to the consumer, ensuring that message data is transmitted in the specified manner.

Exchange: The message switch. Specifies to which queue messages are routed according to what rules.

Queue: Message queue. The carrier of messages, each message is cast to one or more queues.

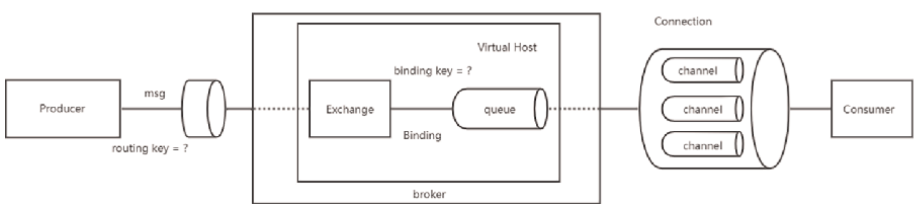

Figure 13.
The process of RabbitMQ.

Binding: The effect is to bind exchange and queue according to some routing rules.

Routing Key: A routing key by which the exchange delivers messages. The key specified when defining the binding is called the binding key.

Vhost: Virtual host. A broker can have multiple virtual hosts, which are used as a separation of privileges for different users. A virtual host holds a set of exchange, queue, and binding.

Producer: Message producer. Mainly delivers messages to the corresponding exchange. It is usually a standalone program.

Consumer: Message consumer. Receiver of messages, usually a stand-alone program.

Connection: TCP long connection between producer, consumer, and broker.

Channel: Message channel, also known as a channel. Multiple channels can be created in each connection of the client, each channel represents a session task. In the RabbitMQ Java Client API, there are a large number of programming interfaces defined on the channel.

4.3.3 RocketMQ

RocketMQ is a distributed messaging middleware open-sourced by Alibaba in 2012, which was donated to Apache Software Foundation and became an Apache top-level project on September 25, 2017. As a homegrown middleware that has experienced the baptism of Alibaba's "Double 11" super project and has stable and outstanding performance, it has been used by more and more domestic enterprises in recent years for its high performance, low latency, and high-reliability features.

The basic components of RocketMQ and its workflow are shown in **Figure 14**.

Producers: Message producers, responsible for producing messages, are selected by the MQ load balancing module to deliver messages to the appropriate broker cluster queue, with fast failure and low latency support, and all message producers in RocketMQ are in the form of producer groups. A producer group is a collection of producers of the same type, which sends messages of the same topic type. A producer group can send messages for multiple topics at the same time.

Consumer: Message consumer, responsible for consuming messages. A message consumer gets the message from the broker server and performs the related business

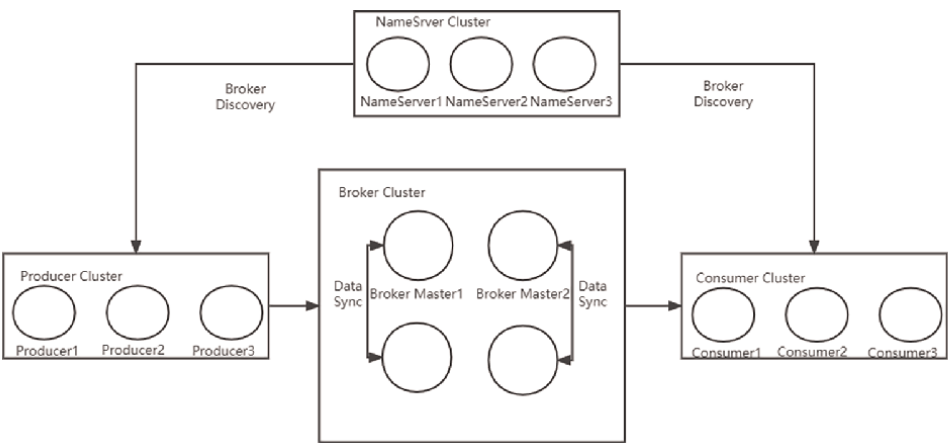

Figure 14.
The process of RocketMQ.

processing on the message; message consumers in RocketMQ are in the form of consumer groups. A consumer group is a collection of consumers of the same type, and such consumers consume messages of the same topic type.

NameServer: It is a registration center for broker and topic routes, and mainly contains two parts, which are as follows:

- Broker management: It accepts the registration information, which is saved as the basic data of routing information. It also provides heartbeat detection mechanism to check the activity of the broker.

- Routing information management: Every NameServer owns the entire routing information of the broker cluster and the queue information for client queries, and the producer and consumer can obtain the routing information of the entire broker cluster through the NameServer to deliver and consume the messages.

Broker: The broker acts as a message relay, storing and forwarding messages, and is responsible for receiving and storing messages from producers in the RocketMQ system and preparing them for pull requests from consumers.

4.3.4 Kafka

Kafka was first developed as a distributed publish/subscribe-based messaging system by LinkedIn Corporation and later became a top project of Apache.

The basic components of Kafka and its workflow are shown in **Figure 15**.

Producer: Producer, as a producer of messages, needs to deliver messages to a specified destination (a partition of a topic) after production. Producer can choose which partition to publish messages according to the specified algorithm for selecting partition or in a random way.

Consumer: In Kafka, there is also the concept of consumer group, which is a logical grouping of some consumers. Because each Kafka consumer is a process, so the consumers in a consumer group will probably be composed of different processes distributed on different machines.

Broker: The main server used to store messages supports horizontal scaling (the more the number, the better the cluster throughput), and the storage of messages is divided by topic+partition (topic partition); the offset (offset) of each message within a particular topic/partition is stored together with the timestamp of the message when the message is stored until the expiration time (in the server). The offset of each message in a particular topic/partition is stored with the timestamp of the message, and when the message is stored until its expiration time (configurable in the server), it is automatically deleted to free up space (whether it has been consumed or not).

ZooKeeper: The broker side does not maintain the consumption state of the data and delegates it to ZooKeeper, which improves performance.

The main features of ActiveMQ, RabbitMQ, Kafak, and RocketMQ are compared in the following **Table 2**.

4.4 Key factors to be considered when designing data transmission

communication middleware is a data transmission platform that isolates application layer components from traditional communication architecture, network details, and operating systems. With the idea of layering, it effectively reduces the

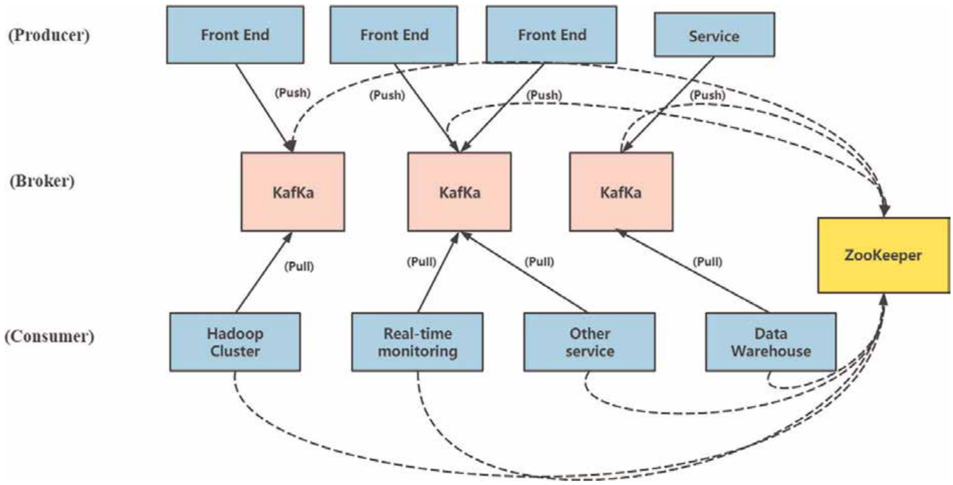

Figure 15.
The process of Kafka.

Characteristics	ActiveMQ	RabbitMQ	RocketMQ	Kafka
Application	Mature	Mature	RocketMQ is used in a large number of applications within Ali Group, generating massive messages every day, and has successfully supported many Tmall Double Eleven massive message tests, and is a powerful tool for data peak shaving and valley filling.	Kafka is more mature in the logging space.
Community activity	Medium-high	High	High	High
Stand-alone throughput	Million	Million	Ten million (less than Kafka)	Ten million (Highest)
Timeliness	Millisecond	Microsecond	Millisecond	Millisecond
Availability	High, master–slave-based architecture for high availability.	High, master–slave-based architecture for high availability.	Very high, distributed architecture	Very high, distributed, multiple copies of data, few machines down, no data loss, no unavailability
Support pacts	OpenWire, STOMP, REST, XMPP, AMQP	AMQP	Own defined set (community provides JMS - immature)	Does not follow the standard MQ interface protocol, relatively complex to use.
Message loss	There is a low probability of data loss.	There is a low probability of data loss.	Optimized configuration with parameters to achieve zero loss.	Optimized configuration with parameters to achieve zero loss.

Characteristics	ActiveMQ	RabbitMQ	RocketMQ	Kafka
Feature Support	The MQ domain is extremely full-featured.	Erlang-based strong concurrency, excellent performance, very low latency	MQ is more functional, still distributed, and scalable.	Support for simple MQ functions, real-time computing in the field of big data, and log collection is used on a large scale.
The impact of topic number on throughput			Topics can reach hundreds/thousands of levels, and there is a small drop in throughput, which is a major advantage of RocketMQ, which can support a large number of topics on the same machine.	When the topic is from tens to hundreds, the throughput will drop dramatically, under the same machine, Kafka tries to ensure that the number of topics is not too much, if you want to support a large number of topics, you need to add more machine resources.

Table 2.
Comparison of message queue features of commonly used distributed systems.

dependence between different layers and improves the software's scalability, reusability, portability, and other performance [37], which is an important direction for the development of radar communication in the future [38, 39].

The traditional communication middleware based on client/server model mainly focuses on business decision-making and display, and the data exchange between nodes is low in efficiency and small in data volume, which cannot meet the transmission requirements of distributed high real-time and large data volume. Therefore, communication products implemented based on this model have been gradually replaced. Aiming at the problems of traditional communication middleware, developing a new generation of real-time communication middleware has become a key task in the field of radar communication. In 2003, OMG developed a new generation of communication middleware based on CORBA. In face of market demand, the new generation of communication middleware must meet the following three requirements [40]:

4.4.1 Support communication between distributed nodes

In multi-radar distributed system, the requirement of real-time communication middleware is mainly reflected in the data transmission mode between communication nodes, including one-to-one, one-to-many, many-to-many, etc., which is mainly characterized by real-time, high bit rate, and concurrent communication.

4.4.2 Support dynamic joining and exiting of communication nodes

The new generation of communication middleware adopts the standard publish/subscribe model and defines the unified standard data transmission interface. It changes the development mode of the traditional communication middleware through the anonymous communication subject information published and subscribed data, so as to realize the dynamic entry and exit of communication nodes.

4.4.3 Loose coupling of communication nodes

Real-time communication middleware uses the data-centered publishing and subscription mechanism to realize the loose coupling between communication nodes. Middleware is located between the application layer and the operating system layer. It provides standard interface services on the upper side and shields the complex communication details and diversified operating systems on the lower side. In view of different environments, the appropriate operating system is selected according to the operating system adapter to realize the decoupling between application components and operating systems.

5. Conclusions

This chapter focuses on the communication and network technologies applicable to AVs, firstly, it discusses the wireless communication technologies and means commonly used in AVs, analyzes the main bottlenecks, and discusses the most important relay communication methods for remote communication in AVs; secondly, it focuses on the networking aspects of AVs, introduces the typical network structure and analyzes the demand characteristics of AVs networking, and proposes a task-oriented network design idea for AVs; finally, it describes the direct and indirect communication modes in distributed AVs, with a focus on DDS and message queues.

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Chapter 4

Mobile Industrial Robotic Vehicles: Navigation with Visual SLAM Methodologies

Xenofon Karamanos, Giorgos Karamitsos, Dimitrios Bechtsis and Dimitrios Vlachos

Abstract

Mobile industrial robotic vehicles are using cutting edge technologies and have been widely accepted as a means of sustainability in the last decade. Recent navigation approaches are commonly divided into two categories (i) Laser-Based and (ii) Visual-Based. Many researchers proposed navigation systems for laser-based SLAM but their efforts both in the two-dimensional (2D) and the three-dimensional (3D) environments are still lacking critical information, such as color and texture, from the facility layout in contrast with visual-based methods. Moreover, visual-based methods use more affordable sensor devices, indicatively monocular, stereo and RGB-D cameras, that provide highly detailed information from the operation's environment. The reconstruction of the 3D digital twin environment is more accurate and detailed, enabling the mobile industrial robotic vehicle to navigate in the facility layout and accomplish a much greater variety of tasks. The proposed research discusses recent developments in Visual-Based methods and analyses various well-known proposed systems. Performance assessment is also reviewed using the Robot Operating System (ROS) to compare the discussed methods and discuss their suitability for various facility layouts.

Keywords: SLAM, ROS, visual SLAM, RGB-D, MIR

1. Introduction

Mobile Industrial Robotic (MIR) systems are emerging in the Industry 4.0 context in order to increase economic, environmental, and social sustainability indicators. Even during the pandemic, while warehouses and manufacturing sites face significant challenges, the technology is still prominent with a high Return of Investment (ROI). Moreover, robotic systems' installations are expected to grow even more with the recovery from the pandemic, according to the International Federation of Robotics [1].

Warehouses and manufacturing sites worldwide continuously strive to improve their automated processes and the quality control of their products. Numerous activities are repetitive and performing them manually is unproductive, non-creative and a lot of times creates safety issues. To overcome this burden, workers can be assisted by autonomous mobile robots performing heavy and tedious tasks, delivery of goods and quality checks. Autonomous agents can accurately and timely move products and deliver raw materials for the manufacturing processes, allowing the human capital to perform specialized and more complex tasks [2]. Autonomous agents could also perform quality and quantity control activities at all the parts and the sub-parts of an order. This improves the quality of services and reduces costs. Autonomous agents should have the capability to sense the environment, as well as perform actions such as localization, path finding, obstacle identification and avoidance, product and semi-product identification and picking. This will enable them to navigate the facility safely and efficiently and cooperate with human capital and the machinery on the production line.

Towards accomplishing all those critical tasks, MIRs need to localize themselves in the facility and identify the relevant position of all the static (machinery, working cells, charging positions) and dynamic (humans, products and semi-products, other vehicles) entities in the industrial facility. Simultaneous Localization and Mapping (SLAM) [3, 4] is considered an essential component of robot navigation. SLAM is also used in a variety of use-cases, such as AR/VR Gaming [5], self-driving cars [6] and healthcare [7].

SLAM is a complex problem and is often described as the chicken and the egg problem. An agent must localize itself in the environment, but that requires some form of map correspondence. To create that map, the agent must accurately identify its position to map the environment accurately. SLAM literature is still evolving, in terms of accuracy, computational costs, and reliability. Many research approaches have been examined to overcome this problem using multiple sensors such as ultrasonic and sonar sensors, cameras (monocular, stereo, depth) and LiDARs. With recent hardware camera developments on affordable Time of Flight (ToF) and RGB-D cameras, the SLAM research moves towards a full Visual SLAM (vSLAM) approach. The main reason for this is the cameras' rich information, including color, depth and after processing semantic knowledge.

2. Materials and methods

SLAM algorithms are necessary for the safe and autonomous navigation of MIR. They are used to map the agent's environment and at the same time localize the agent. SLAM algorithms have many types depending on the use case. They can be categorized depending on their Degrees of Freedom (DoF) into two main categories, the 2D (3 DoF) SLAM and the 3D (6 DoF) SLAM algorithms, with each category having its subcategories. Most of the time 2D SLAM is used due to lower computational costs and excellent results. The most common sensor used in 2D environments is the LiDAR, but other ones are also used such as ultrasonic and sonar range finders as well. 3D SLAM is accomplished using various 3D sensors such as stereo cameras, RGB-D cameras, and 3D laser scanners. Our focus is on the 3D SLAM algorithms, specifically visual 3D SLAM using either stereo cameras or RGB-D cameras. We chose to focus on cameras, due to their lower entrance price points in respect to 3D LiDAR sensors. Moreover, cameras can provide information that otherwise would not be available, such as color and texture and visual SLAM is still ongoing research to lower the computational costs and increase robustness.

Visual SLAM uses information acquired from image sensors, such as monocular, Stereo or RGB-D cameras. Examples of such cameras are any single grayscale or color camera with no depth information, Stereolabs® ZED™[1] and Intel® RealSense™ Camera D435[2] respectively.

Most of the SLAM algorithms, are implemented as standalone applications. Open-source robotic research libraries and frameworks, such as Robot Operating System (ROS), help on providing them through ROS-wrappers. It is also possible to provide the full implementation on top of ROS.

ROS provides a variety of software modules for enabling robot communications and procedures like localization, mapping, path planning and scheduling methods and paves the way for the rapid reconfiguration of mobile robots. ROS-wrappers provide the ability to researchers, to easily deploy the software to various robotic platforms and a wide configuration of sensors, through the publisher-subscriber and topics mechanism.

2.1 SLAM map structures

2D SLAM usually uses the occupancy grid map data structure. The map is split into cells that are either occupied or free or unknown status. The format efficiently provides the data for navigation tasks, such as planning algorithms and obstacle avoidance. Being 2D-structure, if 3D information is present, a single cell may be occupied in the z1 plane but free on the z2 plane. This information is lost when building 2D and the SLAM algorithm must decide what the cell should be, either by heuristics or user defined rules.

3D SLAM on the other hand, keeps that information. It utilizes either 3D meshes or Octree data formats. Octree is a structure similar to the occupancy grid but in 3D. Instead of a cell though, it uses a voxel, a cube. The environment is split into 8 voxels, which are divided into another 8 voxels until the resolution is the one desired. Even though it is computationally costly, it offers significantly more information. Utilizing the 3D environment, we can gather semantic information that otherwise would be lost and use it for both localization and object manipulation. Most algorithms that provide volumetric information also use graph-based optimization techniques to deliver more reliable and compact results.

2.2 Sensors description

Monocular sensors refer to a single camera module producing a single image, whether color or black-white image. Monocular cameras are usually cheap, light-weight and low power consumption devices. They are mostly preferred when in need of low computational costs and lightweight devices such as drones.

Stereo sensors are a pair of, usually monocular, cameras with a known physical relationship. This means information regarding the distance between their focal points and their common field of view is known (see **Figure 1**). After calibration is performed, one can calculate a disparity image on a pair of images captured simultaneously by stereo matching algorithms. Depth and 3D points can also be obtained. If one of the pair cameras is an RGB sensor, colored 3D points can be produced. The cost is higher compared to monocular devices, but recent developments allow more

[1] https://www.stereolabs.com/zed/specs/

[2] https://www.intelrealsense.com/depth-camera-d435/

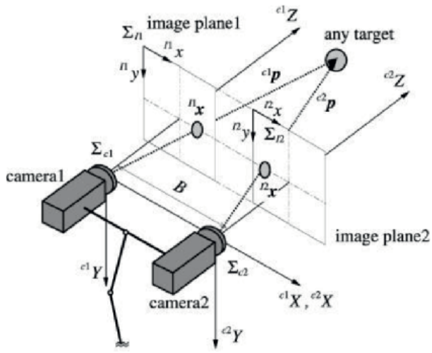

Figure 1.
Stereo camera model [8].

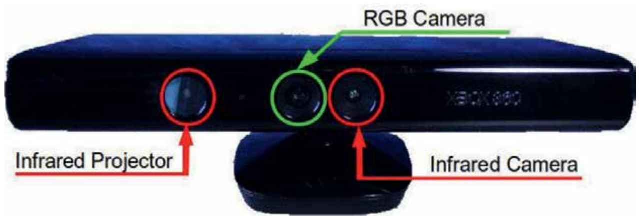

Figure 2.
RGB-D sensor structure (Kinect) [9].

affordable hardware. They are highly usable in outdoor environments where RGB-D sensors are lacking due to their structured light patterns.

RGB-D sensor is a module that has an RGB sensor camera along with some type of depth-sensing mechanisms, such as infrared light patterns. It can produce both a color image, per-pixel depth maps, and 3D point cloud. However, they have limited range and their accuracy is degraded over a certain distance threshold. Due to the nature of their depth-sensing mechanism, RGB-D is most suitable for Indoor Applications. Furthermore, their initial cost is higher than monocular sensors but due to recent developments in the hardware field, the cost has stabilized to a reasonable price range (**Figure 2**).

Inertial Measurement Unit (IMU) sensor combines an accelerometer and gyroscope and provides information regarding changes in robot movement like acceleration, position, and orientation at extremely high rates. Its small size also makes it possible to be incorporated into camera sensors, as an extra source of data. Unfortunately, due to its accumulation of errors over time, it is not considered reliable without additional information and corrective measures (**Figure 3**).

3. Literature review

The identification and classification of SLAM algorithms MIR require an analysis of the literature in the field. Our taxonomy focuses mostly on: (i) the sensors used in the methodology such as Monocular, RGB-D or Stereo cameras; (ii) the map representation used i.e., Landmark, Graph or Volumetric-based; and (iii) availability

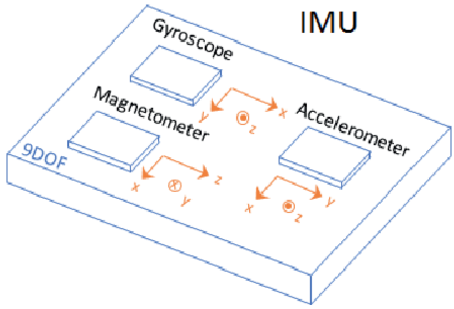

Figure 3.
Inertial measurement unit (IMU) components (Model IMU, GPS, and INS/GPS - MATLAB & Simulink (mathworks.com)).

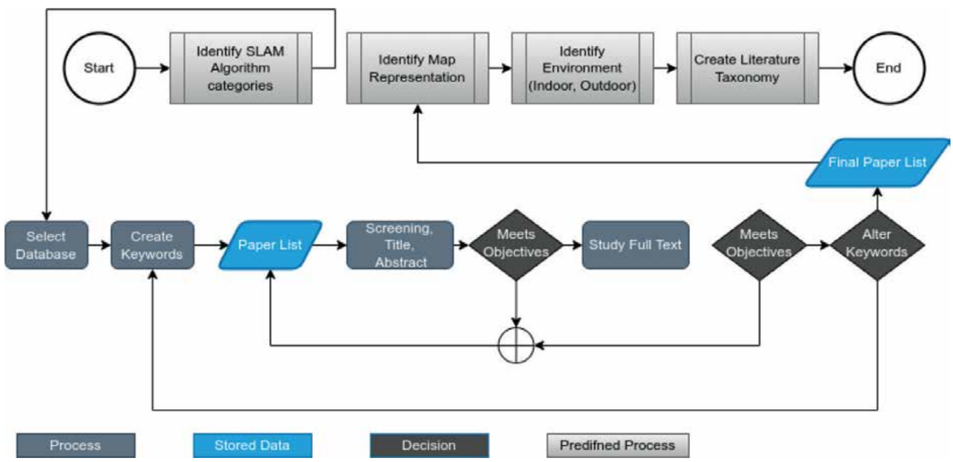

Figure 4.
Workflow to find literature.

as on open-source software and ROS compatibility. Following that, the selected and reviewed articles were critically taxonomized. The procedure can be seen in **Figure 4**.

The search has been conducted in the Scopus of Elsevier database. Terms such '3D SLAM', 'RGB SLAM', 'stereo SLAM' were introduced and but not limited to, and the 'Article title, Abstract, Keywords' field were used. The reviewed studies selected to be included in our taxonomy were written in the English language. A total of 18 studies, were identified to be reviewed.

This section summarizes various SLAM methods (**Table 1**) categorized upon their sensor input. This study focuses on Monocular, Stereo, RGB-D sensor, with IMU (Visual-Inertial SLAM) or without IMU and LiDAR (Light Detection And Ranging) or a combination of those.

3.1 Monocular-based methods

Research [10] introduces MonoSLAM, a real-time algorithm for simultaneous localization and mapping with a single freely moving camera. In this work, localization is the main output of interest. A map is undoubtedly built, but it is a sparse map

References	ROS-wrapper	Open-source	Input sensor	SLAM Type		Map representation			Environment (preferred)	
				Direct	Feature	Landmark based	Graph	Volumetric	Indoor	Outdoor
MonoSLam [10]	✓	✓	M		✓	✓			✓	
T-SLAM [11]			M, L		✓		✓		✓	
DTAM [12]	✓	✓	M	✓				✓	✓	
KinectFusion [13]	✓	✓	RGB-D	✓				✓	✓	
SLAM++ [14]			RGB-D		✓ (object level)		✓		✓	
Kimera [15]	✓	✓	M, S, I		✓		✓	✓(Mesh)		✓
OpenVSLAM [16]	✓	✓	M, S, R		✓		✓			✓
PL-SLAM (2019) [17]	✓	✓	S		✓		✓		✓	✓
Visual-Based Semantic [18]		✓	M		✓		✓			✓
Vitamin-E [19]			M		✓			✓	✓	
RTAB-MAP [20]	✓	✓	M, S, R, L, I		✓		✓	✓(Octree)	✓	✓
SegMap [21]	✓	✓	S, R		✓		✓		✓	✓
DS-SLAM [22]	✓	✓	M, S, R		✓		✓	✓(Octree)	✓	✓
Sparse3D [23]		✓	RGB-D	M/D	✓		✓		✓	
SceneSLAM [24]		✓	M, S, R, L		M/D	M/D	M/D	M/D	M/D	M/D
ProSLAM [25]	✓	✓	S		✓		✓		✓	✓
DPI SLAM [26]			RGB-D		✓		✓	✓ (3D point cloud)	✓	
S-PTAM [27]	✓	✓	Stereo		✓		✓			✓
ORB-SLAM3 [28]	✓	✓	M, S, R, I		✓		✓		✓	✓

Table 1.
List of SLAM algorithms and their properties M, Mono; S, Stereo; R or RGB-D, Pair of RGB image and depth image; L, LiDAR; I, IMU; M/D, Module Dependent.

of landmarks optimized for enabling localization. They use a probabilistic feature-based map, representing a snapshot of the current estimate of the camera and the uncertainty of those estimates. Updates are pushed dynamically by using Extended Kalman Filter and a large patch size of 11x11 pixels is used to identify long-term landmarks. They also initialize the system with the help of known targets placed in front of the camera. A motion model and prediction are developed to re-move the uncertainty of the control inputs. To reduce the time needed to find features in the image, they predict the image position of each feature before deciding which to measure. Efficiency is provided by active feature search, ensuring that no image processing effort is wasted. Feature initialization is done after some frames have passed that include a particular feature in order to have a depth estimation. They also have a map-management algorithm due to the low capacity of max features that they can handle.

In [12], authors created a system for real-time camera tracking and reconstruction with the use of an RGB only camera and direct manipulation of image. DTAM (Dense Tracking and Mapping) consists of three stages. Map initialization by stereo measurements. Camera pose is estimated by matching synthetic views to live feed. Depth information is estimated for every pixel by using multi-baseline stereo. Tracking is done by comparing the input image with synthetic view images generated from the reconstructed map.

Authors in [18] were inspired by the human visual navigation system. They created a SLAM method that incorporates semantic information of the environment. In order to do that, they use the excellent ORB-SLAM2 [29] method for 3D point cloud generation and combine the semantic information provided by Convolution Neural Network (CNN) model PSPNet-101 [30]. The main idea is the extraction of semantic information from the camera. Then the pixel-level semantic result and the current frame are sent to the SLAM system for re-construction. The pixel-level information is associated with the map point using a Bayesian update rule, which updates the probability distribution of each map point. Moreover, the landmarks are projected in the SLAM map and are also associated with the nearest keyframes. The map that is created can be used for re-localization.

Vitamin-E [19] is an indirect monocular SLAM algorithm. The system has high accuracy and robustness because of tracking extremely dense feature points. Feature tracking is accomplished by monitoring the local extrema of curvature on image intensities and builds upon over multiple images. They also predict the position of features in the next frame by using a Geman-McClure kernel function. Then, the reconstructed map is adjusted by bundle adjustment to minimize reprojection errors. Moreover, a new novel optimization technique is introduced called 'subspace Gauss-Newton' and it partially updates variables rather than all of them at once. This results in accurate 3D points allowing point cloud generation and further dense geometry reconstruction such as meshing and noise removal.

3.2 Stereo based methods

PL-SLAM [17] is a method expected to run in a low-textured environment. It uses feature points and line segments found in the scene. It also achieves real-time performance. The system is split into three threads, visual odometry, local mapping and loop closure. Local mapping and loop closure thread is invoked only when a new keyframe is inserted. The map is a set of keyframes and 3D features such as critical points and line segments. The map structure is a graph, and bundle adjustment can be performed. Loop closure is done in parallel to local mapping by extracting a descriptor for each image (keyframe) and then compared to the current one. The best match will be considered a loop closure only if the surrounding keyframes are also similar.

ProSLAM [25] is a graph-based lightweight SLAM system that maps through the pair image stream. The authors implement the system as highly modular and although they claim to be parallelized, they implement the system in a single thread. The four main modules are frame point generation, position tracking, map management, and re-localization. They also provide the data structure's internals and how they interact with all the remaining classes. A FAST detector is used for keypoint detection and BRIEF descriptor is used. An epipolar feature matching is then used to find the pairs of features in the stereo pair images. Subsequently, the position tracking module estimates the motion between the two frames. Map management is responsible for map generation and keeping track of landmarks and local maps from the input of the two modules before it. Finally, the re-localization module performs graph optimization to compensate for the drift that has been produced. Graph optimization uses the following procedure. At first, a similarity search is performed to identify past observations likely to be taken at the current location using Hamming Binary Search Tree. Then, a geometric validation is performed to find a consistent transform that maximizes the overlap between the two locations that were found by similarity search. Finally, a refinement is done for all the local maps to incorporate the newly added constraints of loop closure.

3.3 RGB-D methods

KinectFusion [13] provides real-time mapping of an indoor scene that provides a single global implicit surface model of the scene in real time. Current sensor pose is obtained by tracking the current depth frame relative to the global surface model using the ICP [31] algorithm. KinectFusion can track 6-DOF camera pose using all live data available. It can integrate depth measurements directly into the global dense volumetric model and can change view dynamically. GPU is used for high-speed tracking and reconstruction. The methods used by the authors include surface measurement, surface reconstruction update using TSDF representation, surface prediction that close the loop between mapping and localization, by tracking depth frame against the globally fused model. Finally, sensor pose estimation is performed using ICP between the predicted surface and current sensor measurement.

The authors in [14] present a 3D SLAM paradigm with object-level semantic label SLAM++. Many objects repeat in many areas; hence they are being scanned beforehand and are used to identify during mapping. The method is as follows. First, a database with common objects is created using KinectFusion [13]. A mesh is extracted from the Truncated Signed Distance Volume (TSDV) using marching cubes. The map representation preferred in the article is a graph, where each node stores either the estimated pose of an object or the historical pose of the camera at timestep. Also, each object node is annotated with a type from the object database. Each pose node contains the measurement of the pose of an object from the camera pose as factor. Realtime object recognition with 6 DOF pose of 3D objects is implemented in GPU. An object is detected and localized via the accumulation of votes in a parameter space, the basis of vote being the correspondence between Point-Pair features. Matching similar scene features can be performed in parallel via a vectorized binary search. Camera tracking and accurate object pose estimation are accomplished using ICP [31]. Graph optimization is used to further refine the pose. The system can also include prior information like a common ground plane. It also offers a re-localization mode when the tracking is lost.

SegMap [21] is 3D SLAM method that uses a segment-based approach for map representation in localization and mapping. The system decomposes the robot's surroundings into a set of segments, each segment represented by a distinctive, low dimensional learning-based descriptor. The descriptor is computed through a CNN model composed of three convolutional and two fully connected layers. To train the network, they used the KITTI dataset, and classification and scaled reconstruction losses are used. Those descriptors are then used for data association by segment descriptor retrieval matching. Those same descriptors also allow the reconstruction of the environment's map and extract semantic information. This is the main feature of SegMap, using incredibly low dimensionality features, hench high compression rate can reconstruct the environment.

Sparse3D [23] is an off-line reconstruction system. Given a dataset of ordered (video stream) or unordered set of images, with low intra-frame overlap, it will produce a 3D reconstructed map. The system is composed of three main steps, feature extraction and correspondences, pairwise frame matching and multi-graph global optimization for alignment pruning and refinement. The system uses three distinct kinds of keypoints to build the features. The Shi-Tomasi and SIFT keypoints are used for 2D keypoints and the SIFT descriptor is used. NARF keypoints are used for 3D (depth images) and FPFH descriptors. An affinity matrix is constructed to measure both similarity and spatial coherency between feature points and feature pairs, respectively. The best correspondence creates a transformation between the frames. Keep in mind, that different alignments can be found due to the three different keypoints used. Then a global optimization on multi-graph is performed. Multi-graph means each node may be connected to another node with more than 1 edge.

3.4 Some combination of sensors (mono/stereo/RGB-D and IMU/LiDAR)

In [11], T-SLAM is a map building method that integrates topological and geometric maps created independently using multiple sensors. They use a global topological map and a set of two or more local geometric maps. Each node of the topological map is registered with every local geometric map. In order to build the topological map, the robot samples the environment according to a sampling plan. During this first trip around the environment, called the Environment Familiarization phase, it collects features by using its sensors into the Reference Sequence. A repetition of the motion performed during the place recognition should propel the robot along the path described by the Reference Sequence. Any maneuver other than the ones taken during the Environment Familiarization phase will take the robot to a place that was not sampled in the Environment Familiarization phase, called Lost_Place. The original views can be modeled as left to right graph and are augmented by the insertion of Lost_Places. When the robots need to localize themselves, the current view is compared to the previously collected views and an inference is made of the current position of the robot using the Hidde Markov Model. Local Geometric Maps are created using various SLAM methods from sensor data like DP-SLAM [32] and FastSLAM [33] that produce grid-based metric maps using particle filters. In their implementation two grayscale cameras and a lidar are used.

Kimera [15] is an open-source library for Real-Time Metric-Semantic SLAM. It uses state-of-art efforts in various research areas, combining them and get a SLAM system that is composed of four key modules. Namely, Kimera-VIO, the Visual

Inertial Odometry module, for fast and accurate estimation. Kimera-RPGO, Robust Pose Graph Optimization, Kimera-Mesher, a fast per-frame and multi-frame 3D meshes computation and Kimera-Semantics, that builds more accurate a global 3D mesh using volumetric approach and semantically annotates the mesh using 2D pixel-wise semantic segmentation. Kimera system also supports ROS ecosystem for easy online SLAM or offline datasets. It has real-time capabilities for obstacle avoidance, 3D meshing and it is modular allowing replace each module or executing in isolation. Kimera-RPGO is responsible for Loop Closure detection and computing globally consistent keyframe poses using robust Pose Graph Optimization (PGO). Loop closure is accomplished with the help of DBoW2 library and PGO is implemented in GTSAM [34] with a modern outlier rejection method called Incremental Consistent Measurement Set Maximization.

OpenVSLAM [16] is an open-source software designed to be a modular SLAM framework with high usability and extensibility. Various 3D sensors can be used such as perspective cameras, fisheye, equirectangular and one can implement support for new ones. Another crucial point is the ability to save the created maps and re-use them for localization. Implementation is divided into three modules. The tracking module, which estimates the current camera pose. Moreover, it classifies whether a frame must be regarded as a new Keyframe. If so, it is sent to the mapping and global optimization modules. The mapping module is responsible for creating the map, triangulating new 3D points using the inserted keyframes. Also, bundle adjustment is performed for optimization. The last module, global optimization performs loop detection and pose-graph optimization.

RTAB-Map (Real-Time Appearance-Based Mapping) [20] is an open-source library released in 2013 but evolved since then to full SLAM module. Initially, the library implemented a loop closure detection with a memory management approach. The approach was to limit the size of map so that the loop closure was always processed in real time and for long-term and large-scale environments. The full SLAM approach is graph-based, cross-platform and integrated with ROS ecosystem. RTAB-Map is split into various modules, some of them are Short-Term Memory (STM), working Memory (WM) and Long-Term Memory (LTM), Loop Closure and Proximity Detection and Global Map Assembling. STM is responsible for creating the nodes containing the odometry pose, sensors data and any other information useful for the other modules. The link between the nodes is a rigid transformation, either by STM or by Loop Closure and Proximity Detection module. The links are used as constraints for graph optimization. RTAB-Map memory management is run on top of graph management modules. It limits the size of the graph so that long term online SLAM can be achieved in large environments. When an update fails the real time constrain, some nodes are transferred in LTM from WM. A node that is transferred to LTM is not used in modules in WM. Choosing the nodes depends on a weighing mechanism. When a loop closure is detected within WM, neighbors of this location can be brought back from LTM. RTAB-Map can use external odometry inputs (visual or lidar based). It is a full ROS compatible node, outputting online 3D point cloud or 2D occupancy grids, that can be used by external libraries for navigation.

DS-SLAM [22] is an extended version of ORB-SLAM2. It consists of five threads and utilizes segmentation semantics along with moving consistency checks. The five threads are tracking, semantic segmentation thread, loop closure, local mapping, and dense oct-tree map creation thread. Semantics segmentation is real time using SegNet neural networks classifying objects found in the scene. It also checks for ORB features points and if any of them are found in moving objects, found by moving consistency workflows and semantics, they are dropped to reduce computational time. Finally, they use an octree-based structure in mapping thread, to add semantic segmented information without any moving objects in the map.

SceneSLAM [24] is an extensible modular SLAM framework with scene detection algorithms. The system is comprised of three main components, SLAM module, Scene Detection module, and a Software Bus module. SLAM module and Scene Detection module are interfaces, meaning various algorithms can be implemented and switched on/off on runtime based on some conditions. Software Bus is the module responsible for tracking these changes. The system is based on a finite state. After the initialization phase, a scene detection algorithm is performed and based on the result, switch state is enabled. The switch state switches the SLAM algorithm used based on which scene was found. One SLAM algorithm is used per Scene Detection value. Experiments were performed with Dark/Bright Scene Detection algorithms and Laser/RGB-D SLAM modules, respectively. Any Scene Detection/SLAM method can be used if it implements the respectively interface and can be switched on/off by the module loader of Software Bus module.

DPI-SLAM [26] is dense-planar inertial SLAM that reconstructs 3D dense models of large indoor environments. Its input is RGB-D images and Inertial Measurement Unit (IMU) data. The architecture of the system consists of three main parts. Odometry estimation and frame labeling, local depth fusion, and finally, global planar inertial mapping with structural constrains and loop closing. Starting with an RGB-D frame, the pose is predicted using preintegrated IMU measurement and refined with RGB-D odometry. Depth fusion module fuses the depth of frames to the last frame into a local depth map. In the third part, plane extraction is performed, and the point cluster is produced. Planes are then associated with existing landmarks using a projective method. They are also added into a global factor graph and optimized with existing Visual Odometry (VO) and inertial factors. Loop closure constraints are also added and then optimized again. Loop closures are found with a bag-of-words approach and algorithm based on iSAM2 [35].

ORB-SLAM3 [28] is an extension of ORB-SLAM and ORB-SLAM VI (Visual-Inertial) systems. This combination facilitates short-term, mid-term and long-term data associations with all previously gathered information not only from some seconds before. ORB-SLAM3 also introduces multi-map data association, providing infrastructure for building maps by combing multiple mappings sessions, that can be used later for improved localization. It uses three different threads for each subsystem of tracking, local mapping and loop and map merging. ORB-SLAM3 also introduces camera model agnostic module, meaning it can work not only with a pin-hole model but also any other kind like fisheye model provided someone implemented it. It also offers robustness when an agent gets lost with a two staged method of short-term loss and long-term loss steps. Loop closure is also provided with usage of DBoW2 bag-of-words place recognition system [36]. Moreover, temporal and geometric consistency checks are performed for improved results. Finally, if loop closure is from different map session or non-active map, a map merge is performed.

4. Performance analysis

Robot Operating System (ROS) [37] has an out of the box 2D SLAM but the search for 3D alternative/replacement is still evolving. To identify a suitable solution that they are going to support long term, benchmarking is the way to go.

Review papers exist that experimentally compare a combination of these algorithms. The SLAM algorithms are put to the test through available open datasets deployed by other researchers. Datasets provide a lot of different environments, indoor and outdoor and different camera movement styles such as on-board robot, handheld, rapid changes and pure rotational. This makes it possible to stress test them on edge cases and find the most stable, robust, and best performing algorithm. Notable datasets that many algorithms are tested on are EuRoC MAV, TUM RGB-D and KITTI. Each one contains raw data from different sensors, environments, and camera movement. EuRoC data is stereo with IMU about indoor environment captured by drone, TUM has RGB-D indoor data captured either onboard robot or from handheld device and KITTI has stereo without IMU information in outdoor data captured from camera on top of a car.

In a recent comparison, see [38], authors try to find the best 3D vSLAM to incorporate in ROS 2 ecosystem. They put to the test three of the latest state-of-the-art, modern and feature rich SLAM systems, ORB-SLAM3, OpenVSLAM and RTAB-Map. After comparison OpenVSLAM performed robustly on all three datasets, EuRoC, TUM and Kitti. When there is IMU information, they propose to incorporate it, due to improving the overall accuracy and robustness. While there is still a lot to improve vSLAM such as consideration of lighting conditions, they noted that vSLAM is an essential tool to get away from expensive LiDAR sensors.

Comparisons made in [39] tries to shed light in this matter by benchmarking a separate set of systems and six different datasets. Datasets cover a thorough list of probable situations, such as stereo, rgb-d, imu sensors, fast motion, dynamic objects, illumination changes and sensor degradation captured on ground robots, drones, handheld devices and even on synthesized data. The algorithms that were tested include ORBSLAM2 [29], ORBSLAM3 [28], OpenVINS [40], FullFusion [41], ReFusion [42] and ElasticFusion [43]. Their conclusion is that ORBSLAM3 provides the best balance between the various conditions of illumination, rapid changes, and dynamic objects. This comes at the cost of below 15 FPS. They also confirm that added inertial information in ORBSLAM3 improved overall robustness compared to ORBSLAM2.

VSLAM methodologies performance varies depending on the environment and robot motion. Poor illumination and changes, texture of the environment and fast motion are some contributing factors. Overall, the OpenVSLAM performed the most robustly in all different scenarios with high reliability. ORB-SLAM3, even though hard crashes could occur (segmentation faults), manages to perform robustly and various conditions with good accuracy. Comparisons from [38, 39] can be seen in **Figures 5** and **6**.

		00	02	03	04	05	06	07	08	09	10	Avg	Dur
ORB-SLAM3 (mono)	RMSE,m	9.109	31.928	2.503	1.281	6.351	**15.149**	**3.931**	71.197	**17.452**	9.883	**16.878**	15:04
	st.dev,m	1.175	17.568	0.626	0.303	1.117	0.660	0.246	54.604	11.157	1.514		
OpenVSLAM (mono)	RMSE,m	**6.860**	**31.434**	**1.632**	**0.372**	**5.897**	18.215	5.063	**70.470**	29.923	**9.454**	17.932	15:12
	st.dev,m	1.188	8.035	0.573	0.147	0.702	1.644	0.459	4.814	14.898	1.458		
ORB-SLAM3 (stereo)	RMSE,m	1.348	7.114	0.759	0.249	**0.778**	**0.783**	0.554	3.619	**1.640**	**1.030**	1.787	28:27
	st.dev,m	0.035	0.619	0.053	0.043	0.045	0.107	0.043	0.185	0.045	0.101		
OpenVSLAM (stereo)	RMSE,m	**1.339**	**5.695**	**0.725**	**0.197**	0.783	0.899	**0.547**	**3.446**	2.175	1.235	**1.704**	30:25
	st.dev,m	0.020	0.371	0.059	0.037	0.016	0.090	0.057	0.124	0.611	0.045		
RTABMap (stereo)	RMSE,m	1.370	5.824	1.694	1.389	1.715	2.278	0.665	7.428	4.683	1.120	2.817	15:12
	st.dev,m	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		

Figure 5.
Comparison of [38] between ORB-SLAM3, OpenVSLAM, RTAB-map on KITTI dataset.

	ElasticFusion	FullFusion	ReFusion	OpenVINS	ORB-SLAM2	ORB-SLAM3
Baseline Accuracy	Very good	Good	Good	Very good	Very good	Very good
Illumination	Not robust	Excellent*	Not robust	No data	Excellent	Excellent
Dynamic	Not robust	Good	Very good	No data	Not robust	Acceptable
Fast	No data	No data	No data	Very good	Acceptable	Very good
OpenLORIS (Combined)	Not robust	Acceptable	Acceptable	No data	Acceptable	Good

*FullFusion is not impacted by illumination changes as it does not use color information

Figure 6.
Comparison of [39] between SLAM across various settings.

5. Implementation: Q-CONPASS project

Q-CONPASS is a system currently under development and focuses on assisting the manufacturing process and quality control. A robotic agent will assist the workers and management team in numerous ways. First, the robot will move across workspaces and a dedicated space where small and expendable materials are found. It will pick up the necessary components needed for the current manufactured unit and transport them back to the workspace. This way, unnecessary moves by workers will be removed and the worker will be utilized in a more efficient and productive manner. Moreover, it was found that a lot of shipment orders had missing crucial components, that cost the company either reimbursement or sending individually the missing components. Hence, the robotic agent will also have specific stationery spots in some of the workspaces. One spot will be for quality control. It will monitor the various components needed to complete an order and check if the worker placed that component for boxing. Another spot will be used for monitoring the workers and their ergonomic posture [44]. A report of indicators describing a worker's right and wrong posture will be handed to the management team in order to improve the worker's safety procedures and avoid further health problems.

The most widely used algorithm on ROS, RTAB-Map, was deployed using ROS in the Q-CONPASS project. A TurtleBot 2 was used as the MIR. Equipped with LiDAR and an RGB-D camera, a rosbag file was recorded at site during the initial mapping.

Afterwards, RTAB-Map was run offline to produce a 3D Map of the environment. Using the default parameters and enforcing 3 DoF for localization as it is a ground robot, the RTAB-Map was able to produce the 3D Mapping. Moreover, RTAB-Map enables users to export the point clouds produced, as well as the robot pose and an OctoMap version of the map. **Figure 7** shows the map produced inside RTAB-Map Viewer with point cloud and OctoMap version in ROS RViz.

In **Figure 8** we can see the same scene inside Rtab Viewer and RViz.

6. Discussion and conclusions

SLAM is an essential part of a wide range of applications, including autonomous vehicles, Virtual & Augmented Reality (AR/VR) and robotics. Being able to operate in an environment safely and robustly is a must. To accomplish that, various sensors

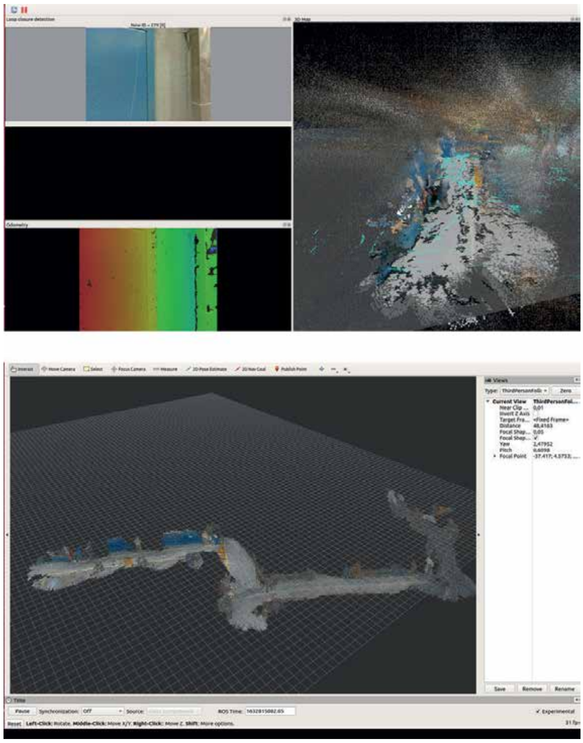

Figure 7.
Mapping using RTAB-map GUI (above) and RViz for visualization (below).

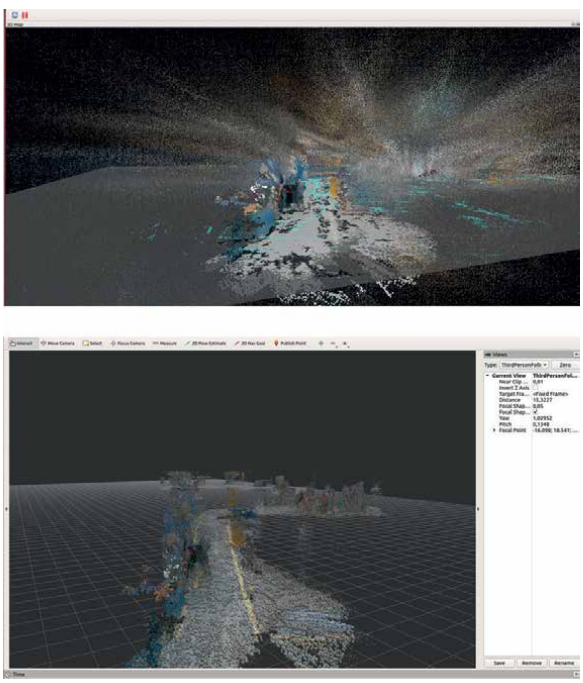

Figure 8.
Same scene visualized from RTAB-map viewer (above) vs. RViz (OctoMap octree) (below).

can be used but one of special interest is the camera sensor, either mono, stereo, or RGB-D. Camera sensors are cheap and provide lots of information in comparison to the high-cost 3D Lidars. Lots of algorithms and methodologies have been proposed to bring out the best of cameras despite being computational costly, and the barriers to do safely and robust localization and mapping have dropped significantly. Out of the many methods that exist, some of them are quite popular and are becoming the baseline to compare other implementations against. ORB-SLAM2, RTAB-Map and OpenVSLAM have been so far the most popular and ORB-SLAM3 is gaining traction. Visual SLAM is increasingly used, and a lot of research is still ongoing on how to minimize the cost, but the improvement so far is tremendous, allowing it to run even on embedding devices but at lower rates. Moreover, combined with more sensors such as an IMU, Visual-Inertial SLAM can provide further improvements and robustness.

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Section 3

Autonomous Vehicles Applications and Potentials

Chapter 5

How the Micro ROV Class Will Change the Maritime Sector: An Introductory Analysis on ROV, Big Data and AI

Michael Stein

Abstract

Although underwater drones are no novel technology, their widespread use in civil and industrial applications has not been widely accepted so far. Apart from that, the decrease in size and costs along with an increase in robustness of underwater drones and the ease of handling provide a strong basis for underwater drone technology to grow in various markets. This chapter introduces the application of underwater drone technology in maritime operations, focusing on the micro ROV class. An introductory framework evaluation based on a structured literature analysis of the current state of research is conducted in order to provide a structured outlook on areas of drone operations in the maritime domain. Furthermore, the combination of micro ROV and artificial intelligence in the form of a neural network based on deep learning is introduced. This contribution provides an introductory analysis regarding both operational sides of science and the industry in order to shed light on the existing literature gap as ground for future research.

Keywords: remotely operated vehicles, underwater unmanned vehicles, underwater drone, 3D modelling, artificial intelligence, neural networks, deep learning

1. Introduction

As 71% of the world's surface is covered by water [1], this element is and will be crucial for our survival. The oceans reflect the largest habitat of wildlife on this planet, whilst also providing very large amounts of crucial resources and facilitating over 90% of the global trade via shipping operations. Knowledge about what happens underwater is important to maintain and explore the ocean's potentials in balance with its fragile ecologic system. However, the oceans even today remain the least explored area of this planet for reasons of unavailability to the human eye. Whilst only about 5% of the oceans were stated to be explored in 2016 [1], the number increased to approx. 20% in 2020 [2]. Advances in underwater robotics have promoted comprehensive studies of oceans and exploration of areas previously out of reach of humans [3]. Even though deep sea and offshore operations of unmanned vehicles have existed for decades through operating working-class systems, their cost and size were a limiting factor accessible to specific industries only. With advancements in the so-called inspection class systems [1], the availability of underwater drones to new markets and research facilities has risen. In the past, researchers were often excluded from deep sea operations due to cost-intense training, resulting in scientists being dependent on a third party data provider or industry partner [3]. The cross-sector partnership of research and industry remains crucial for sustainable human activities in the ocean [4]. However, the widespread availability of reliable, cheap and easy-to-operate systems enhances the independent data-capturing opportunities, allowing both scientific and entrepreneurial developments.

Drones reflect a human-controlled robot that is designed to carry out tasks in remote areas. There are many classes and definitions of these robots generally originating from the aviation industry. The term "drone" dates back to World War 2 air force target practice operations and is still used for unmanned robotics nowadays. In the 1960s/1970s, underwater drones were predominantly developed by the Navy with systems like CURV I–III before the technology was adopted by the oil and gas industry in the 1980s [1].

This chapter follows the terminology for ROV (remotely operated vehicles) that in other contributions might be referred to as UUV (underwater unmanned vehicles). As this chapter focuses on human-controlled hardware, the area of AUV (autonomous underwater vehicles) is acknowledged but disregarded. The systems described in this chapter are operated on the surface through a cable for data connection. From aviation robotics, it is known that two to five times the weight of the pilot in specialised and redundant equipment is needed to ensure both the pilot's and the vehicle's safety [5]. These scales can to some extent be transferred to ROV operations, resulting in a reduction in size and costs of the system by excluding the human from robotic costs. This fact, in combination with current technological advances, allows a growing number of ROV systems to access areas formerly impossible or at least challenging for human intervention. It is worth mentioning that ROV systems and their corresponding operations are seen as individual entities from any infrastructure in the context of this chapter. There are, however, first projects which view ROV technology as a logical extension of infrastructure, such as ARES (Autonomous Robotics for the Extended Ship) [6] that might change this point of view in the future.

1.1 ROV system classification

This chapter follows the general classification of ROV systems provided by [1] as shown in **Figure 1**. Manned and autonomous vehicles are disregarded due to the limitations of this chapter's evaluation. The intervention class ROV systems are named for the purpose of a holistic point of view but are also not part of the evaluation. These systems will remain available for a limited number of industries or sectors only, given their high investment costs and their weight of up to 5.000 kg [1] requiring specialised crew and LARS (Launch and Recovery System). The focus of this chapter lies on the inspection class and its micro sub-category that allows independent, mobile operations of one person or a very small team of pilots.

Micro ROV systems often weigh less than 10 kg and are mobile enough to be transported in a small box or even in a backpack format. This high degree of mobility allows for a flexible operation out of a helicopter (e.g. for disaster response) or onboard a ship even in an open-sea anchorage, where the ROV operator enters the ship over a pilot ladder with the ROV. The micro ROV systems are predominantly

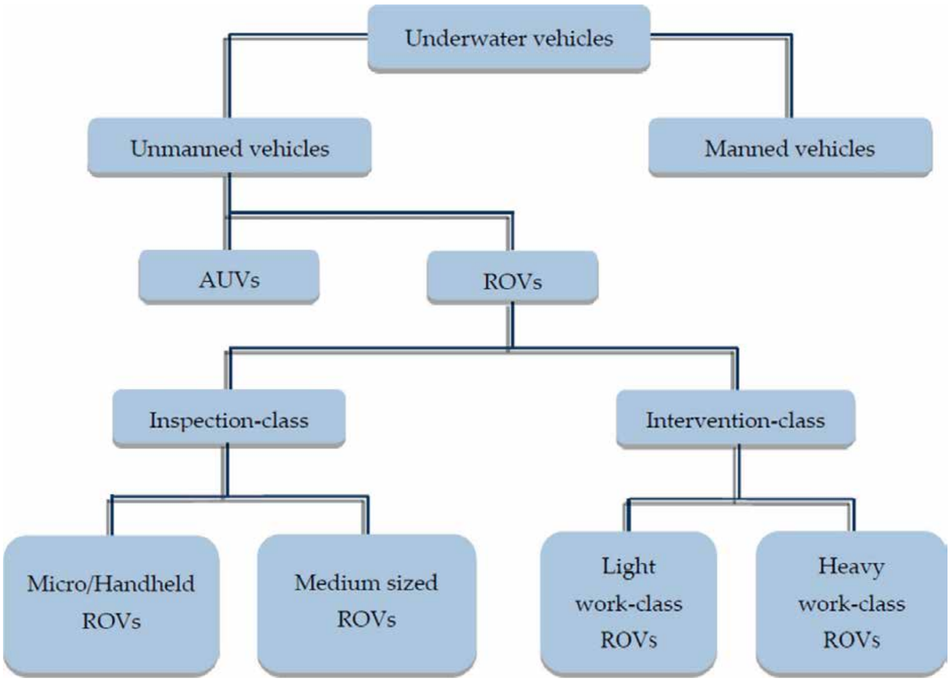

Figure 1.
Underwater vehicle classification matrix Source: Author based on [1].

reduced to video and manoeuvring systems only allowing for a fast and cost effective inspection. Some systems allow basic grabbing attachments for small retrieving operations or automated positioning systems. On a more advanced side, the medium-sized ROV provides open frame space for additional sensors to be added. These additional sensors then come with a trade-off regarding costs and size, often requiring a winch for launch and recovery. Opposite to micro ROVs, medium-class ROVs are operated via a communication station requiring a power supply and more complex human interaction compared to smartphones, tablets and/or handheld controller-operated micro systems. Whilst the early micro ROV systems were limited in operational scope due to limited bandwidth in copper fibre cables, recent generations use transition technologies allowing 500–1000 Mb/s over distances up to 500 m [1]. The technological advances of the micro class provide a huge potential for these small and relatively low-cost systems to enter the different maritime markets for the great benefit of different stakeholders.

2. Methodology

This chapter introduces the inspection class ROVs with a focus on micro or handheld ROVs to evaluate their future potential for scientific and economic operations. Whilst the offshore industry operated ROV systems for decades, micro ROVs have entered the markets only quite recently, resulting in a gap of knowledge and data. In order to cope with the scarcity of existing literature of newly emerging technologies, a mixed method approach of quantitative and qualitative methodologies as well as grounded theory concepts [7–10] are applied. Grounded theory approaches have a widespread acceptance in innovation science and are, therefore, chosen to be fitting for this chapter's methodology.

On the qualitative side of this chapter, an introductory framework evaluation based on existing literature is applied. This method is fitting to examine relationships of key factors within a research setup and combine various data seats to one summarising narrative. The importance of structured frameworks as a basis for future research for academic areas with limited existing literature is pointed out by prior contributions [11–13].

The quantitative contribution of this chapter provides a structured approach describing the global ROV market and provides a 2030 forecast based on a literature review of market reports. Both the inspection- and the intervention-classes are regarded separately in order to gain an understanding of the potential of the relatively new micro ROV class. This approach reflects only a first attempt at providing quantitative insights for reasons of limited available market data on ROV figures.

3. ROV market data

There is sufficient evidence that the underwater drone market will further increase in importance and acceptance, resulting in new market segments using this thriving technology. This chapter identifies 4 major market segments, where micro ROVs are likely to gain market share in the future compared to intervention class ROVs and/or conventional divers. These segments are in line with some of the most recent sustainable development goals (SDG) [14] displayed in **Figure 2**.

As part of the global energy transition, the shift from fossil to renewable energy sources is globally agreed on. Water will play a central role in this transition in the form of hydrogen production, cooling systems, offshore and nearshore wind farms or tidal power plants, to name the current most prominent approaches. Whilst conventional operations like seafloor mapping of new areas, cable operations and deep inspections remain intervention class driven, inspection class ROVs might get a growing market share in medium deep inspections of less than 300 m depth. Apart from the new construction of modern wind farms, existing farms have operated for decades and will be required to be decommissioned over the coming decades [15]. Data provided by ROVs is already seen as essential for timely investigation of the role

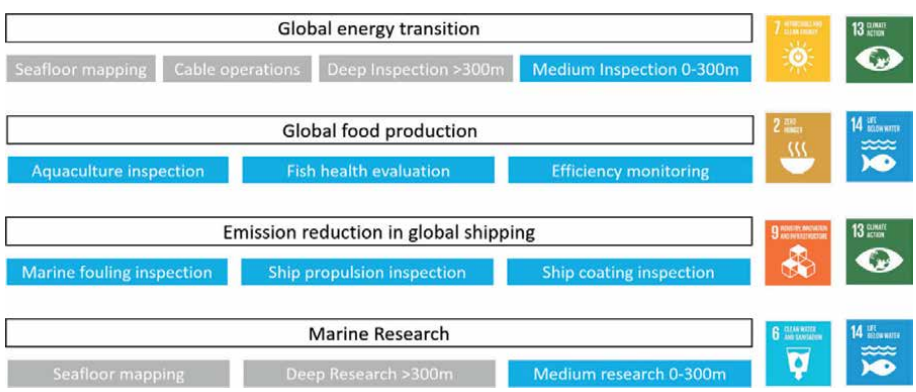

Figure 2.
Major micro ROV growth trends based on SDG Source: Author based on [14].

of offshore infrastructure from an ecological point of view and to predict the environmental effects of their removal [3].

The aspect of global food production will not only affect land-based farming but also the gathering of marine-based food resources. In 2022, the world population has reached 8 billion people with an estimated growth to 9 billion by 2037 [16]. In order to feed the global population, new and more efficient ways of food production are required. This will, amongst others, affect the aquaculture sector, which operates in shallow waters of less than 100 m depth. A growing number of micro ROV systems are already implemented in checking the nets and fish already dating back to 1987 [17] and with a growing number of recent contributions [18–20]. Apart from inspection operations, micro ROV systems can deliver video data of the fish swarm that can be used to train neural networks for various applications of efficiency enhancement as briefly introduced in Chapter 4.

As of January 2023, emission reduction of global shipping has come into force in the form of MARPOL Annex VI at MEPC 76, regulations 23, 25 and 28, resulting in the Energy Efficiency eXisting Ship Index (EEXI) and the Carbon Intensity Indicator (CII) for existing ships. These regulations require ship operators to calculate their fuel consumption and rank ships based on their emission efficiency. If a ship exceeds a certain efficiency level, it will be regarded as unfit for global trade, resulting in decommissioning. This affects a current global fleet of 102.899 vessels [21] with an average age of 21.9 years [21]. In order to stay operational under these regulations, ships must find innovative ways of enhancing their energy efficiency. Micro ROVs will play an important role in terms of hull inspection for marine fouling assessment, which is briefly introduced in Chapter 4.

The area of marine science has greatly benefitted from the rise of low-cost and easily deployable micro ROV systems over the past decades. Whilst the absence of scientists in offshore operations for reasons already explained results in a certain dependency on companies or data providers, researchers can conduct their own data collection in medium-depth operations of less than 300 m. The amount of contributions from operating micro and medium-sized ROV systems has risen and is likely to continue to rise as technology evolves. It is likely for micro ROVs to become even cheaper, more robust, easier to operate and equitable with more external sensor technology in the upcoming years.

As introduced in this chapter's methodology, market data on ROV systems is scarce. Although the offshore ROV market has a forerun of several decades, market data is limited and not fully publicly available. In a first quantitative attempt to evaluate the offshore and the micro ROV markets, a structured analysis of market reports of leading data providers has been conducted. Based on a web search in April 2023, global offshore ROV market data and forecast values have been collected and combined. As a result, a number of 15 market reports were clustered, of which 10 reports contain data of the intervention class and 4 reports contain inspection class data. Approaches of collecting and clustering ROV market data have not been conducted amongst the existing literature and this attempt reflects only a brief analysis based on available market data. The reports evaluated the current global ROV market values between 2021 and 2023 as well as a market forecast based on the compound annual growth rate (CAGR). Fifteen offshore ROV market report data were gathered using a web search of publicly available data. The CAGR values were calculated annually for the period 2022–2030 using the values provided. Due to the fact that the values had a high deviation between the different market predictions, the third quartile of each value was applied. This resulted in 11 reports being included in the calculation and

	Year	2022	2023	2024	2025	2026	2027	2028	2029	2030	CAGR
Intervention class	N	10	10	10	10	10	10	10	10	10	11
	Average (Mil $)	2.800	3.047	3.323	3.626	3.960	4.328	4.733	5.179	5.635	8,21
	Delta (Mil $)	752	870	1.008	1.173	1.368	1.597	1.867	2.185	2.582	2,48
Inspection class ROV	N	4	4	4	4	4	4	4	4	4	4
	Average (Mil $)	420	451	485	522	562	605	653	706	763	8,09
	Delta (Mil $)	168	170	174	177	183	190	200	212	228	3,34

Source: Author.

Table 1.
Global ROV market Forecast 2022–2030.

four reports being disregarded. One report only provided CAGR predictions without the annual value rate of the market, so it was included in the CAGR evaluation but not in the annual value calculation. After the third quartile application, the mean value of each year was calculated from the offshore ROV market data. Only four reports were found on the micro ROV market with limited value deviation so that mean values were chosen without quartile exclusion.

The market evaluation in **Table 1** indicates similar CAGR growth rates till 2030 of 8.21% for the intervention class and 8.09% for the inspection class. The total market values, however, are 5–6 times higher in the intervention class given the very large investment in hardware. The market value for micro ROVs in 2022 is stated as 420 Mill. $ (**Figure 3**). It is noted that CAGR evaluation assumes linear growth that is limited in its explanatory power albeit it underlines a prediction of a certain trend. The trend implies, that the global ROV market of both major classes will almost double by 2030, as shown in **Figures 3** and **4**, once more underlining the argumentation of the innovation potential of this hardware.

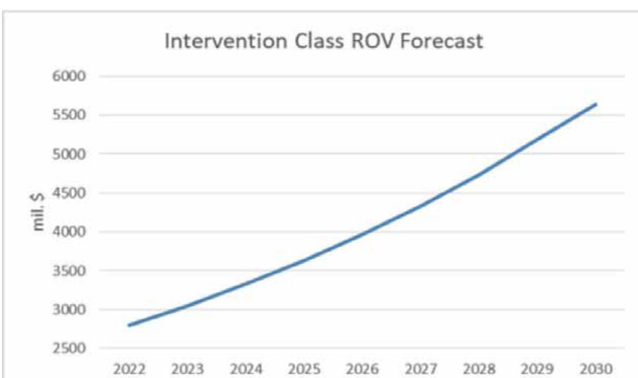

Figure 3.
Global ROV market Forecast 2022–2030. Source: Author.

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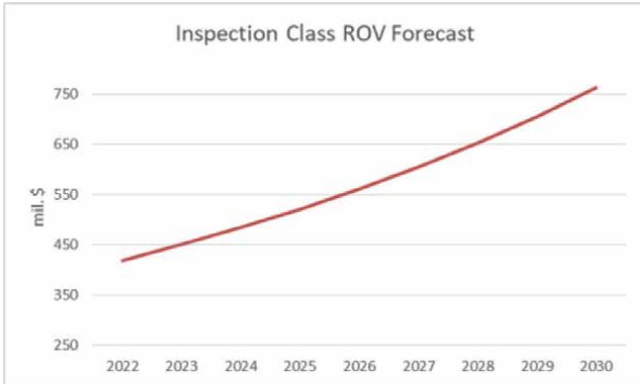

Figure 4.
Global ROV market Forecast 2022–2030. Source: Author.

3.1 Micro ROV system overview

It was reported in 2015, that 700 ROVs were in operation globally whereas over 550 were intervention class systems [21]. This number appears to be excluding the micro ROV class, leaving the existing 150 ROV systems most likely to be related to specialised equipment rather than off the shelf industrial products. A first market analysis using web search on micro ROV systems in **Figure 5** reveals a number of 22 micro ROV systems having entered the market in the past decade since 2012. These ROV systems were launched by 12 global manufacturers mostly founded within the past two decades between 2001 and 2016. In order to differentiate the evaluated systems from other ROV classes, a maximal investment cost of 25.000$ was defined as the upper threshold. Systems exceeding this limit were not regarded in this evaluation. **Figure 5** reveals micro ROV systems by their market entry as well as their costs (based on 2023 values) and their maximum operational depth rating. The SeaOtter-1 marks the turning point in 1994, being the first micro ROV of less than 25.000$. It is possible that this system was more expensive at market entry given the past monetary value, but in 2023, its market price remained around 21.000$. The SeaOtter-1 was upgraded to a

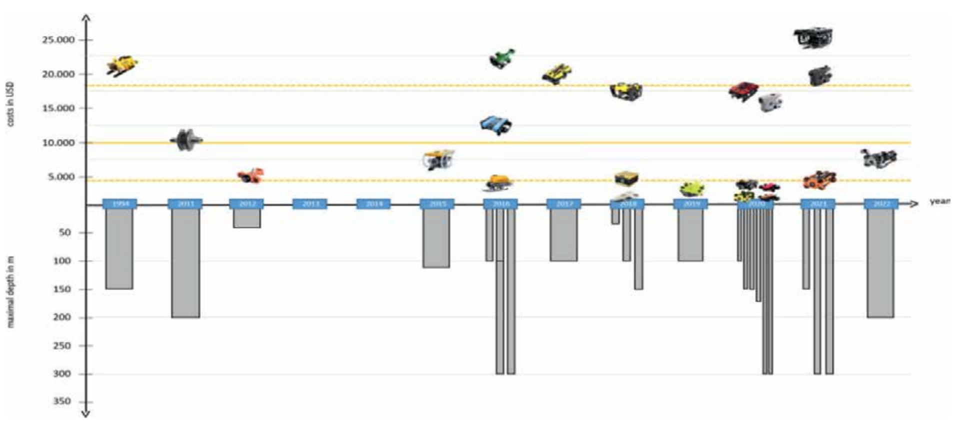

Figure 5.
Market overview of micro ROVs based on price, depth and release. Source: Author.

version 2 in 2007, almost one decade before the majority of other systems entered the market. The average age of market launch is 2017/2018, whereas the largest number of micro ROV systems entered the market in 2020.

From an investment perspective, the average cost of a micro ROV system is 10.350$, however, only the 2011 launched DTG-2, later in 2019, being upgraded to the DTG-3 system ranges at this price level based on 2023 market data. The data reveals, that two clusters within the micro ROV segment have formed, being systems above the average value of approx. 10.000$ and those below. The average price of the more expensive cluster reaches 17.900$ whereas the lower cost cluster ranges at 4.100$ on average. Although these results only provide a first, superficial character where more in-depth research is required for more valid statements, it reveals that two clusters in the micro ROV market have formed since 2011.

From an operational depth point of view, micro ROV systems on average reach a maximum diving depth of 100 m or 305 m (1.000 ft). Some individual systems offer rates in between, but no micro ROV system exceeds the 305 m (1.000 ft) level officially. It shall be mentioned, however, that the standard configuration of the ROV systems evaluated comes with less cable length than their maximum depth rating. Some ROVs such as the BlueROV2 require a different frame material replacing plastic with aluminium for larger depths. In order to reach the operative maximum of the system, the required investments exceed the standard off the shelf values displayed. Of the 12 global micro ROV manufacturers, China is the dominating country of origin with five companies as shown in **Table 2**. It was mentioned in the beginning, that micro ROV systems offer a high degree of flexibility in terms of operations. The system weight data of the ROV and all its necessary control stations, however, require a differentiated evaluation of each system according to the individual operational needs. Some systems weigh up to 37 kg, which is tough to launch in the water without winches and impossible to carry, for example, on a pilot ladder on board a ship at an anchorage. Furthermore, some systems operate on batteries whilst others require a source of electricity.

3.2 Micro ROV operations

After providing a first market overview and system survey above, it is the intention of this chapter to also highlight the different operational options of micro ROV systems that will most likely increase in application in the near future. A first systematic overview has been provided in 2017 [1], whereas **Table 2** introduces an updated version including additional operation areas and a wider spectrum of current and future ROV operations.

Although not purposefully collected for marine science reasons, offshore companies over the past decades have collected a considerable treasure of data through their ROV operation video recording. Both videos and images of industrial ROVs represent one of the most substantial visual datasets available from the oceans [22–24]. Studies have already taken into consideration historical ROV data to characterise fauna communities and reefs within oil and gas infrastructure [3, 25, 26]. This data helps understand the impact of oil and gas operations on marine wildlife and to, therefore, assess its environmental, social and economic benefits. Other contributions apply ROV systems in seafloor mapping [27], where micro ROV systems could potentially find an assisting role in the future as well. Given the depth limitations of current micro ROV systems of 305 m (1.000 ft), Deep sea ROV research operations below [24] will further require intervention class solutions.

Manufacturer	Found.	Country	ROV	start	kg	Depth	Cost
Aquabotix	2011	Australia	Hydroview	2012	16	45	5.500
Aquabotix	2011	Australia	Endura 300	2016	7	305	17–25.000
Blue Robotics	2014	USA	BlueROV2	2016	12	100–305*	10–15.000*
Blueye Robotics	2015	Norway	Blueye Pro	2020	9	305	15.000
Blueye Robotics	2015	Norway	Blueye X3	2021	9	305	20.000
CCROV	2015	China	CCROV	2018	5	100	4.500
Chasing Innovation	2016	China	M2	2020	5	100	2.700
Chasing Innovation	2016	China	M2 Pro	2021	6	150	4.000
Chasing Innovation	2016	China	M2 Max	2022	8	200	7.500
Deep Trekker Inc.	2010	Canada	Pivot	2021	16	305	25.000
Deep Trekker Inc.	2010	Canada	DTG-2 (3)	2011 (2019)	8	200	11.000
Geneinno	2013	China	T1	2020	4	150	3.000
Geneinno	2013	China	T1 Pro	2020	4	175	4.700
Gnom ROV	2001	Russia	GNOM Standard	2015	18	120	7.500
Gnom ROV	2001	Russia	GNOM Baby	2016	11	100	4.000
Gnom ROV	2001	Russia	GNOM Pro	2018	35	150	17.000
JW Fishers	1968	USA	SeaOtter-1(−2)	1994 (2007)	20	150	21.000
MarineNav Ltd.	2005	Canada	Oceanus Mini	2017	37	100	20.400
MarineNav Ltd.	2005	Canada	Oceanus Hybrid	2020	22	305	17.000
Powervision	2009	China	power Ray	2018	4	30	950
QYSEA	2016	China	Fifish V6	2019	4	100	1.500
QYSEA	2016	China	Fifish V6 Plus	2020	5	150	3.000

**variable frame material.*
Source: Author.

Table 2.
Market overview of micro ROVs.

With regard to disaster response, ROV systems have already been applied and delivered scientific insights. In 2011, following the Tokoku earthquake and tsunami disaster in Japan, micro ROV systems have been operated to inspect critical infrastructure and assist with victim identification [28, 29]. Different systems have been applied along the Sanriku coast and the Fukushima Daiichi nuclear power plant. In 2015, a micro ROV was operated on the Costa Concordia Wreck [30] for inspection and documentation purposes. ROV systems provide great value for inaccessible or dangerous environments and will likely find more application in future disaster response. Underwater archaeology already benefits from micro ROV systems for various purposes, such as diving buddy [1] documentation and surface recognition [31] and planning and supporting of underwater sites [32]. Especially for archaeological sites of a limited size, micro ROV systems offer a great benefit for a fast and mobile operation for documentation and 3D mapping. In 2023, a micro ROV type Blueye Pro was operated north of Berlin in Germany to construct 3D documentation of sunken inland shipwrecks of up to 35 m depth. Reaching these wrecks requires advanced diving skills and diving accidents have happened in the past trying to reach these wrecks. The ROV operation launched from an inflatable boat on the surface was again a very successful demonstration of micro ROV capabilities in the context of 3D mapping and underwater archaeology as displayed in **Figure 6**.

The 2022 Russia-Ukraine war has shown that military operations do not take place in remote areas but happen in the vicinity of western borders. It has been reported that sea mines were used in front of Odessa port in the Black Sea with the intention of disrupting maritime trade and preventing grain exports [33]. Retrieving these mines will be a military operation where ROV systems will most likely play an assisting role. Studies have already pointed out the possibilities of ROV-based detection of unexploded ordnance (UXO) in the past. A 2012 contribution [34] described the ROV detection capabilities of UXO in seaport operations. Recent contributions connect specialised ROV systems for electromagnetic detection [35] with UXO detection in the context of offshore site surveys [36]. Although not named specifically in the contributions, micro ROVs can provide a value-adding service of confirming suspicious detections and/or providing visual confirmation on potential UXO findings. Due to high manoeuvrability and low financial risk, small ROV systems are a valuable choice for close proximity evaluation of mines. A 2022 test in German waters confirmed the applicability of micro ROVs in very close proximity to UXOs as shown in **Figure 7**.

From a security point of view, micro ROV systems will furthermore deliver value-adding services to maritime operations. Maritime security has been defined by the

Figure 6.
Micro ROV Operation on archaeological site. Source: Author and Kaffenkahn e.V. /Kai Dietterle und Uwe Klimek.

Figure 7.
Visual UXO detection examples of a micro ROV. Source: Author.

International Ship and Port Facility Security (ISPS) Code since 2002 as part of the Safety of Live at Seas (SOLAS) convention. Drones in general have been evaluated towards their potential for ISPS assistance from an operational point of view [37]. It is shown that ROV operations can assist all 3 major ISPS operation categories of monitoring, inspecting and management, either assisting human operations or replacing them with a full remote operation [37].

Industrial inspection of infrastructure reflects the largest operational area for micro ROV systems as highlighted in **Table 3**. A growing number of inspections and tests has led to an increased number of publications and is likely to further contribute to future studies. Amongst the most important areas of inspection in line with the sustainable development goals (SDG) in **Figure 2** lies the inspection of ship hulls for emission reduction. Marine fouling is defined as algae, pocks, mussels and barnacles that attach to the ship's hull when the vessel is not moving. This fouling increases the drag of the vessel, causing fuel consumption to rise in order to maintain a certain speed. First contributions quantify this excess fuel consumption to range from 6.5 to 17.6% [38]. The aspect of ROV-based ship hull inspection was first introduced by [39] in 1983 using a magnetic vehicle attached to the hull. These systems, however, only operate on relatively clean surfaces, whereas under heavy marine fouling conditions the magnetic wheels cannot attach to the hull. Diving ROV systems have later been tested and found more suitable for these operations, with the first study dating back to 1999 [40]. Diving micro ROV systems allow for a quick inspection of the ship's hull given their good manoeuvrability and, as shown in **Figure 5**, both investment costs and operational depth are uniformly favourable for ship inspections of less than 20 m depth.

As already mentioned, micro ROV systems allow for a new way of gathering important data for various maritime operations displayed in **Table 3**. Making good use of this data follows four main steps revealed in **Figure 8**; being the acquisition of the data, the storage, as well as visualisation and data transformation. Data storage is commonly done by databases either provided by a stakeholder (e.g. a port, a ship operator, a research facility) or via cloud storage on the web, depending on the individual requirements for

Marine Science	**Disaster Response**	**Underwater Archaeology**	**Military Operations**	**Security**	**Industrial Inspection**	
					Offshore	**Nearshore**
Oceanography	Oil spill detection	Retrieving of artefacts	UXO identification	Contraband detection	Wind farm inspection	Port inspection
Reef research	Maritime accidents	Documentation	Surveillance		Pipeline inspection	Ship inspection
Water quality assessment	Search & rescue	Dive buddy			oil Platform inspection	Bridge inspection
Wildlife research	Ghost net detection					Tank inspection
						Aquaculture inspection
						Hazardous environment inspection

Source: Author.

Table 3.
Micro ROV Operation Framework Source: Author based on [1].

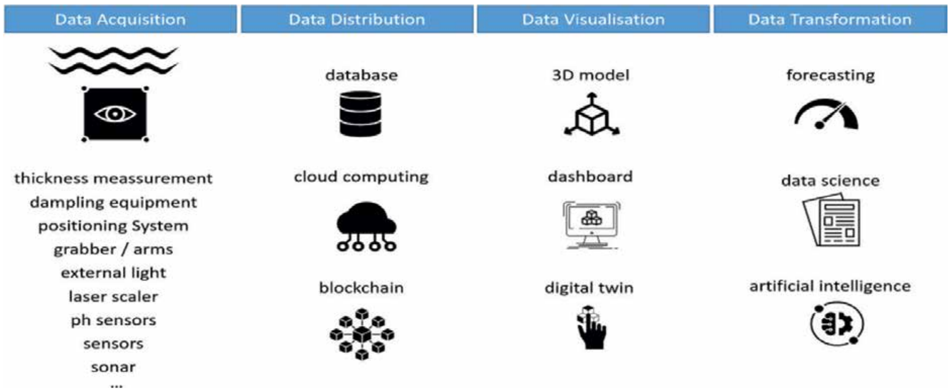

Figure 8.
ROV-based data management steps and its applications. Source: Author.

data accessibility and security. To further enhance data security accompanied with ROV footage, first studies discuss the use of blockchain technology [41] for secure communication within ROV networks. This aspect will likely gain future importance with regard to AUV swarm operations and requires further research towards its applicability in the ROV domain. The visualisation of data is a current topic of interest in the industry and its stakeholder. A classical method of drone data visualisation lies in 3D models based on photogrammetry where points in different photos of the same infrastructure are connected to a point cloud and later a photo realistic 3D model. The use of unmanned aerial vehicles for 3D modelling in port operations has already been introduced [42] whilst 3D modelling of underwater infrastructure is currently growing in importance. 3D models of infrastructure do allow for a three-dimensional spectating of the infrastructure but the model itself remains static with no data integration possible. Data can be aligned to a 3D model using a dashboard structure, where both the 3D model and the data are displayed separately. Another more modern approach with growing industry and academic interest is the combination of a 3D model and data streams into a digital twin as a combination of a 3D infrastructure directly connected to its data sources. First contributions already state that "The combination of computer simulation with techniques to 'sense the environment' and comprehend large amounts of data via Big Data Analytics and Machine Learning are fuelling new Cyber-Physical Systems (CPS) and smart applications in society and industry" [43]. The final step is data transformation, where the collected and visualised data is used to gain new knowledge. This can be achieved via forecasting or more advanced statistical analysis that, for reasons of simplicity, is combined under the more broad term "data science". Furthermore, the transformation step allows for the training of artificial intelligence, as will be introduced in Chapter 4.

4. Introducing AI in micro ROV operations

Artificial intelligence (AI) as part of general algorithms is a topic of modern computer science with a huge interest. Since the acquisition of ChatGPT in 2023 [44] AI has been widely discussed in the media, ranging from value-adding solutions to dystopic science fiction. The example of ChatGPT shows how natural language processing (NLP) can reach human-like logic, also referred to as intelligence. NLP, however, is only one aspect of AI, whereas another aspect of neural networks or deep learning offers far more applicable scenarios for underwater drones, hence becoming "a big research topic" [45] with the emergence of underwater vehicles solving the problem of how to collect underwater images [46]. It is mainly due to the improvements in computing power that neural networks can be integrated into operative tasks. Powerful modern computer languages such as Python and Tensorflow with their fast number of libraries and powerful deep models [47] further boost developments in this area. Getting high quality data for network training was also a challenging task for a long time [48] with already introduced dependencies of researchers on companies or data providers [3] that also change with the rise of micro ROV systems. A remaining challenge lies in the labelling of the data, which to this point requires detailed, manual and time-consuming labour. Labelling steps often need to be duplicated hundreds or thousands of times to build a robust deep network [48]. The absence of existing deep networks for underwater applications defines a current gap in research that needs to be overcome by studies [47]. These projects are further confronted with the fact that underwater visual content is entirely different because of the domain specific object categories, background patterns and optical distortion artefacts [47] hence, making applications of well-known terrestrial data-based neural network approaches models inapplicable [47]. It is furthermore stated that, based on the absence of underwater NN literature, existing networks are often limited to only performing simple tasks but not being suitable for multi-object semantic segmentation [47].

The underlying objective of semantic segmentation is to classify each pixel of an image with regard to its classified category to, finally, predicting a result map containing "semantic" information [46]. The segmentation basically separates the source into individual and non-overlapping portions for computer-based image analysis and understanding [49]. The challenge underwater, however, lies in the changing light conditions, the existence of blur and the absence of clear foreground and background characteristics, causing underwater image segmentation to lag behind land-based methods [49]. Whilst initial contributions focus on fish or other distinguishable underwater patterns, more advanced currently ongoing studies experiment with marine fouling recognition with fuzzy structures as shown in **Figure 9**.

By operating an encoder-decoder model with custom architecture, marine fouling on ship hulls can be identified under the above-mentioned challenging underwater conditions in various examples of complexity. Applying a custom deep neural network to underwater imagery can be an effective way to identify different classes of biofouling on ship hulls. By training the neural network on a dataset of labelled images of biofouling, the system can learn to recognise and classify various types of

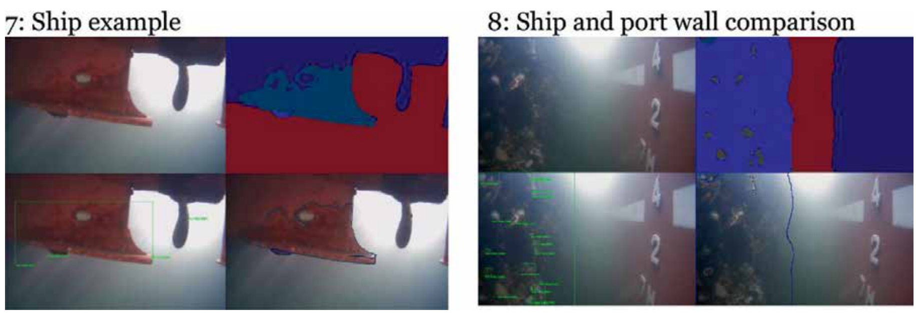

Figure 9.
Underwater AI examples of fouling detection. Top left original; top right output; bottom left and right operation examples. Source: Author.

marine organisms and other debris that accumulate on the hull. This can help ship owners and operators to better understand the extent and type of biofouling on their vessels, which in turn can inform decisions about hull cleaning and maintenance schedules. Additionally, using automated image analysis can be more efficient and accurate than manual inspection methods, making it a valuable tool for marine industry professionals to only name one example of AI and ROV combinations.

5. Conclusion

The rise of micro ROV systems in the past decade has opened a potential game-changing scenario for marine science and entrepreneurship. Since the 1970s ROV systems have been huge, complex and expensive systems only accessible to a few companies, mainly in the oil and gas industry. Comparable to the advent of personal computers in every household, the micro ROV class opens the area of underwater inspection and data collection to the open markets in a fast, easy to operate and relatively cheap manner. Whilst both the use of this new technology in academia and the industry has risen, there is still a considerable research gap existing today.

This chapter introduces the micro ROV class both from an academic and a business perspective by introducing initial market data, a comprehensive literature analysis and a structured framework analysis as basis for future research. The author introduces four main areas of rising ROV growth trends based on the sustainable development goals of the maritime industry, which are the global energy transition, global seafood production and emission reduction in shipping and marine science in general. Based on existing literature, the ROV operations framework of micro ROV systems is differentiated into 6 main categories: marine science, disaster response, underwater archaeology, military operations, security operations and infrastructure inspection. As rising drone hardware and its operation will inevitably generate data, 4 ROV data management steps are introduced. The most advanced step of data transfer, in the eyes of the author, lies in the application of artificial intelligence in combination with ROV hardware. This means in detail the use of ROV-generated data for deep learning approaches of training neural networks for automated image recognition. This relatively new concept for underwater data is briefly introduced.

This contribution adds value to the existing literature in shedding light on the literature gap of micro ROV hardware research in general and especially in combination with artificial intelligence operations. Further applied research including the use of micro ROV systems is required to better draw conclusions on the introduced potential of this emerging technology.

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Chapter 6

Unmanned Ground Vehicle as a Docking Element of a Ground-Aerial Robotic System

Denis Kotarski, Tomislav Šančić, Martin De Bona and Petar Piljek

Abstract

Using semiautonomous and autonomous vehicles to perform various missions can lead to increased safety and efficiency. With all risks and limitations included, great potential exists in the integration of unmanned aerial and ground vehicles into heterogeneous robotic systems. Considering the great advances that have been made in terms of path planning, localization, control, coordinated motion, cooperative exploration, and others, such heterogeneous systems are suitable for a very wide range of tasks. In this research, the architecture that includes the ground robot as a base and the aerial robot as an extension to 3D space is examined. Such an architecture is scalable, it can be used for a wide range of missions from data collection to smart spraying. The ground robot system has been prototyped with a tracked differential drive configuration. Preliminary tests will serve as guidelines for further steps in the system development.

Keywords: unmanned aerial vehicle, unmanned ground vehicle, prototype, heterogeneous robotic system, battery replacement mechanism

1. Introduction

The applications of mobile robots are diverse and continue to expand as technologies advance. From inspecting infrastructure to delivering goods, these robots are making a significant contribution to various industries, improving efficiency and safety while reducing costs. With the development of robotic technologies and artificial intelligence (AI), the potential for mobile robots is huge and we can expect more advanced and specialized robots in the near future. Mobile robots come in different types, including aerial [1], ground [2], and maritime robots [3], each with specific capabilities and applications. Maritime robots, including autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), are used for scientific research and to perform tasks such as ocean exploration, search and rescue, and underwater inspections. On the other hand, unmanned ground vehicles (UGVs) can navigate various surfaces and terrains and are suitable for applications such as delivery, inspection, and security. UGVs come in different configurations that are suitable for different types of terrain and tasks. For applications that require the robot to move over uneven and rough terrain, several configurations should be considered, with wheels [4] or tracks [5]. Aerial robots, also known as unmanned aerial vehicles (UAVs), can navigate the air and perform tasks such as aerial mapping [6], surveillance [7], and infrastructure inspection [8]. Aerial robots have been increasingly explored in recent years due to their versatility and ability to access hard-to-reach areas.

Multirotor UAVs have a number of positive features that make them a valuable tool in a variety of industries. One of the key advantages of this type of aircraft is the ability to vertically take off and land (VTOL), the possibility of stationary flight, but also their agility and maneuverability, and additionally, the ability to perform complex maneuvers. It can be said that due to the performance of the propulsion system, multirotor UAVs are very versatile and provide a unique perspective and access to areas that would otherwise be difficult or impossible to reach. They can be equipped with various sensors, cameras, and other equipment to perform a wide range of tasks. In addition, they are relatively easy to operate and require minimal training, making them available to a wide range of users. Multirotor UAVs are also cost-effective compared to traditional methods because they can perform tasks in a fraction of the time and at a fraction of the cost of manned aircraft or ground-based methods. Furthermore, electric UAVs are environmentally friendly. Their ability to perform tasks quickly and efficiently also reduces time spent on site, reducing disruption to the surrounding area. Overall, the positive properties of multirotor UAVs make them a valuable tool in a variety of cases. There is great potential for the use of aerial robots in various sectors such as inspection, agriculture, transport, and others. Numerous studies have been conducted on this topic and numerous concepts have been tested, such as in papers [9–16].

Nevertheless, the high energy consumption required for multirotor motion in 3D space could result in the need for frequent battery replacement or charging, so extending the autonomy was considered. Heterogeneous robotic systems refer to the combination of different types of robots that work together to achieve a common goal. Such systems are very flexible and adaptable, which allows them to perform a wide range of tasks. In the context of ground-aerial systems, this means using aerial robots along with ground robots to perform specific tasks. Aerial-ground robotic systems offer several advantages, such as improved efficiency and increased range. For example, an aerial robot can use its ability to fly to conduct basic research such as crop monitoring, irrigation, and pest control related to the agricultural sector or to inspect turbine blades related to energy infrastructure maintenance. The combination of land and air enables the efficient execution of missions, reducing the need for human intervention and increasing safety. Overall, the use of aerial-ground robotic systems for missions involving repetitive tasks offers several advantages and is a promising approach for various industries. As technology continues to develop, we can expect more sophisticated and specialized systems that can perform increasingly complex tasks. For this purpose, heterogeneous robotic systems have been investigated in different fields and disciplines [17–21].

In this paper, a ground-aerial heterogeneous robotic system consisting of a UGV and a multirotor UAV is considered, where the UGV robot serves as a base station for a multirotor UAV. Such a system is scalable considering small systems that can be used for wind farm inspections or large ones that can be used in smart agriculture for, for example, smart spraying tasks. From the aspect of system development, the concept of a UGV platform that can move on uneven terrain is being considered, which consists of a landing module that enables precise take-off and landing of UAV, charging, and battery replacement. From the aspect of designing the drive module of the UGV platform, in addition to wheeled robots that can move on a wide range of terrain, from smooth surfaces to rough terrain, another configuration is a tracked robot, which is designed to move on more challenging terrains, such as rocky terrain. Tracked robots use tracks instead of wheels, which allows for better traction and stability, making them ideal for applications such as outdoor inspection and agriculture. Prototyping, assembly, and preliminary testing of the drive module of the UGV platform were carried out. In further work, the integration of the multirotor UAV and the UGV platform is planned.

2. UAV docking stations: literature review

In general, a docking station for UAVs is a multipurpose system that enables them to safely land, take off, charge, and/or replace batteries and transfers data and payload. Some docking stations, usually fixed, can even store UAVs, thus protecting them from adverse environmental conditions, such as rain or snow. The above should be autonomous in order to reduce the need for operator intervention. Therefore, docking stations for UAVs enable longer operating time for the aircraft. Docking stations can be classified according to [22]:

- mobility (mobile and fixed),
- battery charging method,
- automatic battery replacement (swap),
- storage of UAVs (yes/no),
- delivery of packages or cargo for dispersal (refilling),
- positioning (active and passive),
- type of landing (precision, visual, etc.),
- type of landing platform.

The docking station consists of multiple subsystems such as a landing platform, precision positioning mechanism, electronics, power supply, visual aid for landing, battery charging system, battery replacement system, UAV storage system, object storage system, and others. UAV docking stations must meet certain criteria to fulfill their objectives. Given that the paper considers a ground-aerial robot system, **Figure 1** shows the classification of docking stations based on mobility [22].

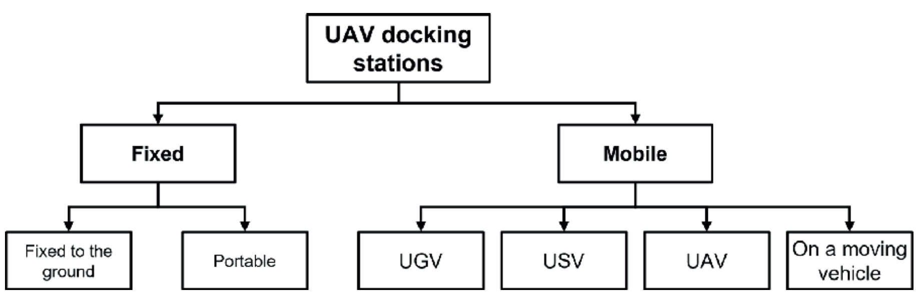

Figure 1.
UAV docking stations classification [22].

The landing system consists of a method of guiding the UAV that should ensure precise landing and final locking of the aerial vehicle at the intended location. Precise positioning during the landing phase is essential for a precise landing. The landing task consists of several different phases. The first phase is the access phase. Usually, systems using the global navigation satellite system (GNSS) are sufficient to access docking stations. Before touchdown, the next stage is the precise positioning of the UAV, which is crucial for a successful landing with minimal error. Touchdown is the final stage of landing. UGVs that have mounted landing systems have been presented in numerous works [23–25]. Mobile docking stations require different software solutions to precisely land the UAV on the mobile robot (UGV). The main requirement is robustness, which means the ability to land in the presence of various disturbances [26–28].

3. Ground-aerial system architecture

A heterogeneous ground-aerial system consisting of one UGV and one UAV can perform various tasks such as surveillance, reconnaissance, mapping, and inspection. The architecture of the system depends on the equipment of the system with sensors, cameras, and other devices for collecting data and performing missions. The UAV serves as the aerial component of a heterogeneous system, providing a bird's-eye view of the area and collecting high-resolution images or video, as well as performing more complex missions. One of the features of the system is the ability to capture data from the air and send it to the UGV or base station for further processing. A UAV can also be used for planning tasks, such as identifying areas of interest or mapping the environment. The UGV serves as the ground component of the system, providing mobility and ground-level access for further data collection and

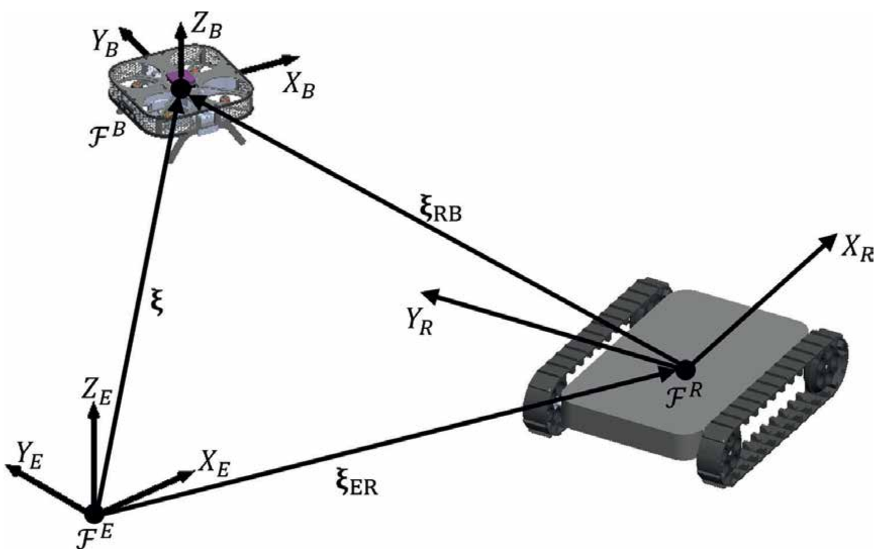

Figure 2.
Ground-aerial system reference coordinates systems.

mission execution. It is responsible for ground navigation using built-in sensors and cameras. UGVs can also be used to transport cargo, such as equipment or samples, to different locations. Furthermore, the paper considers a UGV that can be equipped with a battery replacement (swap) module. In general, UGVs and UAVs can be linked by wireless communication, enabling real-time data exchange and task coordination. The base station serves as the central hub of the system, providing the operator with the necessary tools and interfaces for control, mission planning, and data visualization. **Figure 2** shows the reference coordinate systems of considered ground-aerial systems.

3.1 Multirotor UAV

Given the complexity of the multirotor UAV, which is characterized as an inherently unstable, highly nonlinear, and multivariable system, it is necessary to pay special attention to the control aspect when performing simulations and experiments. These properties make multirotor UAVs challenging to control and require sophisticated algorithms and sensors to achieve stable flight. A key step in system design is the selection of control subsystem (module) components. The Cube flight controller (FC) with sensors and associated components make up the aircraft control module. For outdoor missions, the GNSS is being considered, and from the aspect of remote control, long-range R/C link with two-way communication. With the considered system, regarding the mission, we can single out two key tasks that the multirotor UAV performs during each mission. This is the take-off from the platform and the second, even more, sophisticated task, which is the precision landing of the UAV. For this purpose, the IR-LOCK sensor with associated components is considered. By choosing components based on Cube FC, it is possible to use the experimental PX4 ecosystem in combination with the MATLAB Simulink software package. This enables simple integration of simulations and experiments. **Figure 3a** shows a schematic quadrotor UAV mini platform that can belong to the category of so-called micro aerial vehicles (MAVs). **Figure 3b** shows the image transmitted in real-time from the onboard camera of the experimental quadrotor, where an example of a billboard inspection was tested.

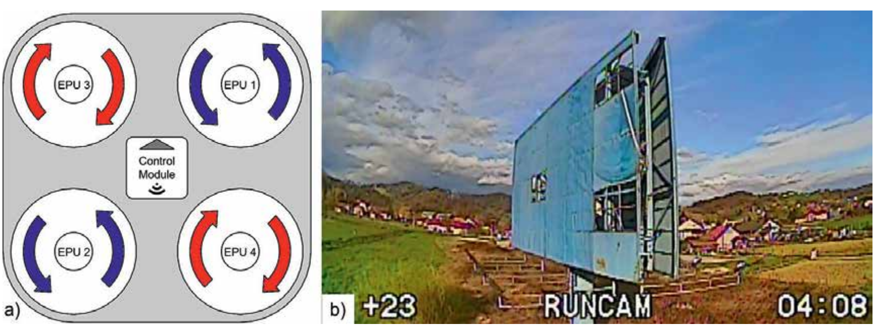

Figure 3.
Quadrotor MAV: (a) quadrotor schematic; (b) on-board camera during quadrotor testing.

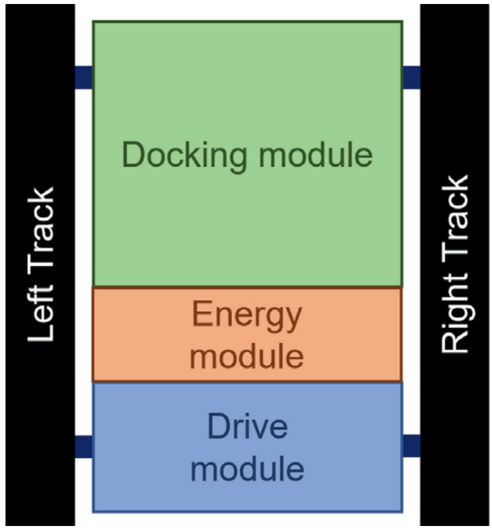

Figure 4.
UGV overall topology.

3.2 UGV outdoor platform

A typical differential drive configuration consists of two electric actuators that independently move the tracks using drive elements. By changing the speed and direction of each motor, the robot can move forward, backward, turn left or right, and even rotate around its axis. This type of UGV platform is widely used in applications where better traction, easier handling, and greater stability on uneven terrain are required. Additionally, robots with a differential drive configuration are more affordable and easier to maintain compared to other drive types. During the initial phase of the development of the UGV platform, the primary goal is to ensure the scalability of the platform, while also aiming for reconfigurability. From the design aspect, the focus is on a simple integration of the basic modules of the UGV platform with the docking module, which will be equipped with a battery replacement (swap) mechanism. **Figure 4** shows the topology of the UGV platform with tracks.

4. UGV platform prototype development and testing

Designing, prototyping, and testing of a UGV platform requires a multidisciplinary approach and a rigorous process to ensure that the final product meets the intended requirements and performs effectively. In this paper, this approach is divided into three main phases, the design phase, the prototyping phase, and the platform testing phase. In the design phase, a software package will be used for 3D modeling of the platform parts that make up the system assembly. In the prototyping phase of the parts, additive manufacturing (AM) technologies will be considered, whereby the so-called slicer tools will be used. Finally, in the third phase, a MATLAB Simulink software package will be used for simulations and experimental testing.

4.1 UGV platform design phase

Designing the UGV platform includes defining specifications and requirements, identifying necessary components and subsystems, and creating a conceptual model. Throughout the process, the design of the UGV must take into account factors such as terrain, payload, speed, and communication capabilities to ensure optimal performance. In this paper, the UGV platform is considered through four main modules, the control module, the drive module, the energy module, and the docking module. Furthermore, the design phase of the drive module of the UGV platform will be presented, and the concept of the docking module will be discussed. The UGV platform comprises a welded steel profile chassis frame onto which the UGV drive module is mounted, comprising various drive components and parts. The design of the drive module's parts that are intended to be produced using AM technologies has been finalized. Considering the loads to which the chassis and drive elements are exposed, the design of the drive module is a challenging problem.

The drive module consists of a pair of molded tracks from the manufacturer Super Droid Robots that are driven by the drive wheels and rotate freely at the opposite end of the chassis using the auxiliary (free) wheels. The freewheel is mounted *via* a wheel-shaft adapter part on a shaft with a diameter of 12 mm, as shown in **Figure 5**. The shaft bearings are connected to the chassis via frame parts and allow the track to be tensioned independently. On the other side, the drive wheel is mounted via a wheel-shaft adapter on a shaft driven with a DC motor and transmission. Prior to the design of the module, a pair of IG52-04 24VDC 285 RPM gear DC motors driven by a Sabertooth dual 25A motor driver was selected.

The motor's torque is transmitted through a chain drive (transmission) to the track's drive wheel via a sprocket with 15 teeth on the motor shaft, a roller chain (ANSI #25), and a sprocket with 25 teeth on the drive shaft. The drive shaft is connected to the chassis through bearings via frame parts, which also connect to the mount for the DC motors. In addition, in the next step, the roller for maintaining track tension and other auxiliary elements of the chassis will be integrated.

The drive module is connected to the energy and control module through a motor driver. The motor driver control circuit is linked to a control module of the UGV platform, whereas the driver's energy circuit is connected to the LiPo battery. The battery

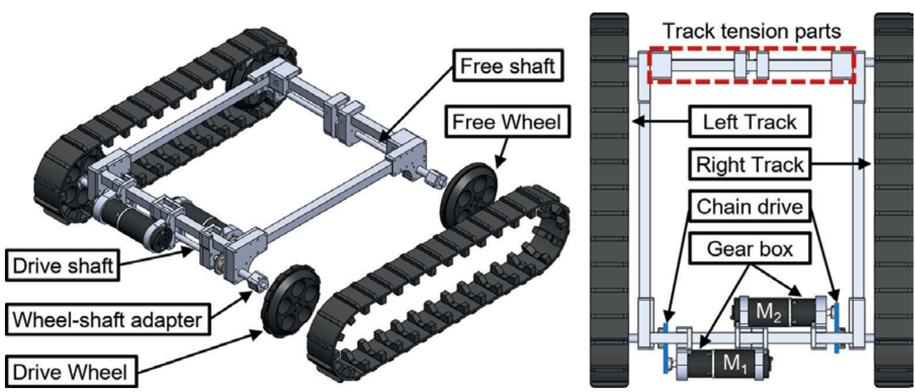

Figure 5.
UGV platform drive module assembly.

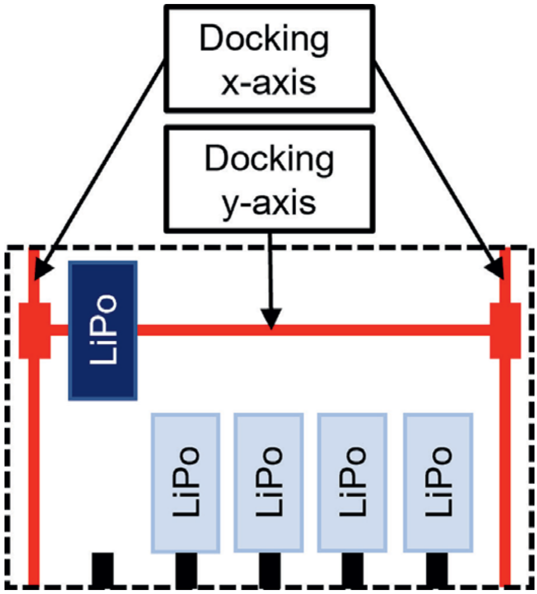

Figure 6.
Schematic representation of the concept of the mechanism for swapping batteries in the x-y plane.

is the central part of the energy module and considering the selected components of the UGV platform propulsion module, and the considered sizes of the multirotor UAVs, a 6-cell LiPo battery/s will be further discussed. The docking module is connected to the energy module via the electronic circuit for charging the batteries. In order to increase the simplicity, the concept of a docking module comprises a translational 3 axes mechanism. The docking mechanism is responsible for three main tasks: removing batteries from the UAV, guiding them to the charging station, and attaching them to the charger connector. To reverse the process, the mechanism retrieves the battery from the charging station, guides it to the UAV, and connects it to the UAV. The axes of the mechanism run parallel to those of the UGV platform. It is crucial to carefully consider the design of the x-axis mechanism as the battery is pulled and pushed along this axis, as shown in **Figure 6**, where the x-y plane of the docking mechanism is shown schematically.

4.2 UGV platform prototyping phase

The process of prototyping allows for the testing of the UGV in a simulated environment, which allows for adjustments and modifications to be made before the final product is built. In this research, two types of technologies were utilized to produce parts. The first involved using a 3-axis CNC router with a milling motor to produce parts from carbon sheet materials of various thicknesses. The second category is AM technologies, which varied depending on whether the part would be subjected to mechanical loads or not. For parts that are not mechanically loaded or are subjected to minimal loads, fused deposition modeling (FDM) technology was used, and the parts were printed using the low-cost Prusa i3 MK3 FDM printer. On the other hand, continuous fiber fabrication (CFF) technology was employed for the production of parts that would be subjected to mechanical loads. The parts were

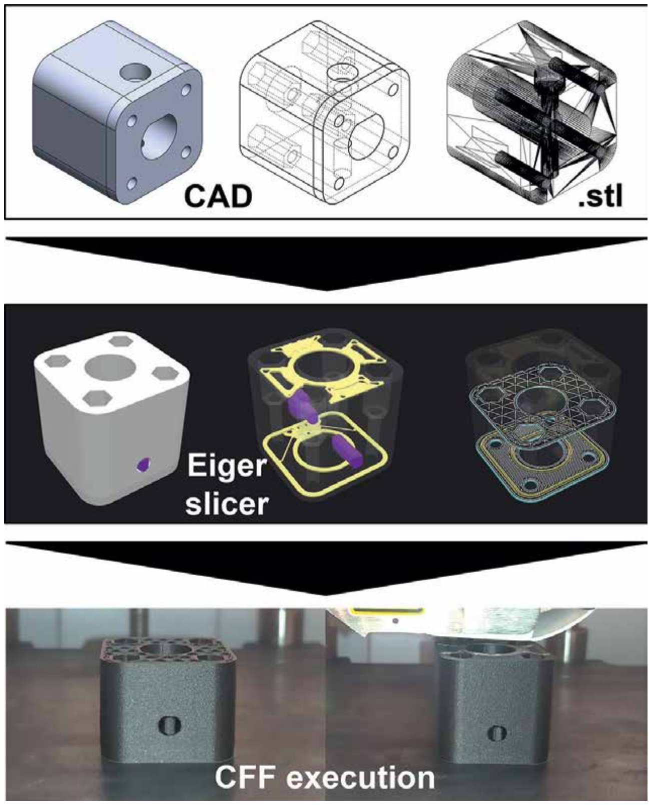

Figure 7.
Additive manufacturing main steps for prototyping parts.

made using a Markforged Onyx Pro 3D printer applying a micro carbon fiber-filled nylon matrix material and fiberglass reinforcement material. During the prototyping phase, software tools known as slicers are used, depending on the used AM technology. The slicers read the generated stl file of one or more parts, and this step is crucial as it allows for the adjustment of the 3D print parameters, as shown in **Figure 7**. Once the adjustments are made, the g-code is generated, which is then executed on the 3D printing hardware. After the printing process is complete, some parts may require post-processing.

4.3 UGV platform testing phase

As the UGV platform consists of modules, it is possible to conduct separate tests on each module. This expedites the development process and enables the distribution of part production. Once the frame components were manufactured, the individual modules of the platform were assembled and tested. The initial tests were conducted on the drive elements and track components of the drive module. The track was tensioned, and the rotation of the track, driven by the drive wheel, was evaluated. Next, a pair of motors and drive elements were installed, and a preliminary test of the drive configuration was performed. As the UGV platform is intended to operate in demanding terrains, **Figure 8** depicts a test of the UGV platform as it crosses an obstacle.

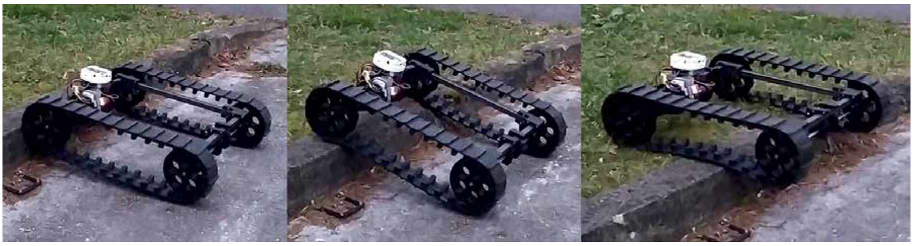

Figure 8.
Testing the UGV platform in case of crossing an obstacle.

5. Conclusion

This study aimed to explore the potential of using a UGV as a docking element in a ground-aerial robotic system. The literature review conducted on UAV docking stations gives insights into the existing technology and research in the field. The proposed ground-aerial system architecture, comprising a multirotor UAV and an outdoor UGV platform, was developed and discussed. The UGV platform prototype was developed in three phases: design, prototyping, and testing. Through this process, the UGV platform demonstrated a high level of adaptability and reliability in outdoor terrains, making it an ideal solution for a range of applications including agriculture, inspection, and search and rescue.

Acknowledgements

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Appendices and nomenclature

3D	three dimensional
AI	artificial intelligence
AUV	autonomous underwater vehicle
ROV	remotely operated vehicle
UGV	unmanned ground vehicle
UAV	unmanned aerial vehicle
VTOL	vertically take off and land
FC	flight controller
GNSS	global navigation satellite system
R/C	remote control
MAV	micro aerial vehicle
AM	additive manufacturing
LiPo	lithium-polymer
FDM	fused deposition modeling
CFF	continuous fiber fabrication

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Section 4

Challenges and Perspectives

Chapter 7

Sharing the Road: Challenges and Strategies

Ayesha Iqbal

Abstract

The idea of autonomous cars has been around for decades, but the recent advancements in automation, robotics and communication technology have given sharp rise to the prospect of self-driving/autonomous vehicles technology. With the recent acceleration in research and development in this field, the dream is now turning into reality and soon autonomous vehicles (AVs) and human-driven vehicles (HVs) will be sharing the road. This chapter presents an insight into the possible challenges and hurdles that need to be addressed in order to make this co-existence possible. Considering all possible scenarios and circumstances is crucial to develop the right technology and infrastructure for future transportation systems. The chapter further discusses the strategies and solutions suggested and developed to overcome these challenges.

Keywords: artificial intelligence, autonomous vehicles, levels of vehicle automation, vehicle navigation, cybersecurity, sensors

1. Introduction

With the recent advancements in vehicle technology, the idea of driverless cars, which was once a dream, seems to be turning into reality, and several companies have started to invest into self-driving cars, and trials are already in progress by some well-known companies. This large-scale research, development, investment, and trials suggest that time is not far when autonomous cars and human-driven cars will be sharing the road. As much as the idea sounds fascinating, it brings about several challenges and considerations, such as safety, regulation, dealing with traffic flows and congestion, to mention a few. This chapter aims to the challenges and barriers in large-scale adaption of AVs. The chapter is organized as follows: Sub-Section 1.1 elaborates the classification of vehicle automation which is important to understand the development of autonomous vehicles on different levels. Section 2 mentions the challenges and considerations that need to be addressed while adapting AVs on a large-scale and allowing them to share road with HVs. Section 3 describes some of the strategies and possible solutions suggested in order to overcome these challenges. Finally, Section 4 concludes the chapter.

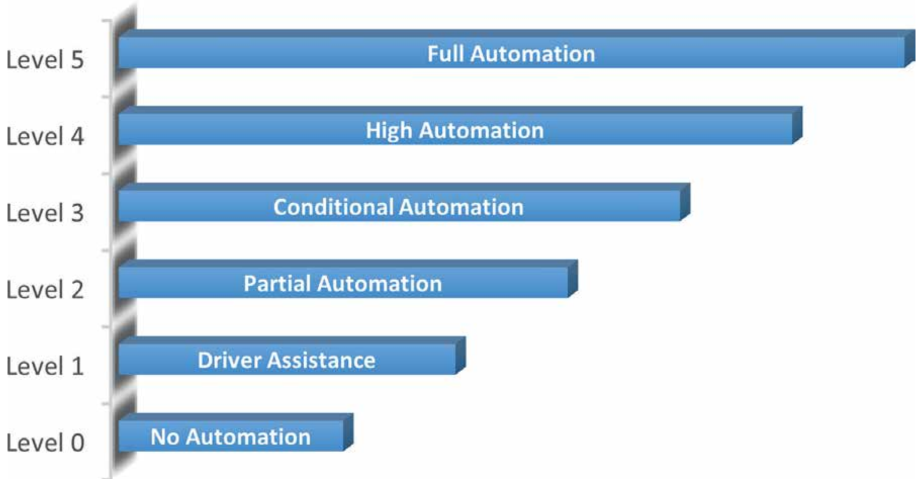

Figure 1.
Levels of vehicle automation (source: Created by author).

1.1 Levels of vehicle automation

Depending upon the level of involvement of human in the driving process of vehicle, levels of autonomy are defined for autonomous vehicles, elaborated in **Figure 1**. The lowest level, Level 0, represents no automation thus all tasks are performed by the driver. Next level, Level 1, has some driver assistance available, e.g., Automatic Braking or Electronic Stability Program. Level 2 is the partial automation level, where some combined automated features are present, i.e., lane-keeping, and adaptive cruise control.

The driver still has to be involved in driving and must monitor the environment. Next level, Level 3, is conditional automation level where driver can stop controlling some of the important functions of the car in certain conditions but must always remain ready to take control of the vehicle without any advance notice. Level 4 is a high automation level where the vehicle can fully execute all driving functions. Level 5 is the full automation level where the vehicle can perform all the functions involved in driving under all conditions and circumstances.

2. Challenges and barriers

As mentioned earlier, research and technology advancements in the field of autonomous vehicles have led to the well-known companies racing to develop and trial self-driving cars, and eagerly competing to bring their AVs up and running on the road. No doubt the idea of self-driving car seems fascinating, and this technology also promises to completely revolutionize the future transport by improving road safety and better connecting the communities. While earlier this year, Mercedes became the first officially certified Level 3 autonomy (conditionally automated) car company in the US [1], recent developments in UK suggest its roads could see fully autonomous vehicles rolled out by 2025 [2]. With all these recent developments, it seems that time is not far when we will be seeing AVs on the roads [3–5], yet there are still several concerns and challenges that need to be accounted for. Researchers have widely discussed possible barriers and challenges in literature [6–12] and are also working towards the strategies to counter them. Some of the most prominent challenges are listed below:

2.1 Safety and reliability

As soon as we think of a self-driving car, the first concern that comes to our minds is safety and reliability. Despite all the progress, development and excitement, safety and reliability still remain the biggest challenges when it comes to self-driving cars, especially the fully autonomous ones.

According to Mcity ABC Test, presented by University of Michigan, testing the safety of autonomous cars includes three main components: Accelerated evaluation, Behavior competence, and Corner cases [13]. **Figure 2** demonstrates the components and sub-components of the ABC Test. As shown in the figure, accelerated evaluation focuses on lane change, car following, and left turns. Behavior competence is about testing the performance in rigorous scenarios, such as, weather and lighting conditions. Finally, corner cases include those cases that are on extremities of the test conditions. For example, zig-zag motion of joggers on the street and detection of dark-colored cars in dark surroundings [13].

2.2 Testing and validation

A comprehensive and rigorous testing and validation process is required to be established before letting the AVs on the roads. Bringing a driverless car on the road is not only about driving and controlling the vehicle, but also about decision-making, and that too in all possible circumstances. It involves many factors, such as, the number of miles the car is driven during test, the interaction with real traffic that includes decision-making as well, and special circumstances i.e., congestion, traffic flow, weather, lighting conditions and other scenarios mentioned in 3.1. Without considering all these factors, an AV, especially an L4/L5 AV cannot be fully validated [14]. For reliable testing and validation, ground truth data must be used. Test tracks are usually designed to create and re-create critical scenarios in a controlled environment. The disadvantage, however, is that only a limited variety of scenarios can be tested in a short period of time, lacking the exact vehicle and traffic dynamics and possible congestions.

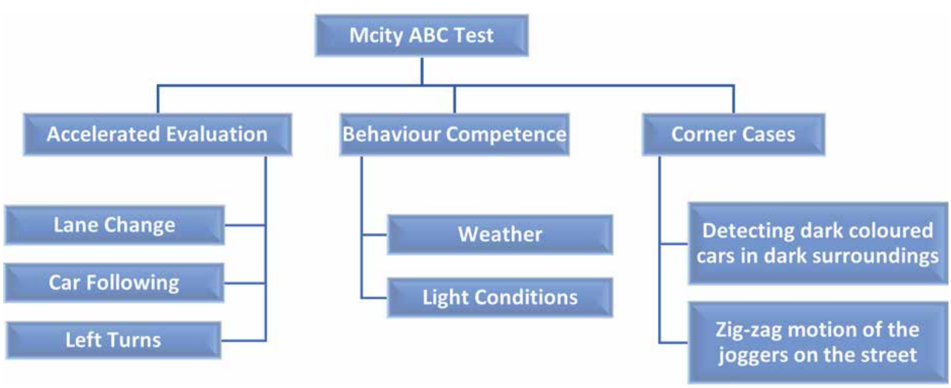

Figure 2.
Mcity ABC test components (source: Created by author).

2.3 Traffic congestion and unexpected encounters

Another important challenge for autonomous vehicles is encountering traffic congestion and other unexpected circumstances e.g., a traffic warden guiding the traffic to pass through a red light [15]. Although, by using Advanced Traffic Management Systems (ATMS), on-street traffic data can be collected and used to predict traffic flows and patterns [16], but still the possibility of unexpected traffic flows and congestion can almost never be eliminated. In addition to traffic flow prediction, autonomous car should be able to take adaptive decisions according to the surroundings objects and conditions. Similarly, driving an autonomous car in tunnels or on mountains, on bridges or intersections, can be challenging.

2.4 Technology and infrastructure

Most of the AVs will be relying on Artificial Intelligence (AI) and Machine Learning to process the data obtained from the sensors and to help in decision-making. These algorithms are going to detect objects, classify them, and take actions accordingly, e.g., buildings, other vehicles, traffic signals, road signs, streetlights, and pedestrians. AI is undoubtedly taking over the world in autonomous vehicle technology as well as in other disciplines of life, there is still a long way to go. AI cannot understand real-world scenarios, for instance, if the AV sees a plastic bag flying in front of the car or if it senses a flock of birds sitting on the road, it will stop unnecessarily. Unlike human drivers, AI cannot understand that birds will fly away as the vehicle moves forward [16–18].

In terms of infrastructure also, major changes will be required. Clear traffic lane markings and traffic signs are required. If the vehicles run on electricity, a robust charging network is needed. Network providers will have to ensure a seamless connectivity in order to avoid communication and connectivity issues. Technology and infrastructure upgradation requires huge investment [16, 17].

2.5 Sensors

Autonomous vehicles use a wide range of sensors to “see” the environment around them, collect the information and feed this collected data to the control system so that decisions can be made and required action can be taken. Cameras help to view objects; LiDAR (Light Detection and Ranging) sensors use light in the form of a laser to measure the distance between the object and the vehicle; RADAR (Radio Detection and Ranging) sensors detect the objects, measures their speed and the direction of their movement [17–20]. Ultrasonic sensors are also used that help to measure short distances at low speeds. They are independent of color, and work well in bad weather conditions and dusty environments [13].

In a fully autonomous car, sensors should be able to detect objects, distance and speed under all weather conditions and environments without the need of human intervention. The accuracy of the sensing capability can be negatively impacted due to adverse weather conditions (fog, snow, or heavy rain), traffic signs with graffiti, heavy traffic, and low light. Cameras and sensors are not able to track lane markings if they are covered by water, ice, oil, or debris [15, 17–20]. **Figure 3** shows the sensors, cameras, and other basic components of an autonomous car.

Figure 3.
Sensors on autonomous car (source: Created by author).

2.6 Complex 3D route map creation and maintenance

Autonomous vehicles heavily rely on pre-defined maps in order to navigate and reach the desired destination. With the help of sensors and maps, AVs are able to detect the obstacles and follow the right path. For AVs to perform accurately, three-dimensional (3D) maps need to be created. This can be done by driving the vehicle on all routes, capturing images and categorizing them into intersections, driveways and fire hydrants etc. It is a time consuming and complex process in terms of coverage and efficiency. If, however, the user wants the car to go to a new location that is not already saved in the maps, or traffic signals are changed, or a new construction work takes place, 3D maps will not be able to help [15, 17].

2.7 Artificial versus emotional intelligence

Emotional Intelligence (EI) refers to the ability to recognize, identify and manage one's own emotions and the emotions of others. It includes characteristics such as self-awareness, self-regulation, motivation, empathy, and social skills. Driving a car is not only about skill and control, but it is also a social process where human drivers interact with each other and with pedestrians, reading their facial expressions and body language, predicting behaviors, and making quick decisions [15]. This is something that seems almost impossible to achieve as human instincts, behaviors and emotions cannot be replicated or replaced by machines.

2.8 Cybersecurity

Cybersecurity and data privacy remain another challenge for practical implementation of autonomous vehicle systems. In past, there have been scenarios where conventional HVs have also experienced cyberattacks. If even the conventional cars are vulnerable to cyberattacks, the risk of being vulnerable to cyberattacks is much higher for AVs [15]. According to the literature, cyberattacks may target infrastructure sign, machine vision, GPS (Global Positioning System), in-vehicle devices, acoustic sensors, RADAR, LiDAR and other in-vehicle sensors, odometric sensors (accelerometers and gyroscope etc.), electronic devices and maps [21]. Considering this, more robust security protocols need to be developed to protect the cloud-based communication system of car so that the risk of cyberattacks can be minimized [17].

2.9 Standards and regulation

With all major companies competing hard to launch fully autonomous vehicles, it is highly important to develop standards and regulation for correct and safe use of this technology. There are some recently proposed regulations e.g., for automated lane keeping systems [22], for safety for evaluation of autonomous products [23], and for safety of the intended functionality [24]. These standards, however, do not address several issues such as, sensors and machine learning etc. [15, 17–18].

Standard/Regulation	Description	Year
ANSI/ITSDF B56.5–2012	Safety Standard for Driverless	2012
ISO/TC 22/SC 33	Vehicle dynamics, chassis components and driving automation systems testing	2014
ASTM Committee F45	Committee on Driverless Automatic Guided Industrial Vehicles	2014
Code of Practice for Testing (UK)	Legal requirements for conducting public trials of automated vehicle technologies and service in the UK	2015
ISO 16787:2017	Intelligent transport systems — Assisted Parking System (APS) — Performance requirements and test procedure	2017
IEEE 1609.2a-2017	Standard for Wireless Access in Vehicular Environments	2017
Automated and Electric Vehicles Act 2018 (UK)	Rules on safe use of automated vehicles on GB roads	2018
ISO 21717:2018	Intelligent transport systems — Partially Automated In-Lane Driving Systems (PADS) — Performance requirements and test procedures	2018
IEEE 1609.2b-2019	IEEE standard for wireless access to vehicular environment	2019
ISO/PAS 21448:2019	Road vehicles — Safety of the intended functionality	2019
PAS 1880:2020	Guidelines for developing and assessing control systems for automated vehicles	2020
ISO 21202:2020	Intelligent transport systems — Partially automated lane change systems (PALS) — Functional / operational requirements and test procedures	2020
ISO/TR 4804:2020	Road vehicles — Safety and cybersecurity for automated driving systems — Design, verification, and validation	2020
UN Regulation No. 157 - Automated Lane Keeping Systems (ALKS)	System for performing dynamic driving tasks under certain conditions	2021
ISO 22737:2021	Intelligent transport systems — Low-speed automated driving (LSAD) systems for predefined routes — Performance requirements, system requirements and performance test procedures	2021
ISO 21448:2022 (Revised Version)	Road vehicles — Safety of the intended functionality	2022

Table 1.
Summary of standards and regulations.

Table 1 summarizes some of the main standards and regulation developed related to safety, testing, connectivity, cybersecurity, design, verification, and validation.

3. Solutions and strategies

Although the challenges seem to be massive, researchers and developers are working hard towards the development of solutions to overcome these challenges and to make it possible for AVs to hit the roads soon. This section covers the strategies and solutions suggested in literature and the latest technologies developed that can eliminate or reduce the challenges that once seemed impossible to overcome.

3.1 Emerging technologies and potential solutions

The emerging technologies for autonomous vehicles are edge computing, software defined networking (SDN), network function virtualization (NFV), vehicular cloud computing (VCC), and named data networking (NDN). Their role in AVs is as follows [25]. Edge Computing helps to improve storage and provides real-time data processing, thus results in rapid decision-making. SDN offers flexibility and scalability to vehicular networks. In the same way, VCC helps in efficient road traffic management, dynamic traffic light management as well as improvement in road safety by instantly using the vehicular resources. NFV helps to improve efficiency and allows network functions to be distributed. NDN fixes networking issues such as those related to IP architecture and provides secure data sharing among AVs. These technologies clearly have a potential to improve connectivity, memory, and efficiency in autonomous cars.

Moreover, quantum cryptography and block chain enabled security algorithms can help to overcome cybersecurity issues related to sensors. AI and deep learning-based solutions can improve real-time data analysis and complex dataset management. Currently used radar technology lacks collision detection and collision avoidance algorithms. Also, when multiple radar sensors operate in overlapping frequency bands in the same vicinity, interference occurs. Therefore, radar interference management is needed with improved identification and classification of obstacles and enhanced algorithms [25]. All these technologies combined with high-speed wireless networks such as 5G and 6G can help to reduce and eliminate several challenges related to the technology, functionality, efficiency, connectivity, and security of autonomous vehicles.

Safety and security can be improved with the help of Responsibility-Sensitive Safety (RSS) framework. It is a safety standard developed by Intel that employs reinforcement learning technique [26, 27]. In the same way, V2X (vehicle to everything) protocols help autonomous vehicles communicate with their surroundings such as, vehicle-to-infrastructure (V2I) communication and vehicle-to-vehicle (V2V) communication. V2I helps to exchange data with the surrounding infrastructure such as speed limit, signs, and traffic lights, whereas V2V helps to communicate with other vehicles that results in collision avoidance and safer operations, especially during unexpected traffic situations and congestion [26].

4. Conclusion

The idea of autonomous vehicles has been around for years, but it seems to be turning into reality in the recent years with companies making huge investments and technology such as AI doing wonders. There are, however, several challenges and barriers that need to be accounted for, and a deeper insight is required to work towards this goal. This chapter highlighted the current barriers and challenges that must be considered and accounted for so that AVs and HVs can practically and safely share the roads. It also discussed some of the emerging technologies and possible solutions and strategies that can help overcome these challenges in order to revolutionize the autonomous vehicle technology and current transportation system.

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Chapter 8

Perspective Chapter: Training Autonomous Ships for Safe Navigation

Bill Karakostas

Abstract

The capabilities of autonomous (surface) sea vessels have been improving in recent years, as a result of advances in communication, sensing and navigation systems. An autonomous vessel must be capable of accomplishing its voyage in a safe manner, i.e., without endangering other nearby vessels or disrupting their navigation. This chapter discusses topics related to safe navigation of autonomous vessels, particularly regarding their ability to plan safe sailing routes under dynamic sea traffic conditions. The chapter proposes an autonomous vessel training approach where the learning vessel's navigation system plans routes in a high fidelity training environment that utilises AIS data. The resulting route is then assessed for safety risks, and a feedback score is used to improve the planning capability. The approach is demonstrated with the scenario of autonomously crossing the English Channel.

Keywords: autonomous ship, safe navigation, COLREG, reinforcement-based learning, ship simulation, AIS

1. Introduction

1.1 Autonomous ships

An autonomous (sea) surface ship, also known as Maritime Autonomous Surface Ship (MASS), can be defined as a ship which, to a varying degree, can operate independently of human interaction. The idea of autonomous unmanned operation of sea vessels is not new [1]. Currently, unmanned but guided sea vessels are used for specialist tasks such as cleaning operations, surveillance etc. Autonomous water vessels have been used experimentally for passenger and cargo transport in restricted (e.g., canals) and fixed routes (e.g., ferries). However, no large unmanned commercial ship is currently operational, due to the inherent safety risks involved.

1.2 Scope of autonomous ships

There are variants to the degree of autonomy of ships. This includes remotely controlled ships, semi-autonomous ships where some of the vessel activities are controlled by a remote station and fully autonomous ships. Autonomy Level 4 is defined in [2] as the level where all operational tasks are always performed by an automated system, and Autonomy Level 3 as the level where control and decision making are autonomous, but human monitoring is also involved. This Chapter focuses on Autonomy Levels 3 and 4, although it does not exclude lower levels of autonomy (Levels 2 and 1) where some remote control of the vessel is involved. It must be noted that such vessels do not currently exist in operation, with [3] predicting that they will become operational towards the end of this decade, subject to regulatory approval.

1.3 Benefits of autonomous ships

Autonomous vehicles are deployed in many fields such as space exploration, logistics, self-driving cars etc., to reduce human errors and improve precision [4]. In transport and logistics applications, autonomous vehicles can help to reduce traffic congestion and therefore pollution. In addition, automation of many ship functions may reduce the risks of human error, however it may introduce new risks [5, 6], as discussed later on in this Chapter.

1.4 Autonomous ship projects

Innovative autonomous ship demonstrators have emerged in the past years such as the one by Rolls-Royce and ferry operator Finferries, who in 2018 demonstrated the world's first fully autonomous ferry in the archipelago south of the city of Turku, Finland. A five-year project from MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) and the Senseable City Lab, produced a fleet of autonomous boats for the City of Amsterdam [7]. The latest version of this boat, Roboat II, which is capable of carrying passengers, uses Lidar, GPS and other sensors to navigate its surroundings.

1.5 Safety of autonomous ships

Safety is paramount for the success of autonomous ships. Their level of safety must match and in certain areas exceed that of manned ships. Autonomous ships may reduce the risk of human error due to absence of crew, but they may create new types of risks. Towards ensuring safety of future autonomous ships, there is ongoing legislation activity led by international organisations such as IMO. The AAWA (Advanced Autonomous Waterborne Applications) initiative [8], a joint industry and academic research project on autonomous ships that ran between 2015 and 2017, sought to analyse different scientific challenges related to autonomous ship operations, technology needs, risks, incentives and regulations/liabilities. According to the AAWA initiative, amongst the different autonomy issues, major topics are marine situational awareness and autonomous navigation [3].

1.6 Regulatory framework for autonomous shipping

It can be argued that the technical barriers to autonomous shipping are less formidable than the regulatory ones. Therefore, international organisations such as the Maritime Safety Committee of IMO, have commenced work on addressing a regulatory framework in order to assess how Maritime Autonomous Surface Ships could be regulated [9]. The Committee also focused on safety, secure and environmentally sound Maritime Autonomous Surface (MASS) operations.

1.7 Chapter organisation

The Chapter is organised as follows. The next section reviews the functional architecture of an unmanned ship and identifies the ship's key functions, focusing on technologies and systems for voyage planning. Then, the section considers the IT architecture onboard an autonomous ship that supports autonomous navigation.

Section 3 is concerned with concepts and regulations of safe navigation of autonomous ships. It covers training issues of autonomous ships to carry out safe operations. It reviews training methods and techniques for safe navigation, such as simulation based training, as well as automated training and learning, from the fields of Machine Learning and Artificial Intelligence.

Section 4 illustrates the concept of training autonomous ship navigation systems in realistic environments. It also discusses safe navigation concepts. It concludes with a scenario of safe route planning through the English Channel.

Section 5 summarises the idea of training autonomous ship safe navigation, its potential and shortcomings.

Finally, Section 6 contains a discussion about the future of autonomous ships in general and how advances in information technologies can shape it.

2. Functional and safety properties of unmanned ships

2.1 Functions of autonomous vessels

Table 1 from the MUNIN project [10], lists the function categories of ships in general, and also those functional areas that do not apply to unmanned ships. From **Table 1**, the focus of this Chapter can be defined, namely Group 1 ('Voyage') that involves the activities of high level voyage planning execution and monitoring. However, functions from other functional categories such as Group 3 ('observations') and Group 4 ('Safety, emergencies') are also incorporated. The next section mainly discusses safety enhancing systems onboard autonomous ships.

2.2 Unmanned ship onboard systems

Autonomous ships utilise a variety of systems for situation awareness and communication with the outside world. This includes GPS, vision, environment (wind, wave) sensors, radar, cameras, sonar and so on for sensing, as well as radio, AIS, satellite transceivers etc., for communications purposes. The signals and data received via such systems are transmitted to the autonomous ships control system.

According to [11], as per **Figure 1**, the autonomous ship consists of a Path Planning subsystem that communicates information about the planned path to a Collision Avoidance subsystem. The Path Planning subsystem is informed about the position and trajectory of nearby objects by a State Awareness subsystem. In turn, the State Awareness subsystem employs sensing devices (camera, radar, sonar, etc.) and communication systems such as AIS. Autonomous navigation systems (ANS), which can make the navigational decisions and command the ship's propulsion systems, are a central part of autonomous or remotely controlled vessels [12].

Group	Description
1. Voyage	High level voyage planning, execution and monitoring
2. Sailing	Manoeuvring, avoidance, communication
3. Observations	Environment, objects, ships
4. Safety, emergencies	Other ships, own ship, environment
5. Security	Antipiracy, ISPS, access control and lock-down
6. Crew, passenger	Not applicable to unmanned ship
7. Cargo, stability, strength	Ship stability, hull integrity, cargo monitoring
8. Technical	Power generation and distribution, emissions to air/water
9. Special functions	Not applicable to bulk ships (tugs, offshore, …)
10. Administration	Log keeping, operational communication, reporting

Table 1.
Function groups of unmanned vessels [10].

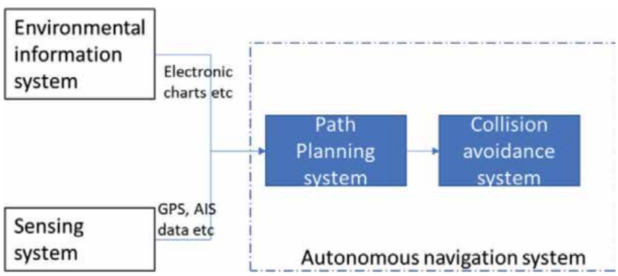

Figure 1.
Autonomous navigation system.

2.3 AIS

Amongst the communications systems onboard an autonomous ship, the Automatic Identification System (AIS) plays a prominent role as a context awareness and navigation safety device. AIS is a worldwide automatic positioning system based on vessel transponders that transmit a signal in the VHF band. This alerts other vessels and shore stations with AIS receivers to the presence of that vessel. The signals and accompanying information can then be received by any vessel, land station or satellite, fitted with an AIS receiver, and is typically displayed on a screen of chart-plotting software.

AIS Provides three types of information [13].

Fixed, or static information including data such as: Maritime Mobile Service Identity, Call Sign and name of vessel, IMO Number, length and beam, type of ship and location of position-fixing antenna.

Dynamic information, which, apart from navigational status information, is automatically updated from the ship sensors connected to AIS. This includes the ship's position with accuracy indication and integrity status, position time stamp, course over ground, speed over ground, heading, navigational status and rate of turn.

Voyage-related information, which might need to be manually entered and updated, such as: ship's draught, hazardous cargo, e.g., dangerous goods, harmful substances, destination, ETA and route plan (waypoints), at the discretion of the ship's master.

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3. Training autonomous ships for safe navigation

3.1 Autonomous Sea navigation

The ability of autonomous navigation is essential in autonomous systems [14]. Autonomous navigation of ship relies on various sensors (vision, radar, sonar) to detect along the navigation path and environment and take into account vessel properties to achieve safe travel [4]. Autonomous navigation is achieved by training or pre-programming the ship with data about the vessel behaviour in various sailing scenarios. The autonomous behaviour then relies on advanced machine vision and other pattern recognition techniques in order for example to detect and avoid obstacles along the navigation path.

3.2 Safe navigation regulations

Safety is an essential prerequisite for the successful adoption of autonomous ships. There is a danger that regulation falls behind technological innovation [15], therefore proactive regulatory forming activities are required. IMO [9] for instance, has recently completed a regulatory scoping exercise on Maritime Autonomous Surface Ships that was designed to assess existing IMO instruments to see how they might apply to ships with varying degrees of automation.

COLREGs is a set of safety regulations by IMO that describe potential collision scenarios such as crossing, head-on and overtaking, and suggests possible manoeuvres to avoid a collision. Although the rules provide a set of guidelines for safe manoeuvring at sea, they are aimed at human control navigators [16]. This subjective nature of COLREGs is one of the major causes of ship collisions. Indeed, it is estimated that human error contributes to between 89% and 96% of marine collisions (Rothblum, 2000 in [16]).

Safe navigation means that the autonomous ship does not endanger itself or other nearby ships through its course. The ship should avoid interrupting the course of other ships, should not force them to take evasive action, i.e., to stop, reduce/increase speed or alter their course.

3.3 Safe sailing concepts and techniques

Most of the ship collision accidents are due to human errors, which is a large threat in open sea [4]. In autonomous vessels, the actual risks of collision are currently unknown, as such ships have yet to be deployed, it is however important that collision avoidance technologies are developed and integrated in the overall ship control system.

To understand the risks of collision at sea and what constitutes safe sailing, some concepts must be introduced. Collision risk assessment is vital before the vessel makes any course changing decisions. Collision risk assessment must determine the closest point of approach (CPA), the corresponding time to the closest point of approach (TCPA) and a projected area of danger (PAD), by extrapolating the other vessel's position over time [16]. A typical method based on the distance factor in ship collision evaluation is the ship domain [17]. The ship domain is created as a safe area around the ship, based on the safe distance. The ship domain shape and radius depend on the ship's characteristics such as its geometry. Once a vessel is inside the autonomous ship domain, the autonomous ship should anticipate and then execute the correct manoeuvres, based on the predicted course of the other vessel. **Figure 2** illustrates the ship domain concept. In addition, as shown in **Figure 2**, the risk of collision depends on the angle of approach of the two ships. As per COLREG regulations, a head on approach is more risky than one where a ship crosses the path of another ship (or overtakes it) from a stern direction.

3.4 AI and machine learning approaches for training autonomous ships for safe navigation

As the safe sailing and collision avoidance of autonomous ships must equal or better those of human ship operators, it is important that such ships are equipped with artificial intelligence capabilities. Already, machine learning techniques such as Deep Learning, are being applied in various fields of the maritime industry such as detecting anomalies, ship classification, collision avoidance, risk detection of cyberattacks, navigation in ports and so on. Of particular interest to this Chapter is the machine learning technique of reinforcement-based learning [18].

3.5 Reinforcement based learning

Reinforcement learning is an approach to machine learning in which the agents are trained to make a sequence of decisions. It is defined as the learning process in which an agent learns action sequences that maximise some notion of reward [19]. The trained agent interacts with the environment and make decisions or choices. The agent is provided with contextual information about the environment and choices. After it makes a choice, the agent is then provided with the feedback or rewards based on how well the action taken, or the decision made by it, resulted in achieving the desired goal. In many practical applications, the goal is not merely to reach a particular destination, but to do so while maximising some desired utility measure, which could include obeying the rules of the road, maintaining safety, etc. [20].

3.6 Simulators and reinforcement-based learning

Various simulators are used in maritime field to train personnel to navigation, ship handling and the ship bridge equipment. Simulators typically consist of real equipment, real consoles, and instrumentation while the ship and its environment are virtual [21].

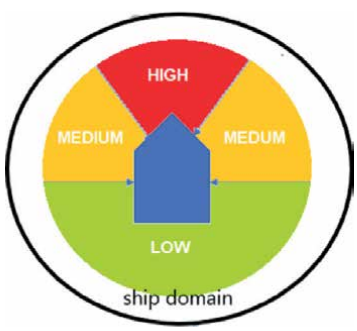

Figure 2.
Risk zones around a ship.

As in most cases it is not practical or safe to train an autonomous ship in a real life environment, a high fidelity simulation environment can provide a substitute. In such an environment, the actions of the trained autonomous ship system interact with the simulation actions, and the system receives feedback ('reward') from the simulation. Effectively, therefore, the simulation environment becomes the reinforcement based learning agent's training environment. This is the basis of the approach explored in the next section.

4. Case study: autonomously crossing the English Chanel

4.1 Background

According to Wikipedia, the English Channel shown in **Figure 3**, is about 560 km long and varies in width from 240 km at its widest to 34 km at its narrowest in the Strait of Dover. The English Channel contains some of the busiest shipping lanes in the world. To ease navigation and improve safety, southbound and northbound traffic lanes were introduced in the 1980s. There is a lateral separation of approximately one nautical mile. This lateral separation removed the need for the ships to alter course for each other as risk of collision does not exist.

4.2 Simulation environment for autonomous navigation training

Using publicly available AIS data from Marine Traffic (www.marinetraffic.com), we recorded ship positions in the area of interest (an area of approximately 40 km^2 off the English coast as shown in **Figure 4a–d**, on regular intervals, over a period of 7 days. The recording interval was set to 10 min. Recorded data included ship's type, heading and speed. Some of these recordings are visualised in **Figure 4a–d**. Effectively, the recorded data allowed us to replay any ship's trajectory over a time period. The collected AIS data were used to create a high fidelity simulation/training environment for training an autonomous ship's navigation system to plan a safe route across the westbound traffic lane of the English Channel. The training approach consists of several training sessions where the steps of a training session can be summarised as follows:

1. Set the initial position of the autonomous ship, in this training scenario just north of the westbound traffic lane as shown in **Figure 4a–d**.

2. Set the autonomous ship domain radius. In this scenario we set the ship's domain to be a circle with a radius of 1 nautical mile (1.852 km). This safety range is common according to the literature; however, it applies to manned vessels. Minimum separation guidelines for situations involving unmanned vessels have not yet been defined, to the best of our knowledge.

3. Set the heading and the speed of the autonomous ship. In this training scenario heading values range from 45 to 135 degrees relative to the direction of the southbound traffic. Speed is approximately 18 kph (~10 knots). Both heading and speed remain constant for the duration of the session.

4. At 10 min intervals, update the ship's position based on its heading and speed. For the new ship position and from the AIS data, find all ships that are within the autonomous ship's domain (i.e. safety radius).

Figure 3.
The English Channel and the simulated area (shown as a red circle). Source: OpenStreetMap.

5. Calculate the safety risk for each nearby ship, taking into account the angle of the ship's direction relative to the autonomous ship's direction, using as reference the diagram of **Figure 2**. Calculate a total risk index for each step and a total risk index for the entire session.

6. Record the heading, initial traffic state in the area and total risk index.

7. The training objective is that, over a period of several training sessions, the autonomous controller will become increasingly more capable of plotting a route that minimises the total risk index, for any initial traffic state.

The main difficulty of this training approach is calculating a meaningful and realistic risk index as the current regulations on safe navigation are (a) oriented towards humans and (b) are vague in several aspects.

Figure 4a–d serve to visualise the collision risk index calculation approach. In these figures, the ship domain corresponds approximately to one grid cell and therefore the ship represents potentially a collision risk to other ships occupying the same cell, subject also to their relative headings as explained in Section 4.2.

In **Figure 4a** for instance, at 7.37 am and 7.47 am the autonomous ship (shown as a black shape) is being approached at approximately right angles (medium risk) by two other ships. A similar situation is shown in **Figure 4b**, although the collision risk appears visually to be lesser. Interestingly, COLREG recommends that traffic is being approached at right angles, i.e., as approximately shown in **Figure 4a**. The collision risk seems to be lower in **Figure 4c** and least in **Figure 4d**, where there are fewer states (grid cells) where other ships are entering the autonomous ship's domain at unsafe angles.

It may be difficult to completely automate the calculation of the rewards function (i.e. the risk index) in an unsupervised fashion, mainly due to lack of precise regulations and consensus regarding collision risk scenarios. However, a supervised (and therefore, more time consuming) approach might prove more feasible. In supervised training, human safety experts manually evaluate different ship encounter scenarios and label them with risk indices that reflect the ships' relative angles of approach, but also speed and ship types. A challenge in supervised training would be to include sufficient numbers of scenarios and provide adequate coverage of all possible situations the autonomous ship is likely to encounter in a particular sea region.

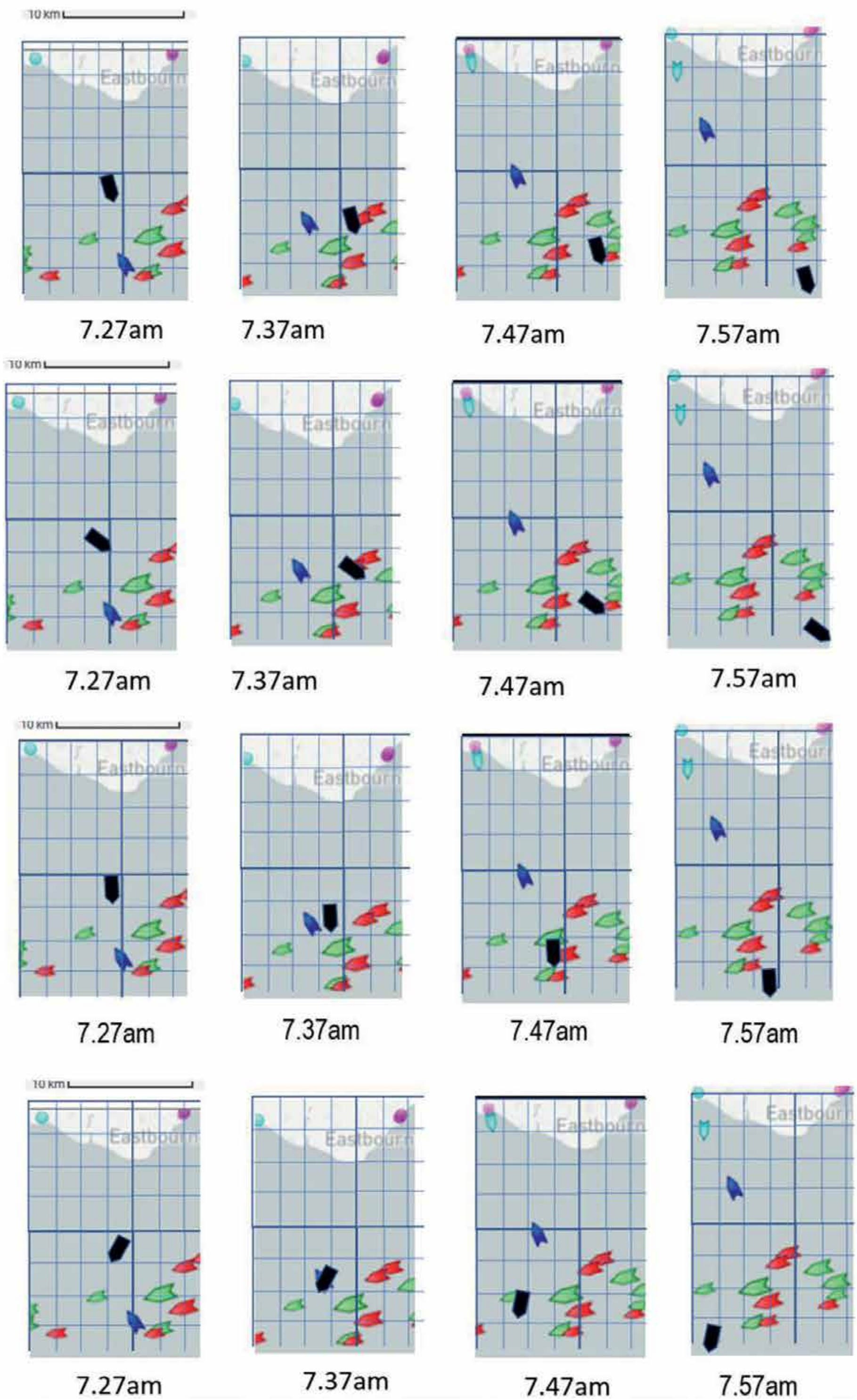

Figure 4.
(a) Crossing traffic at right angles (b) paths using different crossing angles (c) a different traffic lane crossing angle (d) another traffic lane crossing angle.

5. Conclusions

While most of the underpinning autonomous ship technologies are available, the overall framework (technical, human, legal) required for their adoption is not. In this Chapter, we illustrated some of the safety issues facing unmanned ships in real life navigation conditions. While autonomous decision making capabilities can indeed by developed, the behaviour of unmanned vessels must also be predictable and understood by other seafarers As argued in [22], navigation is about coordination. This means that there is a need for the autonomous navigation system to decide independently what to do, in a situation where other ships must also make independent decisions. Therefore, collision avoidance, for instance becomes a game of co-ordination, since both ships have to choose independently mutually compatible strategies (Cannell, 1981 in [22]), and must trust the other to comply with their obligations. Along the same line of thinking, the autonomous ship also needs some means of understanding the plans and intentions of the human operated ships. Yanchin and Petrov [23] proposes that the crew of the manned ship uses dedicated equipment to communicate with the autonomous ship to explain their plans, so that the autonomous ship is aware of the human's decisions and thus can infer its own.

Although the approaches advocated in this chapter are based on concepts of machine learning (in particular reinforcement based learning), they can be embedded in other types of applications such as high fidelity simulation environments for training ship crews. It can become, for example, part of software to train crew to identify and analyse marine traffic situations [24]. In fact, due to the wealth of ship data (Big Data) accumulated mainly from AIS, but also by other monitoring stations, the feasibility of intelligent tutors, underpinned by Big Data and used for both machine and human training is a possibility. An intelligent navigation tutor can provide realistic navigation scenarios (using real life data from AIS databases), and also critique the navigation decisions of the autonomous or human navigator, including the remote operators of unmanned ships, and also analyse and explain the consequences of a navigation decision. It must be noted however, that the current simulation approach, although based on real data, can never become a complete substitute for training onboard real ships, in real sea environments. In the current simulator, for instance, other ships behave as if they are not aware of the existence of the autonomous vehicle, thus their possible reactions to it cannot not be simulated.

However, more advanced future simulations based on intelligent agent concepts, could introduce a new type of simulation environment where virtual ships react to their encounters with the autonomous ship by for instance, altering their speed, course, etc. Thus, we argue that the future of autonomous ship training might require more advanced simulation environments that employs intelligent (software) agent approaches. This of course ties with the future vision of autonomous ships as agent-based systems with intelligence distributed amongst them [25].

A survey of the autonomous ship literature, carried out by [26], reports that nearly no paper discussed typical encounter situations in high-density traffic areas, such as traffic separation schemes and narrow channels. Thus, this Chapter has hopefully created awareness of the need for more research into safe navigation/collision avoidance in high traffic sea environments, where the risks of collision is higher.

6. Future directions

Fully autonomous ships seem currently to be a medium to long term goal. For example, according to Rolls-Royce, the first voyage of a fully automatic ship will happen by 2035 [8]. As Section 1 of this Chapter has reported, although autonomous and remote-controlled ships are being trialled in some sea areas, these are limited to specific ship types such as ferries [27] and waterways [28]. For example, cities with canals can utilise autonomous boats that ferry goods and people, helping to reduce road congestion. IMO also predicts that autonomous or semi-autonomous operation would be limited to short voyages, for example from one specific port to another, across a short distance. Many national regulators, as for example in Norway and in Finland, have encouraged the trialling autonomous or remotely controlled ship operations within national waters. This has led however, to many countries developing their own regulations during the initial trial stages. Therefore, in the long run, cooperation is needed between different countries to ensure consistency of regulations.

The AAWA initiative [8] concluded that hybrid variations between remote and autonomy solutions are more likely to occur first. As previously mentioned, although the technology to make ships autonomous current exists, much still needs to be done to ensure it is reliable. For example, as this Chapter argued earlier on, autonomous ships may reduce the risk of human error given they have no crew, but new types of risks will be created, and this means that vessels will need to be as safe as existing ships, and possibly even more so. A major topic that was addressed in the AAWA initiative was situational awareness and autonomous navigation. At present, human operators supplement any sensor technology that has been installed onboard autonomous ships. In the future, in totally autonomous ships, an array of complimentary (and redundant) sensing technologies has to be installed and fused, to provide sensory data to their collision avoidance systems. In conclusion, this chapter has identified novel perspectives and issues for the safe navigation of autonomous ships that stem from the complex rules and situations that apply to navigation in real life sea environments. Existing technological solutions for autonomous ships will have to be evaluated in greater depth to understand new risks, legal challenges and the stakeholders involved in autonomous operations, and liability issues need to be addressed. As IMO recommends, new autonomous ship terminology and definitions, must be created that clarifies the meaning of conventional marine terms such as 'master', 'responsible person', etc., in an autonomy context.

Finally, although machine learning and, in particular, deep learning based systems are proving to be an effective mechanism for safe navigation and collision avoidance, [25, 26, 29], they need to coexist and safely interact with more conventional ship technologies, and with the human crew too.

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In recent times, remarkable progress has taken place in the field of autonomous vehicles, reshaping industries such as logistics, transportation, defense, and more. The quest for achieving fully autonomous systems has been a thrilling yet demanding journey, as researchers and engineers continually push the limits of technological ingenuity. *Autonomous Vehicles - Applications and Perspectives* delves into the field of autonomous vehicles across eight chapters that cover various facets of this domain. The book is organized into four sections: “Introduction”, “Autonomous Vehicles Enabling Technologies”, “Autonomous Vehicles Applications and Potentials”, and “Challenges and Perspectives”. Its main goal is to provide an informative resource for those interested in autonomous vehicles, inspiring progress and discussions for researchers, students, and professionals alike.

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