electronics

Review

Autonomous Vehicles for Healthcare Applications: A Review on Mobile Robotic Systems and Drones in Hospital and Clinical Environments

Paolo Marmaglio, Davide Consolati, Cinzia Amici and Monica Tiboni *

Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze, 38, 25123 Brescia, Italy; paolo.marmaglio@unibs.it (P.M.); davide.consolati@unibs.it (D.C.); cinzia.amici@unibs.it (C.A.)
* Correspondence: monica.tiboni@unibs.it

Abstract: The development of autonomous vehicles, both ground and airborne, for hospitals and clinical settings is an extremely interesting topic that has developed rapidly in recent years. Given their significant potential to improve operational efficiency and safety protocols, these devices are gradually gaining an important place in the healthcare industry. This is true for both in-hospital and out-of-hospital functions. The integration of autonomous vehicles into these environments will greatly increase operational efficiency and enrich the experience for both medical staff and patients. This document provides an updated and comprehensive overview of the current state-of-the-art in the development of autonomous vehicles for the healthcare sector. Particular emphasis is placed on design, functionality, and level of autonomy. The review is organized on two levels: a prospective review highlights the main trends in the design and application of autonomous vehicles, and an analytical review performs an in-depth analysis of the main aspects of the technical solutions developed and implemented in the scientific research reviewed. The results are presented in a schematic approach.

Keywords: autonomous vehicle; drone; UAV; healthcare; mobile robotics

check for updates

Citation: Marmaglio, P.; Consolati, D.; Amici, C.; Tiboni, M. Autonomous Vehicles for Healthcare Applications: A Review on Mobile Robotic Systems and Drones in Hospital and Clinical Environments. *Electronics* **2023**, *12*, 4791. https://doi.org/10.3390/electronics12234791

Academic Editor: Mahmut Reyhanoglu

Received: 25 October 2023
Revised: 20 November 2023
Accepted: 22 November 2023
Published: 27 November 2023

1. Introduction

In recent years, rapid advances in autonomous vehicle technologies have revolutionized various industries and fundamentally changed the way we perceive transportation, logistics, and mobility. This technological evolution has paved the way for autonomous vehicles to have a significant impact on the healthcare sector by transforming hospital and clinic environments for improved efficiency, safety, and patient care [1].

The integration of autonomous vehicles into healthcare encompasses a wide range of applications, from autonomous delivery robots and smart carts to streamline logistics in medical facilities [2], to self-navigating patient transport vehicles, and robotic assistants that work with medical professionals to improve healthcare delivery [3]. In addition, the use of drones for medical device delivery and patient localization has proven to be transformative [3].

Increasing demand for streamlined healthcare services requires innovative approaches to optimize operations and resource allocation in hospitals and medical facilities. The integration of autonomous vehicles into healthcare offers a promising opportunity to address challenges related to patient transport, medication delivery, and inventory management [4,5]. This integration holds the potential to not only reduce wait times and improve patient safety but to also increase staff productivity and lead to significant cost savings.

Drones have attracted considerable attention primarily because of their role in transporting critical medical supplies such as defibrillators, medications, and other important devices [6–8]. This focus is underscored by extensive literature discussing these technologies, with airspace being a notable area of research. In particular, the provision of automated external defibrillators (AEDs) after out-of-hospital cardiac arrest (OHCA) has become an important topic of scientific discourse. Rapid defibrillation, ideally within 3 to 5 min, significantly improves survival rates, underscoring the importance of efficient AED deployment. Public-access defibrillation (PAD) networks are effective in public spaces but reach their limits in domestic emergencies, highlighting the need for innovative solutions. Drones, originally associated with military applications, are now used in a variety of fields, including education, medicine, and rescue missions. In the context of OHCA delivery, drones offer the potential to bridge geographic gaps and overcome the challenges of complex road networks, benefiting both urban and remote rural regions [9].

The integration of autonomous vehicles into healthcare provides an unprecedented opportunity to optimize and revolutionize hospital and clinic operations. The introduction of mobile system solutions promises to improve patient care, increase operational efficiency, and redefine the landscape of modern healthcare [1].

This comprehensive scientific review addresses the current landscape of autonomous vehicles in healthcare, focusing on mobile system solutions in hospitals and clinical settings. Through a critical examination of technological advances, practical implementation, and challenges encountered in the adoption of autonomous vehicles, this work aims to provide literature insights suitable for both researchers and practitioners. To facilitate this examination, an extensive compilation of articles and reviews is provided that focuses on various aspects of autonomous vehicles in healthcare. Analysis of the existing knowledge enables the investigation of technical details and specific topics, such as the effectiveness, reliability, and limitations of autonomous vehicles in healthcare. The literature analysis revealed a lack of reviews on the topic of autonomous vehicles for healthcare. While there are many papers describing specific tasks, it is difficult to find reviews that provide an overall picture. Furthermore, the few identified reviews are focused on describing the use of drones without any technical discussion. Having identified this gap in the literature, we decided to propose a review that covers these aspects.

The research was made possible by a dual-level investigation:

- a prospective review that resulted in the phase and component classification of papers and made it possible to observe how the literature changed over time, by process stage, and by intervention level;
- an analytical review that produced a mapping of documents by the implemented methods and involved components.

The paper is organized as follows: With particular attention on design requirements, Section 2 describes the methodology and processes used to select the papers and the evaluation criteria chosen to analyze the results. The proposed integrated functional design framework is introduced in Section 3, together with the main results of the prospective review. In Section 4, the analytical review is presented, and Section 5 summarizes the main results.

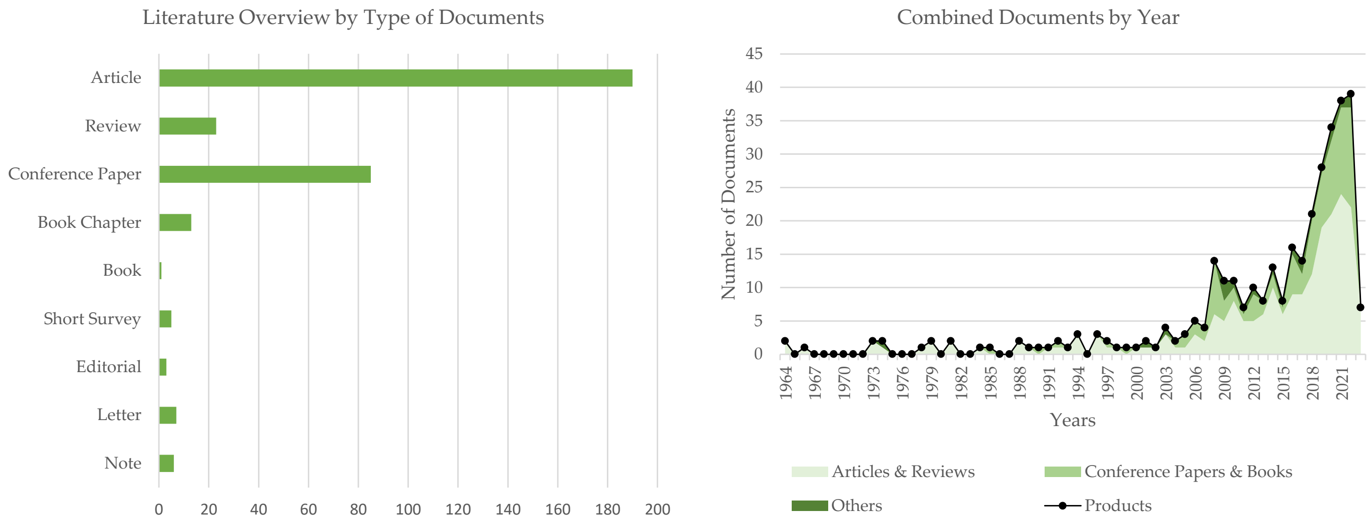
2. Materials and Methods

This section explains the methodology used for the selection of articles and the taxonomies used for the prospective and analytical reviews.

2.1. Article Selection Protocol

Data selection was done by querying the Scopus database with the search term "TITLE ((agv* OR vehicl* OR troll* OR drone*) AND (hospit* OR clinic* OR medic*))". The last search query update was performed on April 12, 2023, and resulted in a total of 333 research products. These included 190 articles, 23 reviews, 85 conference papers, 1 book, 13 book chapters, and 21 others.

Figure 1a provides a brief overview of the distribution of these results by document type, while Figure 1b shows the distribution of results in terms of their evolution over the years. The literature analysis shows a large number of articles and a medium-high number of conference papers. Before 2007, publications on this topic were not widespread; since 2007, there has been a regular increase.



(**a**) (**b**)

Figure 1. Literature overview. (**a**) Overall number of documents by type, according to the Scopus classification. (**b**): Document evolution throughout time, displayed in a stacked diagram. The cumulative function is indicated by connecting lines and black dots. Product classes were merged by combining articles (190) with reviews (23) and conference papers (85) with book chapters (13) and books (1). The category 'Others' collects documents classified as short survey (5), editorial (3), letter (7), and note (6).

A set of precise inclusion and exclusion criteria was used to choose the pertinent literature in light of this initial inquiry.

Inclusion criteria:

- Papers published in journals in the categories 'Article' or 'Review';
- The study involves the application of autonomous vehicles for healthcare purposes;
- The study addresses at least one of the following aspects of autonomous healthcare vehicles: vehicle development and/or design, software description, vehicle performance evaluation, or analysis of the regulations governing these devices;
- The autonomous vehicles are intended for transporting patients or goods;
- The document considers autonomous, semi-autonomous, and/or manual vehicles.

Exclusion criteria:

- The document type is neither 'Article' nor 'Review';
- The document language is different from English;
- The article was published before 2000.

The 333 identified products underwent a thorough review to ensure that they were consistent with the inclusion criteria and to exclude off-topic or irrelevant results. For example, many papers were excluded because of the word *Dronedarone*, which recurred because of its similarity to the word *Drone*. Dronedarone is an antiarrhythmic agent and therefore not eligible for this review. A flowchart depicting the selection procedure, the number of found records, details of included and excluded documents, and explanations for the exclusions is displayed in Figure 2. Finally, the final dataset consists of 45 documents that meet the established criteria.

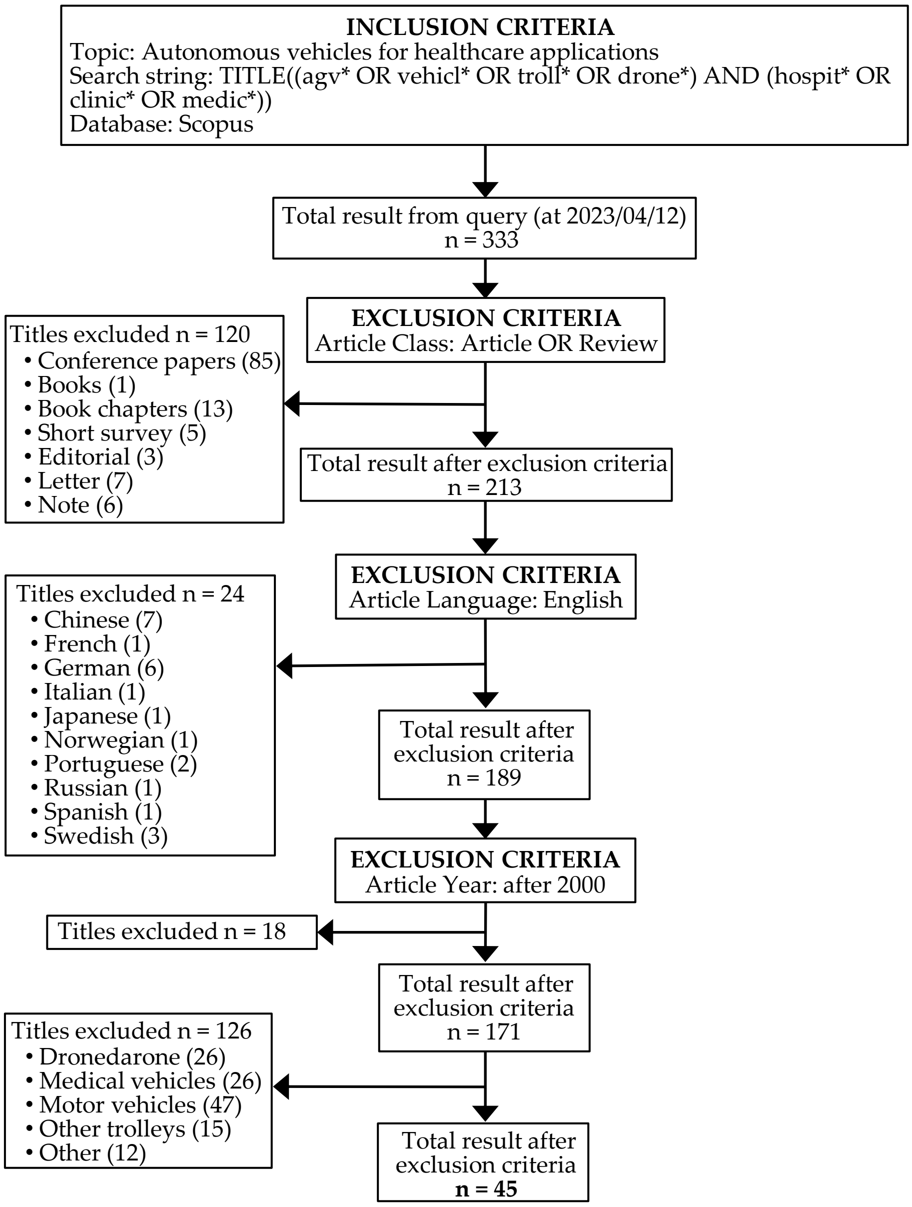


Figure 2. Flowchart mapping the selection process, with the number of identified records, included and excluded documents, and the reasons for exclusions.

2.2. Taxonomy

As described above, a total of 162 papers were excluded from the original database (333 documents) based on the exclusion criteria: they were not articles or not reviews, they were published before 2000, or they were not in English. The remaining 171 articles were analyzed in more detail. The analysis resulted in the exclusion of an additional 126 papers because their topics were not related to the research objective.

The 45 documents in the final dataset were evaluated at two levels of analysis: an initial observational study of the document distribution in terms of quantity, operating environment, document type, vehicle autonomy, and scope, and a subsequent detailed study of the investigated literature. These two analyses facilitated the development of both a prospective review and an analytical review of the existing literature. The ultimate taxonomies resulted from a two-step process that directed the identification and selection of potential classification elements. During the initial stage, comprehensive analysis of review articles related to the subject matter was conducted. This analysis, combined with the authors' expertise, led to the initial definition of domains and subdomains. The first set of elements underwent iterative revisions while the full articles were reviewed. Some fields were incorporated to address previously overlooked aspects, while others were removed or merged if they were not covered in any articles or were only minimally addressed.

2.2.1. Prospective Review

The documents were evaluated with respect to the following aspects:

- The **operating environment**, meant as the settings in which the vehicle is able to work;
- The **document topic**, i.e., the main focus covered by the article;
- The **vehicle autonomy**, which is considered as the degree of autonomy that is enabled for the vehicle by provided control and actuation systems;
- The **application sector**, defined as the context in which the vehicle works.

A separate taxonomy was designed for each aspect.

For the analysis by **operating environment**, the following categories were considered:

op1 Air;
op2 Ground;
op3 Water.

For the analysis by **document topic**, five categories were considered:

t1 Development and Design: this category contains those papers whose focus is on the device design and development.
t2 Software: documents assigned to this category describe the development and implementation of the software for the correct operation of the described vehicle.
t3 Performance: this category includes papers mainly assigned to the description of the functions and features of the treated vehicle.
t4 Regulation: this category collects the documents that describe the regulatory aspects related to the use of the vehicle analyzed in the selected application areas.
t5 Other: documents designated to this category deal with vehicles used in hospital and clinical environments but present as the main focus a different topic.

The analysis by **vehicle autonomy** includes the following categories:

aut1 Manual: this category contains those papers that describe vehicles without any automatic handling systems.
aut2 Semi-Autonomous: this section includes devices that are driven by humans but are equipped with an assisted movement system.
aut3 Autonomous: documents assigned to this category deal with vehicles capable of moving autonomously, without the need to be driven.

In the analysis by **application sector**, three categories were defined:

as1 Logistics Service: this category investigates the solutions implemented to improve the efficiency of the transportation of non-medical items in hospitals. These vehicles can also be used in the industrial sector.
as2 Medical: this category contains the solutions used in hospitals and clinics to handle and manage medical goods, such as medicines, defibrillators, and others.
as3 Other: documents assigned to this category discuss the use of autonomous vehicles for purposes unrelated to healthcare.

The overview of the taxonomy used for the prospective review is shown in Figure 3.

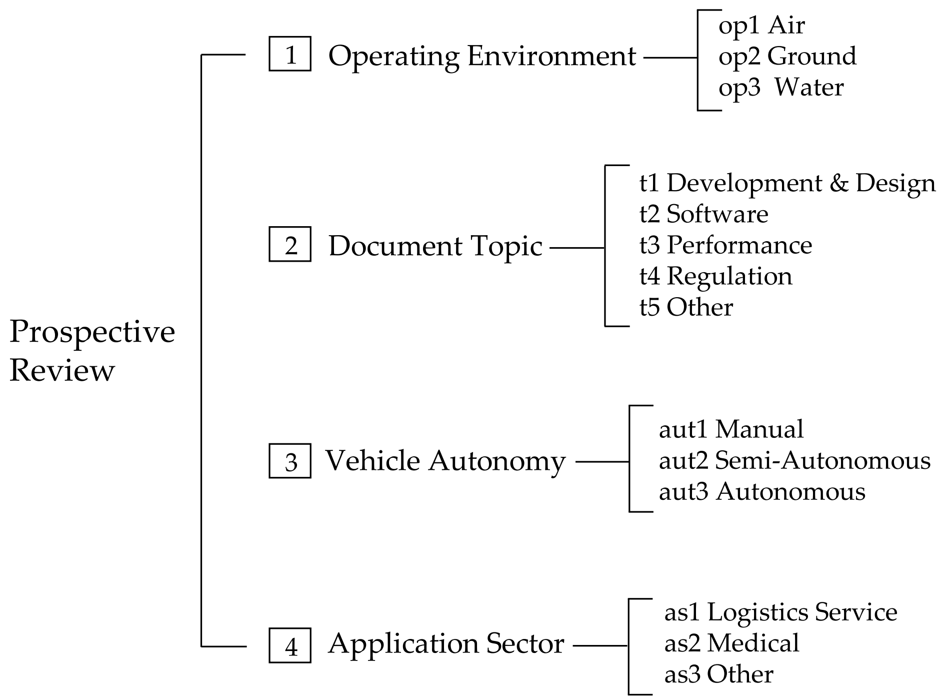


Figure 3. Adopted taxonomy for the prospective review.

2.2.2. Analytical Review

For the analytical review, the dataset was classified according to a more-detailed taxonomy. In particular, the focus of the articles, the main treated functions of the vehicles, and the sensors most commonly used in these devices were examined in detail.

For the analysis by **document focus**, intended as the main subject of the work, four main categories were defined:

F1 Optimization Algorithms;
F2 Development and Design;
F3 Vibration Analysis;
F4 Drones for Defibrillator Transportation.

The analysis by **vehicle functionality** investigates the tasks that the devices are required to perform. The following categories were selected:

FUN1 Medical: the articles in this category describe any activity intended to improve patient health, including delivery and distribution of drugs or the transportation of the patients themselves. This category includes the subclasses:

- FUN1.a Goods: this section includes papers describing the use of vehicles for transporting medical supplies, such as drugs, medical equipment, defibrillators, and blood bags.
- FUN1.b Patients: vehicles in this category are dedicated to the transport of subjects for healthcare-related activities.

FUN2 Logistics Service: this category contains articles dealing with systems for the organization of ancillary activities that are indispensable in a hospital facility.

In the analysis by **sensors**, the following categories were selected, which investigate the presence of the referred sensors on the device under evaluation:

S1 LIDAR (light detection and ranging);
S2 Camera;
S3 Temperature;
S4 Humidity;
S5 Accelerometer;

S6 GPS (global positioning system);
S7 Gyroscope.

Figure 4 provides the overview of the taxonomy adopted for the analytical review.

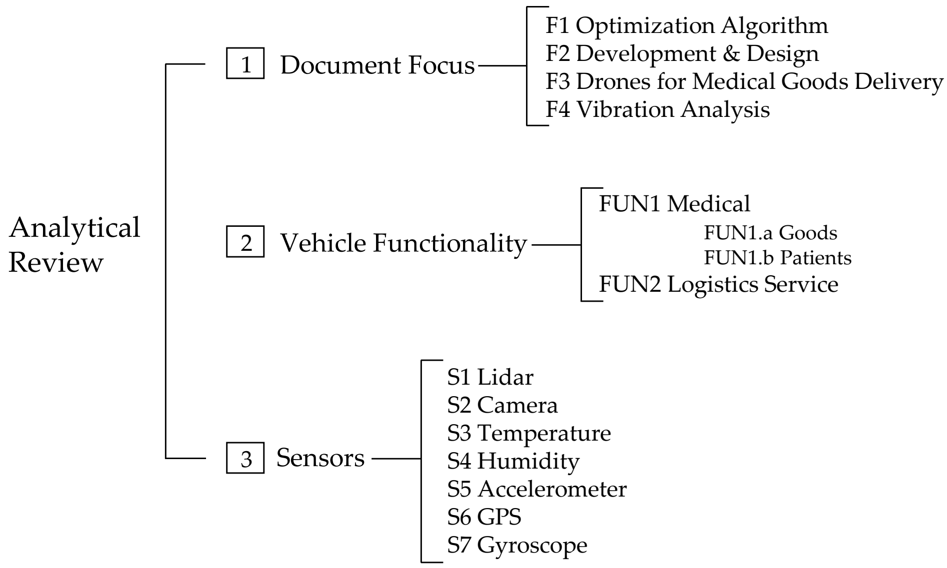


Figure 4. Adopted taxonomy for the analytical review.

2.3. Data Analysis

The 45 documents in the final dataset were subjected to extensive analysis using the indicated taxonomies, and the results were summarized in special tables (see Table A1 in Appendix A for an extract). It is important to note that the categories within each classification were not treated as mutually exclusive classes. That is, a single document could be classified into multiple categories based on the presence of certain features. The data were then reorganized and further examined. The main results are presented schematically below to provide a summary and structured overview.

3. Prospective Review

Considering that only articles and reviews were investigated in the literature analysis, it should be noted that articles clearly predominate among the 45 contributions in the final dataset, and only 3 reviews were identified.

Several aspects were considered in the prospective review, i.e., operating environment, document main topic, vehicle autonomy, and scope.

To evaluate the literature by operating environment, the selected documents were analyzed for distribution among categories overall (Figure 5) and by year (Figure 6). From the data, it appears that most of the documents are related to airborne vehicles and address the various aspects related to the use of drones in the hospital environment. The articles that do not describe drones deal with vehicles operating in contact with the ground, mainly innovative trolleys for transporting items in healthcare facilities or robotic systems for logistics management. No articles were found describing the use of vehicles that can operate in water for medical applications. The literature indicates that there are no specific applications in the healthcare sector that require the use of this type of device. However, reference is made to how autonomous water vehicles are used in other sectors, particularly the military one.

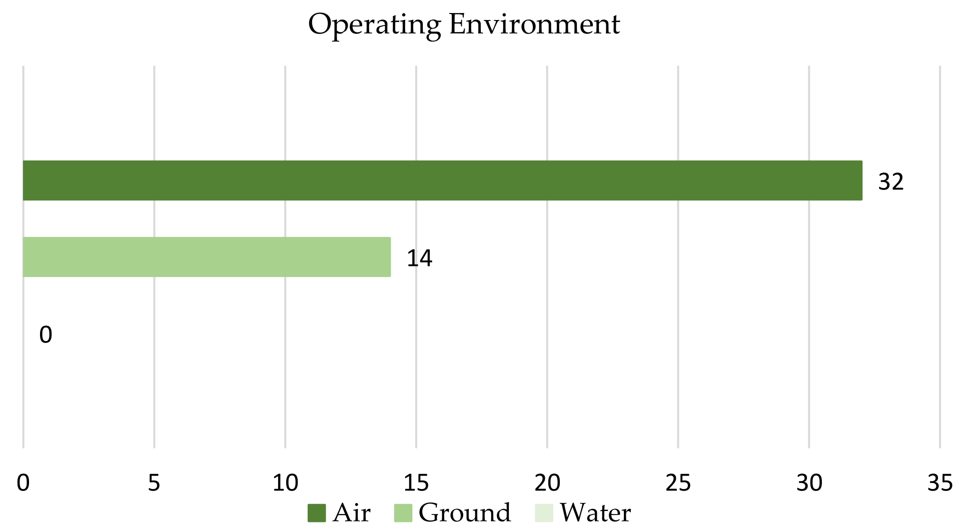


Figure 5. The distribution of vehicles by operating environment. Studies on UAVs, ground vehicles, and water vehicles cover 70%, 30%, and 0%, respectively.

Figure 6 shows that articles on the use of autonomous vehicles in hospital environment have been written continuously since 2012. In the early years until 2017, there were many articles about ground-based vehicles and few about drones. However, in recent years, the trend has reversed, and the number of publications on aerial vehicles has greatly increased. This interest is steadily growing thanks to the myriad of new applications that drones seem to fulfill in the medical field.

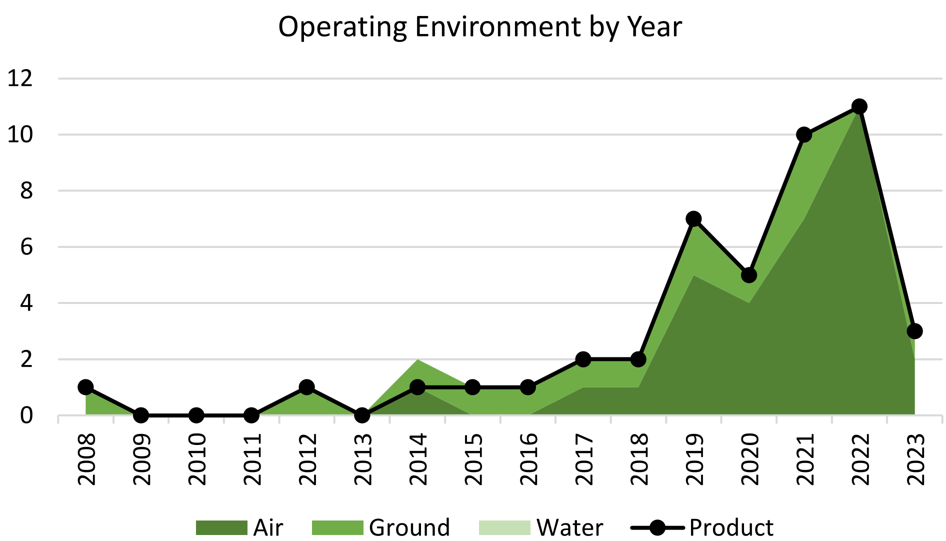


Figure 6. Distribution of the recognized documents by year and taxonomy category by operating environment. The distribution across subclasses, displayed in a stacked format, is not mutually exclusive. The total number of documents each year is shown by a black line with dots.

The analysis by document topic (see Figure 7) shows that the most-discussed topic is the development and design of innovative autonomous vehicles, with 20 out of 45 articles, representing 44%. This result shows that the scientific community considers the introduction of new devices of this type in the current healthcare system as absolutely necessary to improve the medical care of patients in terms of efficiency and safety. In addition, the use of autonomous vehicles also improves the general ergonomics of healthcare personnel, allowing them to focus more on interpersonal relationships with patients.

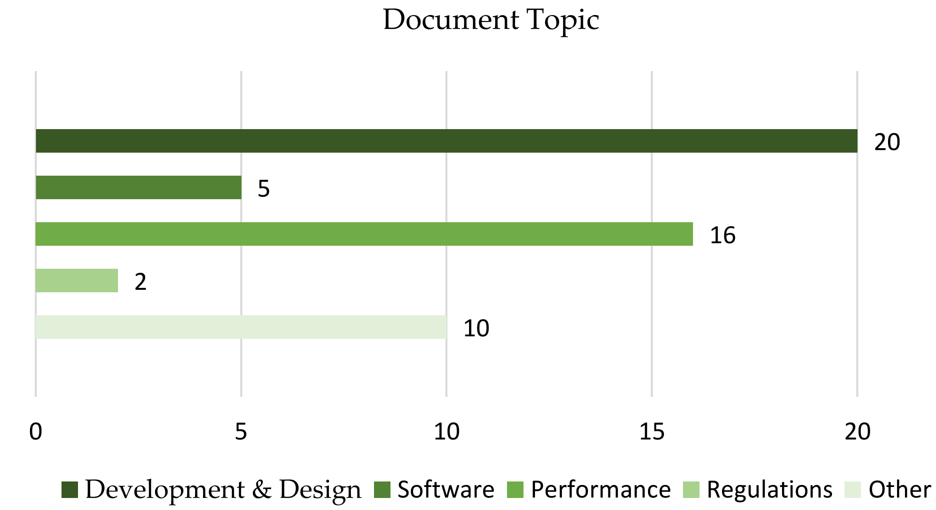


Figure 7. The distribution of papers by document topic.

Another much-discussed topic is the description of the performance of the studied autonomous vehicles. These papers analyze the operational characteristics, such as battery autonomy or movement speed, of new devices or the use of established vehicles in innovative applications. The description of the technical characteristics is often limited to the exclusive presentation of the hardware without examining the structure of the software.

Only two articles were identified in the final dataset that addressed regulations for the use of autonomous vehicles in healthcare. Both addressed regulatory issues related to the delivery of medications [10] or automated external defibrillators (AEDs) in emergency situations [11]. Given the popularity that drones are experiencing in the delivery of vital medications and the fact that this application is still in the research phase, more contributions on this topic were expected.

Among the articles in the *other* category, the most-recurring topics are the analysis of the costs associated with the implementation of an autonomous vehicle solution [12], staff training to enable health workers to make the best use of the new devices [13], and the implementation of optimization algorithms for drones aimed at reducing travel time or maximizing battery life [14,15].

Finally, Figure 8 shows the trend of the document topic by year, with an increase in publications from 2015, likely due to the increasing development and use of drones in the medical field.

The analysis of the dataset by vehicle autonomy is summarized in Figures 9 and 10, which describe the distribution of documents across categories in aggregate form and by year. The analyzed articles were divided into three categories representing the degree of autonomy of the described vehicle: *Manual*, *Semi-autonomous*, and *Autonomous*. As shown in Figure 9, a small part of the papers deals with manual devices represented by hospital carts used in healthcare facilities. The described trolleys are mainly used for the delivery of drugs or medical supplies within hospital wards [16–18], while only two articles deal with equipment combined with stretchers for simultaneous transport of goods and patients [19,20]. Technological development in autonomous driving systems has clearly shifted the focus to innovative semi-autonomous or autonomous vehicles. A look at Figure 10 shows that there were no publications on non-manual vehicles until 2016. However, from 2017 onwards, there has been a significant increase in publications, and this is due to semi-autonomous and autonomous devices.

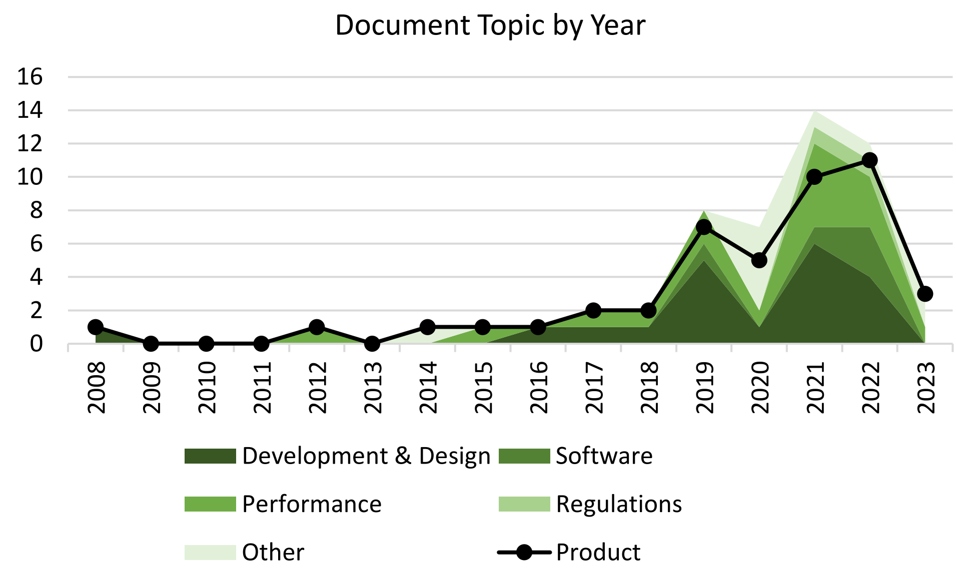


Figure 8. Distribution of the recognized documents by year and taxonomy category by document subject. The distribution across sub-classes, displayed in a stacked format, is not mutually exclusive. The total number of documents each year is shown by a black line with dots.

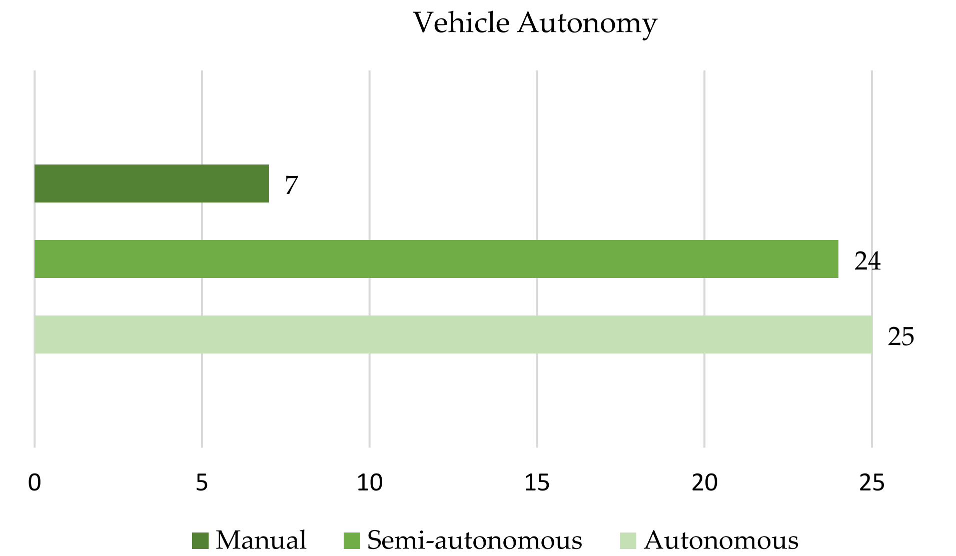


Figure 9. The distribution of vehicles by level of autonomy. Studies on manual, semi-autonomous, and autonomous vehicles cover 16%, 44%, and 40%, respectively.

Most articles in the *Semi-Autonomous* or *Autonomous* categories describe the use of drones, while few (only 18%) deal with autonomous driving vehicles in healthcare. These include analyses of automated devices for managing hospital logistics [5], such as medical waste sorting systems [21] or devices for automated transportation of medical goods [22,23]. A paper describing the use of drones, if not clearly validated by UAV design or application, is categorized as both *Semi-Autonomous* and *Autonomous*, as these vehicles can encompass both forms of movement.

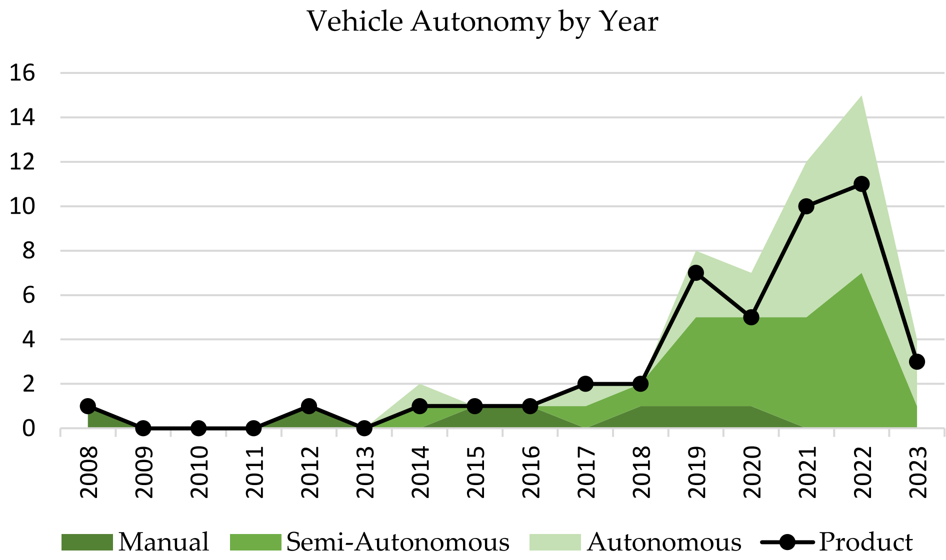


Figure 10. Distribution of the recognized documents by year and taxonomy category by vehicle autonomy. The distribution across sub-classes, displayed in a stacked format, is not mutually exclusive. The total number of documents each year is shown by a black line with dots.

Analyzing the documents by application (see Figure 11), it appears that most of the vehicles are used for healthcare tasks, i.e., distribution of drugs or medical supplies inside and outside the hospital. In fact, 94% of the work is related to these applications, while 4% is related to logistics management and 2% to other areas.

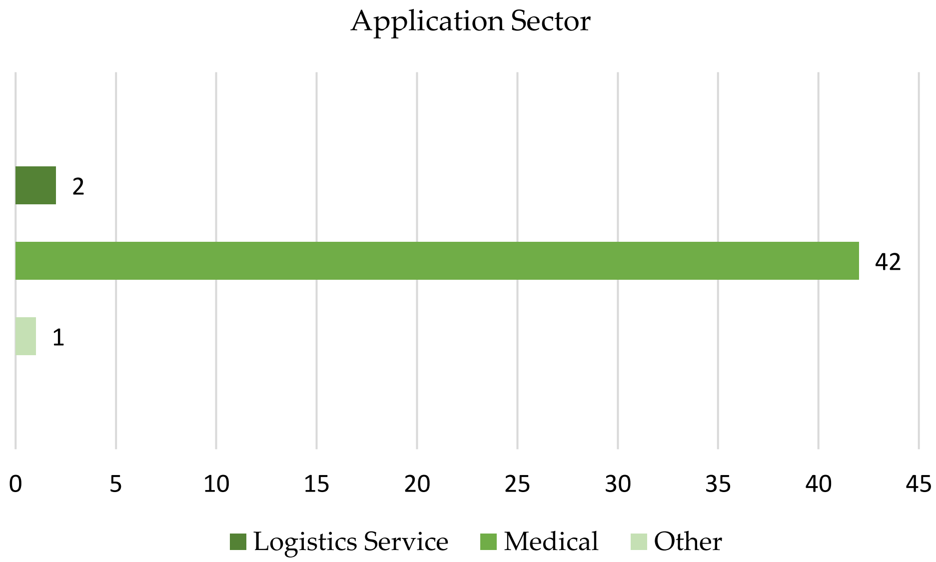


Figure 11. The distribution of vehicles by application sector. Studies on logistics service, medical sector, and other sectors cover 94%, 4%, and 2%, respectively.

Among the articles not related to medical applications, two deal with logistics management: in this case, hospital logistics in terms of medical sorting systems for waste [5,21]. Devices of this type can also be used for logistic management in sectors other than healthcare and are therefore not included in the scope *Medical*. In addition, the only document assigned to the *Other* category represents an overview of autonomous vehicles used in various sectors, such as military, agriculture, industry, and also medicine [2].

Finally, Figure 12, which represents the temporal trend in the field of vehicle applications, also shows a significant increase in publications since 2016, most likely due to the development and spread of the use of UAVs for medical applications [6,24,25].

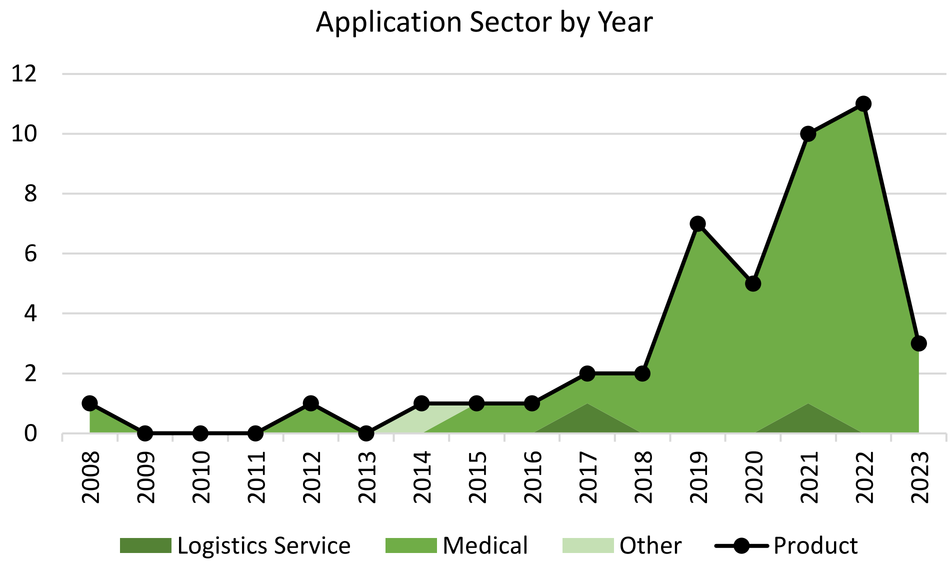


Figure 12. Distribution of the recognized documents by year and taxonomy category by application sector. The distribution across sub-classes, displayed in a stacked format, is not mutually exclusive. The total number of documents each year is shown by a black line with dots.

4. Analytical Review

4.1. Document Focus

Given the results of the literature research, more scientific papers addressing the technological features of the autonomous vehicles under consideration could be expected. Instead, it was found that almost all articles do not address the design features of the devices but rather describe applications for which they are used. With respect to drones, for example, no projects were identified for the development and/or realization of innovative drones, but rather, the papers described commercial devices used for innovative applications [6,26,27]. With regard to trolleys used in hospitals, which are present in smaller numbers, more papers describing devices under development were found than studies on ergonomics and training in usage.

The topics most frequently covered in the articles fall into four categories:

- Optimization Algorithms;
- Development and Design;
- Vibration Analysis;
- Drones for Transport of Defibrillators.

The main points of each of these themes are analyzed below.

4.1.1. Optimization Algorithms

This issue has received much attention in studies of UAV use. There are several papers describing the use of drones in the medical industry for the transport of drugs [28,29], medical devices [30,31], or even biological material [32]. In these applications, the device is used in automatic mode, meaning that it performs the entire mission from take-off to landing autonomously without the assistance of an operator. In such applications, it is important that the drone can make as many flights as possible before it needs to be recharged, which results in significant downtime. Because of these factors, flight time and battery usage are the features that the optimization algorithms focus on the most. Indeed, once the start and end points of the application have been determined, it is desirable to reduce both the battery consumption and the amount of time required to perform the task.

Otero et al. presented in 2020 [33] a strategic model to determine the optimal configuration of the supporting infrastructure for urgent drone deliveries between hospitals by selecting an optimal number of hubs and the number of UAVs required to meet the total demand. The method is based on solving a linear programming problem for which objective is to minimize a total cost function calculated as the sum of the general, battery, vehicle, and hub setup costs. A CPLEX optimizer is used for the solution, which uses the primary or dual variants of the simplex method or the interior point method.

Escribano et al. in 2020 [7] addressed a similar problem: namely, optimizing drone-assisted drug distribution by simultaneously considering hub location, battery allocation/charging, split delivery, and trajectory. They minimize the total cost of relief distribution by minimizing a cost-based objective function. The optimization algorithm is based on a custom-developed Large Neighborhood Search (LNS) metaheuristic that uses a probabilistic search to navigate through a constrained search space. In contrast to genetic algorithms, this algorithm is able to avoid local optima.

The algorithm goes through the following steps, in the following order:

1. Flight trajectory optimization;
2. Hub selection-routing algorithm.

The determination of the optimal flight trajectory is carried out with the aim of achieving the lowest battery consumption while taking into account the terrain constraints. The parameter used to monitor the energy consumption is the State of Charge (SOC) of the battery. Of course, to accurately calculate battery consumption, it is essential to determine the mass of the object to be transported and to make considerations about flight speed and acceleration. After determining the characteristics of the best trajectory, the algorithm provides for the identification of possible hubs to increase the efficiency of transporting medical equipment to healthcare facilities and then selects the most-suitable ones. In this way, it is possible to find an efficient solution for the delivery of medical equipment between different warehouses distributed throughout the territory. A warehouse is usually a hospital or healthcare facility equipped with a place for the take-off and landing of drones as well as loading and charging stations. Optimization algorithms of this type are based on the following important assumptions:

- Vertical Take-Off and Landing (VTOL) of drones;
- UAVs powered by electric batteries: this assumption allows consideration of 95% of the drones on the market;
- Flight at an altitude between 50 and 70 m: this allows for obstacle-free flight and compliance with the majority of national flight laws, which set a maximum altitude for low-weight drones between 100 and 150 m (in EU countries) [34];
- Uniform transport goods in terms of dimensions and weight;
- UAVs in Beyond Visual Line of Sight (BVLOS) mode;
- Hubs with unlimited capacity, which is a coherent hypothesis given the small size of the package a drone can transport.

In the proposed approach, the point-mass and force-balancing model is fundamental and is formulated as an optimum control problem (OCP). The model considers aerodynamic and kinematic aspects as well as battery consumption and establishes relationships between these factors. Specific state and control variables are taken into account as they influence the system state. A trajectory OCP model is then formulated. This model primarily focuses on minimal changes to heading angles, aligning with the overarching objective of minimizing battery consumption. The ultimate aim of the model is to maximize the state-of-charge at the conclusion of the flight [7].

Among the identified papers, an article by Chen et al. in 2021 [22] evaluates the performance of an off-the-shelf medical transport system by Telelift (Telelift GmbH, Munich, Germany). The system is an in-hospital medical material delivery system for the automation of transport from the warehouse to the patient and, according to the authors, has been installed in hospitals in more than 40 countries. The delivery is made by a conveyor system installed on the ceiling or on top of the wall. The item to be transported is placed in a movable container that slides on rails through the hospital wards. The automatic drug delivery system consists of two basic components:

1. Locked and electronically controlled vehicles;

2. A track network realized through horizontal, vertical, and curved rails.

The process-optimization study is carried out under two different conditions: a first one in which there is regular demand for medicines, and a second one in which a significant increase in the demand for medicines is assumed due to an exceptional situation. For each scenario, some strategic decisions are analyzed with the aim of respecting a lead time defined by the process requirements. The algorithm is able to determine the optimal number of vehicles to increase the efficiency of the system, both for regular demand and for peak demand. In addition, the trade-off between the number of vehicles and the number of pharmacists can be explored to determine whether adding more vehicles or medical staff leads to better performance. Finally, the algorithm for managing high-priority departments provides two different uses for the vehicles: first, the vehicles can be shared among departments so that each department has an equal opportunity to use them, and second, some vehicles can be assigned only to high-priority departments. By calculating the ideal number of vehicles and medical staff to meet the given time and drug distribution constraints, the optimization algorithm enables the determination of the best strategies to minimize drug delivery times within the hospital. The authors developed a stochastic model to capture the stochastic interactions between demand, pharmacy, and transport. Specifically, two nested queuing models were created, one for regular and one for peak demand, and a two-moment approximation method and an aggregation approximation algorithm were used for the solution. The analytical model was validated in the simulation by a 3D simulation model created in Flexsim.

With the help of optimization algorithms, drones can be more effectively used in the Emergency Medical Service System [15] or as devices to improve the management of pandemic situations. In particular, the article by Lv et al. from 2022 [35] examines the effect of Digital Twins (DTs) in UAVs for the prevention and control of the COVID-19 pandemic. The authors present a digital twin to be used to predict possible situations in the process of urban COVID-19 prevention and control. They developed a prediction model algorithm that includes an improved AlexNet, a deep convolutional neural network (CNN) with multiple layers that extracts features from the image data transmitted by UAVs, and a SoftMax classifier. The prediction accuracy was 95.58%, and the prediction speed was about 35 frames per second. In this context, the use of drones offers numerous potential applications, such as area inspection, temperature measurement, aerial panoramic reconnaissance, crime detection, and information sharing. In terms of temperature measurement, drones equipped with infrared thermometers and facial recognition cameras are used to measure and record the body temperatures of numerous people simultaneously [36,37]. This system is particularly efficient in densely populated cities where conventional methods cannot provide the required performance. In addition, the same drones, when equipped with high-resolution cameras and 5G technology, can be used to monitor urban areas, for example, to detect violations of the lockdown protocol in place during COVID-19 [38]. Finally, one can consider the use of UAVs in information dissemination, for example by sharing data on pandemic development or disseminating knowledge on epidemic prevention [39].

4.1.2. Development and Design

For this topic, 12 papers out of 45 were found. In the articles dealing with the design and development of autonomous vehicles for the hospital sector, the TRL (Technology Readiness Level) is used as a parameter to determine the level of development of devices. The analysis of this indicator shows that almost all the identified papers present devices with a TRL value between 4 and 7, indicating the description of technologies or, at most, prototypes tested in industrial environments. Only three papers, all with a TRL value of 9, the highest possible, deal with already developed and tested devices. The first article, by Amicone et al. in 2021, details a Smart Capsule that allows medical personnel to initiate drone autonomous deliveries to convey medical supplies [8]. The work by Chen et al. in 2021 [22], as discussed before in Section 4.1.1, evaluates the performance of a new automated medicine delivery (AMD) system used to transport medical supplies from warehouses to the patients inside hospitals. The third paper, by Saad et al. in 2019 [23], presents an automatic medical surgical trolley for surgeons to grab operating tools easily.

In addition, the literature investigation reveals that articles dealing with design issues focus on hospital trolleys [19,20], while development issues are more related to UAVs used for innovative applications [29,40,41]. Works have also been identified describing the performance of a drone used for transporting medical products [3] or a neurological emergency trolley [17].

Of particular interest is the work by Amicone et al. in 2021 [8] that describes the development and implementation of a system to manage the transport of medical products using drones. The device, called Smart Capsule, consists of a smart artificial intelligence (AI) enclosure that is mounted on the drone used for transport. The innovation of this device as stated by the authors is that it is designed as a container for transporting medical materials, but it can also control and guide the drone. The main components of the system are:

- Mechanical container, made of polyurethane;
- Electronics;
- Software platform, consisting of backend software, an app, and electronic firmware.

The device is equipped with various sensors that monitor both the product being transported and the flight. There are temperature, vibration, and humidity sensors to detect the condition of the contents and GPS and 4G systems to monitor trajectory and flight data. Through the use of AI, the Smart Capsule is able to make autonomous decisions to ensure the efficiency and safety of transportation, such as stopping or pausing a flight, changing a mission or correcting inaccurate trajectories (the device has its own GNSS positioning system in addition to the one integrated in the drone). According to the authors, the Smart Capsule is capable of autonomous flight management and does not require the presence of an experienced pilot. The flight is technically managed by the commercial controller integrated in the drone, but the Smart Capsule controls and defines the actions to be performed. Machine learning has been used to develop proprietary algorithms based on data sets. The article does not provide details about the types of AI algorithms developed and their functionalities but provides a general overview. The central role of AI becomes clear, as it enables the on-board control intelligence to take command of the flying vehicles to which it is attached, or it can make the on-board control redundant. This dual function provides additional security for the successful execution of missions. The AI-equipped Smart Capsule is able to make autonomous decisions about distances, route changes, emergency maneuvers, and landings. This AI-driven autonomy proves indispensable when it comes to complying with strict regulations for drone flights in urban areas and systematically mitigating operational risks through mandatory, specialized risk assessments. The authors also explain that in anticipation of future advances, artificial intelligence (AI) algorithms developed for visual imaging, such as object recognition, could be utilized. The device is designed to fit all professional drones on the market and has a modular and flexible configuration that allows the delivery of different medical products such as blood bags, organs, and drugs. It complies with the European Medicines Agency and Food and Drug Administration (FDA) Good Distribution Practice (GDP) requirements. Testing of the device has shown that it can significantly reduce delivery time (up to 80%) and also transportation costs (up to 28%).

In the work of Saad et al. [23], the development of an automated medical surgical trolley to assist surgeons and nurses in the operating room is discussed. The automatic surgical trolley is a technological solution that improves surgical procedures and ensures safety in the operating room by facilitating the transport of medical equipment. The cart is expected to make surgical procedures more efficient and reduce accidents. The authors emphasize the importance of workplace safety given the potential impact on patient care and the hospital staff. The main focus in the development and production of the trolley is the need for a safe working environment. Precautions include avoiding over-voltage, providing adequate insulation, increasing the grip of the cart's tires, and using food-safe coatings to protect against germs and rust. The trolley's hardware includes an Arduino

Uno R3 microcontroller, ultrasonic sensors for obstacle detection, an electric window motor for movement, and an IP camera with Wi-Fi for monitoring. The algorithm governing the automated medical surgical trolley, which is driven by an Arduino Uno R3, controls a systematic process. A touchscreen controller is used to issue user instructions that control the movement of the trolley. At the same time, the Arduino communicates with an IP camera for real-time video guidance. The user instructions are processed by the Arduino and translated into commands for the motors to move the trolley. Ultrasonic sensors are used for collision avoidance by dynamically adjusting the trolley's movement when obstacles are detected. Safety measures include reducing the torque of the motors to minimize impact and changing the tire surface for enhanced grip. Data are transmitted and received between an IP camera and a Wi-Fi module. A smartphone is used to control the autonomous medical surgical trolley's entry into and exit from the operation room. The medical surgical trolley can move automatically in accordance with the instruction given. Consequently, the trolley can lead nurses and surgeons throughout the operation room. To ensure that the automated surgical cart does not hit anything else, ultrasonic sensors help to prevent collisions [23].

4.1.3. Drones for Medical Goods Delivery

The use of drones to transport medical supplies, such as medications, medical devices, and biological materials, has received a lot of attention in the literature when it comes to autonomous vehicles in healthcare [42].

Most of the works addressing this topic describe the use of UAVs for the delivery of AEDs (Automated External Defibrillators) in the event of out-of-hospital cardiac arrest [31,43]. In emergency situations like this, where time to intervene is very short, the immediate availability of a defibrillator is critical. The use of drones can increase the efficiency of intervention and significantly reduce the time. Transporting AEDs using drones is analyzed from several perspectives, including the influence of local topography and weather conditions [44], improving efficiency in terms of shorter delivery time compared to using ambulances [41], and conducting simulations of this application [11].

For instance, the article by Schierbeck et al. in 2022 [31] presents a feasibility study on the use of drones to transport AEDs in the case of OHCA. The number of investigated cases is small, as only 12 interventions are considered. The degree of success of the transport was 92%, with 11 successful transports and one failed. In 64% of the successful cases, the drone arrived ahead of the EMS (emergency medical service), saving an average of 1:52 min. The average flight distance was 3.1 km, and AED delivery was feasible within 9 m. The AED is delivered with a commercial drone, the DJI Matrice 600 Pro Hexacopter (by DJI, PRC), which is modified in its structure so that it can carry the load. It is equipped with a winch system for delivering the defibrillator and a parachute for emergency situations. When an emergency call is received, the pilot starts the flight procedure, and the optimization software estimates the optimal flight path to minimize the delivery time. The drone performs the flight autonomously until it reaches the coordinates of the suspected OHCA, at which point the remote pilot confirms the delivery of the AED. This service is intended to support the traditional ambulance rescue service.

Valenzuela et al. in 2000 [45] analyzed the effect of intervention time on the probability of survival from cardiac arrest. The study examined the use of AEDs in 105 cases of ventricular fibrillation (VF) that occurred in several casinos in the USA. The defibrillator is used by casino security officers, who are trained in advance. The location of the AEDs within the building ensures an intervention time of less than three minutes. According to the data, the survival rate was 74% when the intervention was within 3 min, but it decreased to 49% when the 3-min limit was exceeded. Although no drones or other autonomous vehicles are actually used in this article to deliver the defibrillator, this paper introduces a significant technical requirement for drones expected to work as defibrillator delivery systems since it identifies a 3-min reference threshold for a time-saving intervention.

To assess the importance of reducing intervention time in cardiac arrest, Claesson et al. in 2017 [46] compared the chances of survival when the AED was used before the arrival of the emergency medical services (EMS). OHCA cases occurring in western Sweden were analyzed for the study. Of the total 1092 interventions, 15% of ventricular fibrillations were defibrillated before the arrival of the EMS, with 46% performed with a public AED on site and 54% by first responders (FR). The results of the analysis show that the average intervention time is 6.5 min when an AED is used, 11 min when defibrillation is performed by FR, and 14 min when EMS arrives. The 30-day survival rate is 68% when a defibrillator is used but decreases to 29% when defibrillation by FR is used and to 23% when intervention by EMS is considered. The results show a significant correlation between intervention time and survival probability, with the latter decreasing rapidly over time. The article does not specifically address the provision of AEDs with drones but conducts a study aimed at assessing the chances of survival in cardiac arrest depending on the time of intervention. Once again, the importance of rapid intervention is emphasized.

Analysis of the literature shows that there is a strong correlation between defibrillation time and the chance of survival in cardiac arrest, which emphasizes the fundamental importance of an efficient and rapid intervention service. The creation of intervention systems, whether by ambulance or drone, is based on these medical considerations. Once a maximum intervention time for defibrillation has been set, this becomes a technical requirement for the configuration of the service, as intervention must be guaranteed within this limit.

Other articles describe more generally the transport and delivery of medical supplies using drones. Considerable attention has been paid to the possible use of this application in developing countries, where it would have enormous potential. For example, studies have been done on the distribution of drugs or vaccines in rural areas far from population centers [28], on the transport of blood bags in Rwanda [32], and on the delivery of medical equipment in Ghana [30].

Particularly noteworthy is the use of drones in medical facilities as described in the paper by De Silvestri et al. in 2022 [40]. UAVs are intended for the exchange of medicines and medical equipment within the hospital: that is, between the different buildings of the San Raffaele hospital in Milan, Italy. According to our data, this is the only case/example of use of drones for delivery across the buildings of a single hospital. In the paper, the goal of the research is to improve the efficiency of the exchange of medical supplies in hospitals. The authors assert that healthcare workers are responsible for internal transportation, but this system suffers from a number of inefficiencies and bottlenecks, including the need to move between different buildings within the healthcare center and to use elevators. Drones can be used to transport goods from collection points to nearby locations where they are needed, taking advantage of the shorter delivery times that a drone-based system can provide. This means that healthcare workers do not have to travel long distances to pick up potentially vital medical supplies. However, the system, as designed, requires the introduction of two new professions: a fleet manager who oversees the various drones in use and remote pilots who perform the actual delivery flights. According to the authors, the project would make it possible to increase the readiness of the medical goods exchange system within hospitals, increasing the safety of healthcare, especially that related to urgent drug delivery.

Besides the mostly technical evaluations, the products in this class are also concerned with additional, cross-cutting aspects, such as the acceptance and user-friendliness of these devices by the end users. When evaluating the use of drones for the transport of medical devices, it is important to consider the acceptance of this innovation by employees. This issue was explored in the work by Sham et al. of 2022 [28] with a survey to 272 healthcare workers from various hospitals in rural Malaysia. The average age of the respondents was 36 years. Respondents were asked to give their opinions on the use of drones for the delivery of medicines and vaccines. The result of the survey shows that more than half of the healthcare workers strongly agree with this innovative application.

This trend is also confirmed by the work of Comtet et al. in 2021 [47], in which 400 employees from three Norwegian healthcare organizations were asked the same question. The majority of respondents, about 70%, supported the widespread use of drones to transport medical equipment.

4.1.4. Vibration Analysis

As discussed in the previous paragraph, the use of drones to transport medical materials is becoming increasingly popular in various application areas. However, there are several articles in the literature about the impact that aerial transport can have on the quality and integrity of medical products. Even though the use of UAVs guarantees greater efficiency and shorter delivery times, it can expose the object to deterioration due to the vibrations caused by drone transport. Some negative consequences due to vibration can be:

- Decreased quality of the transported load;
- Decreased equipment reliability;
- Decreased fatigue life;
- Inaccurate information from measuring instruments.

The article by Geronel et al. in 2022 [6] presents an analysis of the vibrations to which cargo is subjected during drone transport. Data were collected by simulating flights with a commercial quadcopter. The used drone was the DJI Phantom 3 Standard (by DJI, Shenzhen, China) with a weight of 1.3 kg and a diagonal length of 0.35 m. The object being transported was an iPhone XR (by Apple, Cupertino, CA, USA) weighing 194 g. The same tests were performed with four different payload attachment configurations:

1. No payload, to set a zero-point of comparison;
2. Fixed payload, directly attached to the quadcopter body;
3. Swing payload, free to move in all directions;
4. Fixed payload with additional mass of 150 g.

The vibrations caused by drone transport were evaluated in the three phases of flight, i.e., take-off, cruise, and landing. The performed tests showed how environmental phenomena (such as gusts, aggressive maneuvers, and propeller rotation) can increase the vibrations transmitted from the drone components to the payload. Consequently, when analyzing the use of drones for the transport of medical equipment, it is important to pay particular attention to the development of a payload attachment suitable to reduce vibrations. Several controllers have been developed specifically to solve vibration problems in quadcopters and helicopters [6,30]. In one particular strategy [48], a controller was integrated with a Kalman filter to derive estimated states and vibration characteristics, which were then applied to the system with the goal of compensation. Various Neuro-Fuzzy controllers were used to mitigate the effects of the vibrations. A controller was configured to intervene when vibrations occur and to increase the stability of the camera by mitigating the negative effects of the vibrations on the subsystems [6].

4.2. Vehicle Functionality

An important aspect to evaluate is the functionality of autonomous vehicles, i.e., the purpose for which the device is used. In fact, the examined vehicles can be used not only in direct patient care but also in logistical operations and auxiliary services that are fundamental to the proper operation of a hospital facility. Further, the final use of the vehicle may introduce relevant characteristics in the design of the device, as well as significant constraints, like technical elements or normative requirements.

Nearly all autonomous vehicles used in healthcare perform functions that serve patient care. As a result, 94% of the publications analyzed deal with devices that are classified as medical. The remaining 6% perform tasks related to logistical services (see Figure 11).

4.2.1. Medical

Most of the vehicles mentioned in this category are devices for moving objects. For example, the use of drones to transport medicines, medical equipment, or AEDs is widespread. These drones are used when immediate distribution is required and traditional ambulance transport is not sufficient. Other vehicles used for transporting objects include hospital trolleys, which are exploited to transport medications or medical equipment within healthcare facilities. There are articles in the literature about transporting people with hospital trolleys. These are usually coupled to a stretcher and are used for emergency care of patients in critical condition.

For instance, in a work by Yin et al. [19], a team of "Human Factors" and "Design Thinking" experts conducted an analysis of the emergency room environment, including a thorough observation of used procedures and items. After identifying commonly used items in patient care, a prototype of a new reading table was developed for attachment to stretchers. The new table had an expandable surface, a compartment for smaller items, hooks for hanging equipment, and a transparent pocket for documents. While the prototype was not used in the emergency department, the article highlights the importance of collaboration between ergonomics and design professionals to improve healthcare processes and tools [19].

Another device is the system proposed by Saltzerr et al. [20]: a trolley equipped with a life support unit that is used in emergencies to stabilize patients in order to prevent their condition from deteriorating while they wait for medical personnel to arrive. In fact, transporting critically injured trauma patients within a hospital, whether from the resuscitation room to the operating room, radiology department, or intensive care unit, is a critical moment for maintaining and monitoring vital signs. By evaluating critically ill patients in the ICU, research has identified that multiple adverse events can occur in up to 70% of cases, with serious complications requiring intervention occurring in up to 12% of patient transports. Transport of critically injured trauma patients carries a similar or higher risk of complications. This system, called trauma life support cart, consists of a transport trolley, a life support unit, and a patient couch. The patient is placed on the radiolucent stretcher, which can be used for scans and other procedures. The transport cart is directly connected to the stretcher, so the patient does not need to be repositioned. The life support unit includes equipment such as a ventilator, monitor, suction device, oxygen and air cylinders, and infusion pumps. The cart is designed to operate for at least 30 min without recharging. According to the authors, the trauma life support cart has been in use since March 2006 and has reduced the number of disorganized and potentially life-threatening events when transporting trauma patients in the hospital [20].

4.2.2. Logistics Service

This category includes vehicles used for activities necessary to maintain the smooth operation of a healthcare facility. There are few articles in the literature that address this type of equipment. Nonetheless, among them there are studies that describe the use of automated guided vehicles (AGVs) for waste disposal in hospitals, which serve as an automated system for sorting medical waste. According to He et al. [21], the exponential growth of China's healthcare sector, exacerbated by the COVID-19 pandemic, has led to a surge in medical waste generation, making its safe and efficient disposal an urgent concern. Automation technology, particularly in sorting systems, offers a solution to the challenges posed by the enormous volumes of medical waste. This study suggests that the use of a vertical sorting system, as used in e-commerce warehouses, can improve the sorting process. The study introduces a mixed-integer linear programming model to optimize the allocation of resources such as presorting stations and AGV to improve the efficiency of medical waste sorting. To solve this problem, a variable neighborhood search algorithm based on dynamic programming was developed.

The 2017 paper by Bacik et al. [5] analyzes the use of autonomous vehicles to transport food, medical equipment, and waste between hospital wards. Researchers have created a logistics solution suitable for the demanding tasks performed in hospitals. The capabilities of the system, called Pathfinder, were demonstrated during initial on-site testing in July–August 2017 at Košice-Šaca Hospital in the Slovak Republic. It was used to transport medical supplies between a logistics warehouse on the first floor and various sections throughout the hospital. Navigation over multiple floors presented an additional challenge and required extensive map management. Dynamic map switching was used, with synchronization tags placed near the elevator doors on each floor. The Pathfinder used its wide-angle camera to detect these tags, determine the current floor, and load the appropriate map.

4.3. Sensors

Another point to be examined is the presence of sensors on board the devices studied in the articles under review. As shown in Figure 13, there is a high presence of cameras, accelerometers, GPS, and gyroscopes, which correlates with the relevant presence of articles with drones, as they represent the typical minimum set of sensors available on those devices.

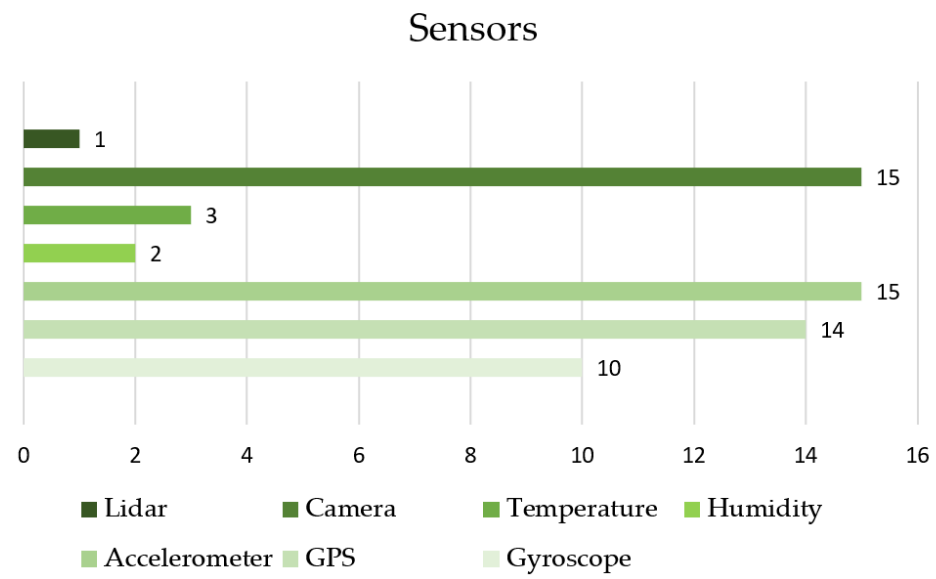


Figure 13. Sensors present in the articles under review.

In the literature, references can be found regarding the equipping of analyzed vehicles with temperature and/or humidity sensors that are used to monitor the environmental conditions during the delivery of medicines, vaccines, organs, or blood [8,20,49].

In the following, an analysis of the individual sensors is presented.

4.3.1. LIDAR

Light detection and ranging (LIDAR) technology allows direct measurement of three-dimensional (3D) objects and spaces. Active sensors emit light and record the reflection of this light as the depth of objects [50]. In the current analysis, the LIDAR sensor was found in a single article: it is used in the Pathfinder driverless transport vehicle for hospital logistics [5]. The Pathfinder's navigation system is based on state-of-the-art SLAM (Simultaneous Localization and Mapping) technology. This technology is responsible for creating and continuously updating a map of the surrounding area while simultaneously monitoring the position of the device within that map. The primary data sources of the navigation system are the front and rear LIDAR sensors. Specifically, the version of the Pathfinder described by the authors is equipped with two LMS100 LIDARs (by SICK, Minneapolis, MN, USA) that provide detailed line scans of the robot's environment. These LIDARs provide a resolution of 0.25 degrees, a maximum detection range of 18 m, and a wide field of view of 270 degrees, and they operate at a frequency of 25 Hz. To ensure safe and collision-free operation, a full 360-degree scan of the robot's environment is essential, and this technology is one of the most-advanced in terms of spatial mapping [5].

4.3.2. Camera

As depicted in Figure 13, cameras can be found in 15 articles. This kind of sensor is indeed a basic tool onboard drones, allowing them to see and record from the drones' perspective, and since there is a high presence of articles about drones, also a high number of papers involving cameras was to be expected. Drones equipped with cameras play a critical role in the remote delivery of medications, especially in difficult or inaccessible areas. These camera systems provide operators with a real-time view of the drone's surroundings, enabling precise navigation and obstacle avoidance [41]. This live video feed enables pilots to make informed decisions, ensuring the safe and efficient delivery of medicines or medical equipment such as AEDs to remote or disaster-affected locations. The use of drone cameras also improves operators' overall situational awareness, reduces the risk of accidents, and improves the reliability of medical deliveries, ultimately contributing to more effective and timely access to healthcare in areas where traditional transportation methods are impractical or may be delayed [31]. In times of epidemics or pandemics, the role of camera-equipped drones in delivering medicines becomes even more important. These unmanned aerial vehicles can quickly transport critical medical supplies, including vaccines and medicines, to quarantine zones or isolated communities without exposing human couriers to the risk of infection [35,42]. Cameras are also used as image processing systems for streaming images to AGVs or for label detection and identification [5]. In other cases, a camera can be used for automatic visual guidance of self-propelled robots in hospital areas [23] or can help drones perform some critical operations, such as safe landing, automatically [29].

4.3.3. Temperature

In the analyzed literature, temperature sensors integrated into drug delivery drones serve as critical components for the safe transport of temperature-sensitive drugs and medical products [8]. These sensors constantly monitor and record environmental conditions in the drone's cargo compartment during flight. In cases where the drugs are susceptible to temperature fluctuations, such as vaccines or certain medications, these sensors play a critical role in preventing spoilage or decomposition [49]. By combining the capabilities of drones with advanced temperature monitoring technology, healthcare providers can deliver medications under controlled conditions, ensuring the effectiveness and safety of medical care upon arrival, even in remote or disaster-stricken areas [8]. Temperature sensors are also medical devices used on trauma life support trolleys to monitor the condition of patients [20].

4.3.4. Humidity

According to the collected data, moisture sensors integrated into drones ensure the integrity of pharmaceuticals and medical devices during transport. By incorporating humidity sensors, healthcare providers can maintain optimal conditions for their cargo, ensuring that drug efficacy and medical device functionality are maintained upon delivery, even in high-humidity environments [41]. This technology contributes significantly to the overall effectiveness and reliability of drone-based medical deliveries [8].

4.3.5. Accelerometer and Gyroscope

Accelerometers and gyroscopes are integral components in drones, providing essential data for flight control, stability, navigation, and safety, allowing these unmanned aircraft to operate efficiently and autonomously. This is essential for the operation of drones built for biomedical applications, like Medisky, developed by Oblesu et al. [51], or factory-integrated into commercial models used for medical purposes [29].

4.3.6. GPS

GPS (Global Positioning System) is an important technology used in drones for navigation and positioning [52]. All articles that mentioned GPS referred to drones. Drones use GPS to determine their precise geographic location, including latitude, longitude, and altitude. This information is critical for various drone applications such as mapping, surveying, and aerial photography. GPS data can be recorded in flight for analysis, which is valuable for applications such as surveying and scientific research. In urban environments with tall buildings or in heavily forested areas, GPS signals can be obstructed or degraded, which can affect drone performance [53].

5. Conclusions

This paper comprehensively examines the current state-of-the-art on the topic of autonomous vehicles for healthcare applications through a review of the scientific literature. For the analysis, 45 documents were reviewed, including articles and reviews published since 2000. The study contains two analyses with different levels of detail: a prospective review, which includes a quantitative analysis of the considered articles, and a subsequent analytical review, which addresses key aspects of the examined literature.

The tables and graphs that emerged from the analyses are intended to provide the reader with a "practical" aid for interpreting the technologies currently being used in healthcare-related sectors. However, the applied taxonomy was created to especially capture the unique features of the present dataset, whereas alternative categories and taxonomies could be used to analyze the same dataset in a different framework and for different purposes. The analysis shows that the development of technologies aimed at increasing the efficiency and quality of the services offered at hospitals and, more generally, in the clinical field related to mobile devices is of great interest not only to commercial developers but also to the scientific community. A limited number of publications addresses autonomous, ground-based mobile devices used for specific tasks, such as the transport and distribution of pharmaceuticals or medical devices or the transport of patients. For the studied application areas, most of the papers found in the literature concern the development and use of drones.

The results of the study indicate a growing trend in research questions related to drones delivering AEDs as well as medical devices and pharmaceuticals; this shows the great interest of the research community in these topics. New trends will certainly emerge in these areas, and given the rapid proliferation of drones and the new technologies associated with them, it is very likely that they will become a fundamental support in healthcare.

From the carried-out analysis, it appears that there is still much room for further scientific and technological contributions and progress for various lines of research, such as: (i) the development and integration of artificial intelligence techniques in these devices to develop ever-more effective decision-making autonomy and movement planning and ever-better interaction with users; (ii) the ever-greater integration of sensors, with analysis of the potential additional functions that higher levels of sensor integration can enable, or, again in the specific case of drones, (iii) the development of more-effective techniques for compensating for vibration phenomena, which can significantly reduce the risk of injury of the delivered items. This review aims to be a useful tool for other researchers interested in the addressed topics by easing access to the solutions studied, developed, and described by others and enhancing their visibility as inspiration for researchers and healthcare professionals in a constantly evolving sector such as healthcare.

Author Contributions: Conceptualization, P.M., D.C., C.A., and M.T.; methodology, P.M., D.C., C.A., and M.T.; formal analysis, P.M. and D.C.; investigation, P.M., D.C., C.A., and M.T.; data curation, P.M., D.C., C.A., and M.T.; writing—original draft preparation, P.M. and D.C.; writing—review and editing, C.A. and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

Abbreviations

The following abbreviations are used in this manuscript:

AED	Automated External Defibrillator
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AMD	Automated Medicine Delivery
BVLOS	Beyond Visual Line Of Sight
CNN	Convolutional Neural Network
DT	Digital Twin
EMS	Emergency Medical Service
EU	European Union
FDA	Food and Drug Administration
FR	First Responder
GDP	Good Distribution Practice
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
ICU	Intensive Care Unit
LIDAR	LIght Detection And Ranging
LNS	Large Neighborhood Search
MDPI	Multidisciplinary Digital Publishing Institute
OCP	Optimum Control Problem
OHCA	Out-of-Hospital Cardiac Arrest
PAD	Public Access Defibrillation
SLAM	Simultaneous Localization And Mapping
SOC	State-Of-Charge
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
USA	United States of America
VF	Ventricular Fibrillation
VTOL	Vertical Take-Off and Landing

Appendix A. Classification Tables

In the following, an extract of the tables resulting from the applied classification procedure is presented as Table A1.

Table A1. Literature classification. From the left: Reference ID) unique code of the entry; Document Type) A = article, R = review; Operating Environment) 1 = air, 2 = ground, 3 = water; Document Topic) 1 = development and design, 2 = software, 3 = performance, 4 = regulation, 5 = other; Vehicle Autonomy) 1 = manual, 2 = semi-autonomous, 3 = autonomous; Application Sector) 1 = logistics service, 2 = medical, 3 = other.

Reference ID	**Document Type**	**Operating Environment** ***op***			**Document Topic** ***t***					**Vehicle Autonomy** ***aut***			**Application Sector** ***as***		
		1	**2**	**3**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**1**	**2**	**3**
Søraa_2021 [4]	A		✓						✓			✓		✓	
He_2021 [21]	A		✓			✓						✓	✓		
Otero_2020 [33]	A	✓							✓		✓			✓	
Bacik_2017 [5]	A		✓		✓							✓	✓	✓	
Ren_2023 [14]	A		✓						✓			✓		✓	
Geronel_2022 [6]	A	✓					✓				✓	✓		✓	
Prasad_2019 [3]	A	✓					✓				✓	✓		✓	
Escribano_2020 [7]	A	✓							✓		✓	✓		✓	
Park_2023 [15]	A	✓							✓			✓		✓	
Goetzendorf_2021 [54]	A	✓			✓						✓			✓	
Bloss_2014 [2]	R	✓	✓						✓		✓	✓		✓	✓
Yakymets_2022 [55]	A	✓					✓				✓	✓		✓	✓
Lv_2022 [35]	A	✓				✓						✓	✓	✓	✓
Fernàndez_2020 [13]	A		✓						✓	✓				✓	

Table A1. *Cont.*

Reference ID	Document Type	Operating Environment *op*			Document Topic *t*					Vehicle Autonomy *aut*			Application Sector *as*		
		1	2	3	1	2	3	4	5	1	2	3	1	2	3
Saltzherr_2008 [20]	A		✓		✓					✓				✓	
Rajeswaran_2012 [56]	A		✓				✓			✓				✓	
Tow_2015 [16]	A		✓				✓			✓				✓	
Tsima_2019 [18]	A		✓				✓			✓				✓	
Yin_2016 [19]	A		✓		✓					✓				✓	
Saad_2019 [23]	A		✓		✓							✓		✓	
Ajzenberg_2018 [17]	A		✓				✓			✓				✓	
De Silvestri_2022 [40]	A	✓										✓		✓	
Liu_2023 [9]	R	✓					✓				✓	✓		✓	
Choi_2021 [44]	A	✓					✓				✓	✓		✓	
Schierbeck_2022 [31]	A	✓					✓				✓	✓		✓	
Claesson_2017 [26]	A	✓					✓				✓			✓	
Rees_2021 [11]	A	✓			✓		✓	✓			✓			✓	
Poljak_2020 [57]	R	✓			✓				✓		✓	✓		✓	
Ll_2021 [58]	A	✓			✓							✓		✓	
Mohd_2021- [59]	A	✓			✓		✓				✓	✓		✓	
Damoah_2021 [30]	A	✓					✓					✓		✓	
Shi_2022 [60]	A	✓			✓						✓	✓		✓	
Sham_2022 [28]	A	✓							✓			✓		✓	
Rahul_2019 [43]	A	✓			✓						✓			✓	
Nedelea_2022 [42]	A	✓			✓	✓					✓			✓	
Josephin_2018 [49]	A	✓			✓						✓			✓	
Baloola_2022 [29]	A	✓			✓						✓			✓	
Nimilan_2019 [41]	A	✓			✓	✓					✓			✓	
Nenni_2020 [12]	A	✓					✓		✓		✓			✓	
Obulesu_2019 [51]	A	✓			✓							✓		✓	
Hogan_2022 [10]	A	✓						✓				✓		✓	
Ackerman_2019 [32]	A	✓			✓						✓			✓	
Purahong_2022 [27]	A	✓			✓	✓					✓			✓	
Amicone_2021 [8]	A	✓			✓							✓		✓	
Chen_2021 [22]	A		✓		✓		✓				✓			✓	

References

1. Khalid, M.; Awais, M.; Singh, N.; Khan, S.; Raza, M.; Malik, Q.B.; Imran, M. Autonomous Transportation in Emergency Healthcare Services: Framework, Challenges, and Future Work. *IEEE Internet Things Mag.* **2021**, *4*, 28–33. [CrossRef]
2. Bloss, R. Unmanned vehicles while becoming smaller and smarter are addressing new applications in medical, agriculture, in addition to military and security. *Ind. Robot. Int. J.* **2014**, *41*, 82–86. [CrossRef]
3. Prasad, G.; Abishek, P.; Karthick, R. Influence of unmanned aerial vehicle in medical product transport. *Int. J. Intell. Unmanned Syst.* **2019**, *7*, 88–94. [CrossRef]
4. Søraa, R.A.; Fostervold, M.E. Social domestication of service robots: The secret lives of Automated Guided Vehicles (AGVs) at a Norwegian hospital. *Int. J. Hum. Comput. Stud.* **2021**, *152*, 102627. [CrossRef]
5. Bacik, J.; Durovsky, F.; Biros, M.; Kyslan, K.; Perdukova, D.; Padmanaban, S. Pathfinder-Development of Automated Guided Vehicle for Hospital Logistics. *IEEE Access* **2017**, *5*, 26892–26900. [CrossRef]
6. Geronel, R.S.; Begnini, G.R.; Botez, R.M.; Bueno, D.D. An overview on the use of unmanned aerial vehicles for medical product transportation: Flight dynamics and vibration issues. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 349. [CrossRef]
7. Macias, J.E.; Angeloudis, P.; Ochieng, W. Optimal hub selection for rapid medical deliveries using unmanned aerial vehicles. *Transp. Res. Part C Emerg. Technol.* **2020**, *110*, 56–80. [CrossRef]
8. Amicone, D.; Cannas, A.; Marci, A.; Tortora, G. A smart capsule equipped with artificial intelligence for autonomous delivery of medical material through drones. *Appl. Sci.* **2021**, *11*, 7976. [CrossRef]
9. Liu, X.; Yuan, Q.; Wang, G.; Bian, Y.; Xu, F.; Chen, Y. Drones delivering automated external defibrillators: A new strategy to improve the prognosis of out-of-hospital cardiac arrest. *Resuscitation* **2023**, *182*, 109669. [CrossRef]
10. Hogan, W.; Harris, M.; Brock, A.; Rodwell, J. What Is Holding Back The Use of Drones for Medication Delivery in Rural Australia? *Sustainability* **2022**, *14*, 15778. [CrossRef]
11. Rees, N.; Howitt, J.; Breyley, N.; Geoghegan, P.; Powel, C. A simulation study of drone delivery of Automated External Defibrillator (AED) in out of Hospital Cardiac Arrest (OHCA) in the UK. *PLoS ONE* **2021**, *16*, e0259555. [CrossRef] [PubMed]
12. Nenni, M.E.; Pasquale, V.D.; Miranda, S.; Riemma, S. Development of a Drone-Supported Emergency Medical Service. *Int. J. Technol.* **2020**, *11*, 656–666. [CrossRef]

13. Achával, M.I.F.; Mammi, L.F.; FortiniCabarcos, N.; Guiñazú, G.G.; Robledo, C.A.M.; Dvorkin, J.; Monteverde, E.; Pascual, C.; Costa, C.E.; Vainstein, E.O. Assessment of emergency trolley drugs in a children's hospital. Before and after study on an educational intervention. *Arch. Argent. Pediatr.* **2020**, *118*, 234–239. [CrossRef]
14. Ren, P. Local Path Planning Method for Unmanned Vehicle Based on Model Predictive Control in Hospital Environment. *J. Test. Eval.* **2023**, *51*, 20210441. [CrossRef]
15. Park, Y.; Lee, S.; Sung, I.; Nielsen, P.; Moon, I. Facility Location-Allocation Problem for Emergency Medical Service with Unmanned Aerial Vehicle. *IEEE Trans. Intell. Transp. Syst.* **2023**, *24*, 1465–1479. [CrossRef]
16. Tow, C.Y.; Kuen, K.W. Force Evaluation and Comparison for Supply Trolley in a Hospital. *Procedia Manuf.* **2015**, *3*, 1861–1864. [CrossRef]
17. Ajzenberg, H.; Newman, P.; Harris, G.A.; Cranston, M.; Boyd, J.G. A "Neurological Emergency Trolley" reduces turnaround time for high-risk medications in a general intensive care unit. *Intensive Crit. Care Nurs.* **2018**, *44*, 40–44. [CrossRef]
18. Tsima, B.M.; Rajeswaran, L.; Cox, M. Assessment of cardiopulmonary resuscitation equipment in resuscitation trolleys in district hospitals in Botswana: A cross-sectional study. *Afr. J. Prim. Health Care Fam. Med.* **2019**, *11*, a2029. [CrossRef]
19. Yin, S.; Jun, J.; Siew, H.; Bee, S.; Ng, I.; Putra, A.S.; Ang, A. Functional redesign of the Hospital trolley-Bed tray table. *Ergon. Des.* **2016**, *24*, 20–26. [CrossRef]
20. Saltzherr, T.P.; Luitse, J.S.; Hoogerwerf, N.; Vernooij, A.S.; Goslings, J.C. Facilitating in-hospital transport of trauma patients: Design of a trauma life support trolley. *Injury* **2008**, *39*, 809–812. [CrossRef]
21. He, X.; Quan, H.; Lin, W.; Deng, W.; Tan, Z. AGV Scheduling Optimization for Medical Waste Sorting System. *Sci. Program.* **2021**, *2021*. [CrossRef]
22. Chen, W.A.; Koster, R.B.D.; Gong, Y. Performance evaluation of automated medicine delivery systems. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *147*, 102242. [CrossRef]
23. Saad, N.M.; Abdullah, A.R.; Noor, N.S.; Hamid, N.A.; Syahmi, M.A.M.; Ali, N.M. Automated medical surgical trolley. *Int. J. Electr. Comput. Eng.* **2019**, *9*, 1822–1831. [CrossRef]
24. Tuğrul, K.M. *Drone Technologies and Applications*; IntechOpen: London, UK, 2023.
25. European Commission. *A Drone Strategy 2.0 for a Smart and Sustainable Unmanned Aircraft Eco-System in Europe*; European Commission: Brussels, Belgium, 2022.
26. Claesson, A.; Svensson, L.; Nordberg, P.; Ringh, M.; Rosenqvist, M.; Djarv, T.; Samuelsson, J.; Hernborg, O.; Dahlbom, P.; Jansson, A.; et al. Drones may be used to save lives in out of hospital cardiac arrest due to drowning. *Resuscitation* **2017**, *114*, 152–156. [CrossRef]
27. Purahong, B.; Anuwongpinit, T.; Juhong, A.; Kanjanasurat, I.; Pintaviooj, C. Medical Drone Managing System for Automated External Defibrillator Delivery Service. *Drones* **2022**, *6*, 93. [CrossRef]
28. Sham, R.; Siau, C.S.; Tan, S.; Kiu, D.C.; Sabhi, H.; Thew, H.Z.; Selvachandran, G.; Quek, S.G.; Ahmad, N.; Ramli, M.H.M. Drone Usage for Medicine and Vaccine Delivery during the COVID-19 Pandemic: Attitude of Health Care Workers in Rural Medical Centres. *Drones* **2022**, *6*, 109. [CrossRef]
29. Baloola, M.O.; Ibrahim, F.; Mohktar, M.S. Optimization of Medication Delivery Drone with IoT-Guidance Landing System Based on Direction and Intensity of Light. *Sensors* **2022**, *22*, 4272. [CrossRef]
30. Damoah, I.S.; Ayakwah, A.; Tingbani, I. Artificial intelligence (AI)-enhanced medical drones in the healthcare supply chain (HSC) for sustainability development: A case study. *J. Clean. Prod.* **2021**, *328*, 129598. [CrossRef]
31. Schierbeck, S.; Hollenberg, J.; Nord, A.; Svensson, L.; Nordberg, P.; Ringh, M.; Forsberg, S.; Lundgren, P.; Axelsson, C.; Claesson, A. Automated external defibrillators delivered by drones to patients with suspected out-of-hospital cardiac arrest. *Eur. Heart J.* **2022**, *43*, 1478–1487. [CrossRef]
32. Ackerman, E.; Koziol, M. The Blood R Zipline's medical delivery drones are changing the game in Rwanda. *IEEE Spectr.* **2019**, *56*, 24–31. [CrossRef]
33. Arenzana, A.O.; Macias, J.J.E.; Angeloudis, P. Design of Hospital Delivery Networks Using Unmanned Aerial Vehicles. *Transp. Res. Rec.* **2020**, *2674*, 405–418. [CrossRef]
34. Stöcker, C.; Bennett, R.; Nex, F.; Gerke, M.; Zevenbergen, J. Review of the current state of UAV regulations. *Remote. Sens.* **2017**, *9*, 924. . [CrossRef]
35. Lv, Z.; Chen, D.; Feng, H.; Zhu, H.; Lv, H. Digital Twins in Unmanned Aerial Vehicles for Rapid Medical Resource Delivery in Epidemics. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 25106–25114. [CrossRef] [PubMed]
36. Deren, L.; Wenbo, Y.; Zhenfeng, S. Smart city based on digital twins. *Comput. Urban Sci.* **2021**, *1*, 4. [CrossRef]
37. Alsamhi, S.H.; Lee, B.; Guizani, M.; Kumar, N.; Qiao, Y.; Liu, X. Blockchain for decentralized multi-drone to combat COVID-19 and future pandemics: Framework and proposed solutions. *Trans. Emerg. Telecommun. Technol.* **2021**, *32*, e4255. [CrossRef]
38. Gupta, M.; Abdelsalam, M.; Mittal, S. Enabling and Enforcing Social Distancing Measures using Smart City and ITS Infrastructures: A COVID-19 Use Case. *arXiv* **2020**, arXiv:2004.09246.
39. Hussain, Z. Paradigm of technological convergence and digital transformation: The challenges of CH sectors in the global COVID-19 pandemic and commencing resilience-based structure for the post-COVID-19 era. *Digit. Appl. Archaeol. Cult. Herit.* **2021**, *21*, e00182. [CrossRef]
40. Silvestri, S.D.; Pagliarani, M.; Tomasello, F.; Trojaniello, D.; Sanna, A. Design of a Service for Hospital Internal Transport of Urgent Pharmaceuticals via Drones. *Drones* **2022**, *6*, 70. [CrossRef]

41. Nimilan, V.; Manohar, G.; Sudha, R.; Stanley, P. Drone-aid: An aerial medical assistance. *Int. J. Innov. Technol. Explor. Eng.* **2019**, *8*, 1288–1292. [CrossRef]
42. Nedelea, P.L.; Popa, T.O.; Manolescu, E.; Bouros, C.; Grigorasi, G.; Andritoi, D.; Pascale, C.; Andrei, A.; Cimpoesu, D.C. Telemedicine System Applicability Using Drones in Pandemic Emergency Medical Situations. *Electronics* **2022**, *11*, 2160. [CrossRef]
43. Rahul, S.R.; Arun, V.; Prasad, S.V. Design and implementation of GPS based medical services using drone. *Int. J. Eng. Adv. Technol.* **2019**, *8*, 1683–1686. [CrossRef]
44. Choi, D.S.; Hong, K.J.; Shin, S.D.; Lee, C.G.; Kim, T.H.; Cho, Y.; Song, K.J.; Ro, Y.S.; Park, J.H.; Kim, K.H. Effect of topography and weather on delivery of automatic electrical defibrillator by drone for out-of-hospital cardiac arrest. *Sci. Rep.* **2021**, *11*, 24195. [CrossRef] [PubMed]
45. Valenzuela, T.D.; Roe, D.J.; Nichol, G.; Clark, L.L.; Spaite, D.W.; Hardman, R.G. Outcomes of Rapid Defibrillation by Security Officers after Cardiac Arrest in Casinos. *N. Engl. J. Med.* **2000**, *343*, 1206–1209. [CrossRef] [PubMed]
46. Claesson, A.; Herlitz, J.; Svensson, L.; Ottosson, L.; Bergfeldt, L.; Engdahl, J.; Ericson, C.; Sandén, P.; Axelsson, C.; Bremer, A. Defibrillation before EMS arrival in western Sweden. *Am. J. Emerg. Med.* **2017**, *35*, 1043–1048. [CrossRef] [PubMed]
47. Comtet, H.E.; Johannessen, K.A. The moderating role of pro-innovative leadership and gender as an enabler for future drone transports in healthcare systems. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2637. [CrossRef] [PubMed]
48. Arcara, P.; Bittanti, S.; Lovera, M. Periodic control of helicopter rotors for attenuation of vibrations in forward flight. *IEEE Trans. Control Syst. Technol.* **2000**, *8*, 883–894. [CrossRef]
49. Dhivya, A.J.A.; Hemalatha, R.J.; Thamizhvani, R.T.; Joseph, J.E.; Babu, B.; Chandrasekaran, R. Medical Drone—A Life Saver in Emergency Situations. *Int. J. Eng. Technol.* **2018**, *7*, 14. [CrossRef]
50. Reutebuch, S.; Andersen, H.E.; Mcgaughey, R. Light Detection and Ranging (LIDAR): An Emerging Tool for Multiple Resource Inventory. *J. For.* **2005**, *103*, 286–292.
51. Obulesu, D.; Arunkumar, G.; Mishra, B.P.; Spoorthi, J.; Manjunath, T.C. Recent advances in the design and development of a drone used for bio-medical engineering applications: Medi-sky. *Int. J. Innov. Technol. Explor. Eng.* **2019**, *8*, 796–800. [CrossRef]
52. Spilker, J.J.J.; Penina, A.; Bradford W.P.; Per, E. *Global Positioning System: Theory and Applications, Volume I*; American Institute of Aeronautics and Astronautics: Washington, DC, USA, 1996. [CrossRef]
53. Kakaes, K.; Greenwood, F.; Lippincott, M.; Dosemagen, S.; Meier, P.; Wich, S. *Drones and Aerial Observation: New Technologies for Property Rights, Human Rights, and Global Development*; New America: Washington, DC, USA, 2015.
54. Goetzendorf-Grabowski, T.; Tarnowski, A.; Figat, M.; Mieloszyk, J.; Hernik, B. Lightweight unmanned aerial vehicle for emergency medical service—Synthesis of the layout. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2021**, *235*, 5–21. [CrossRef]
55. Yakymets, V.M.; Pechiborshch, V.P.; Yakymets, V.V.; Volianskyi, P.B.; Yadchenko, D.M.; Buyun, L.I.; Ohorodniychuk, I.V. Prospects for Using Unmanned Aerial Vehicles for Medical and Biological Protection of the Civilians and the Military in the Safe Zone and the Joint Forces Operation (JFO) Area. *Sci. Innov.* **2022**, *18*, 49–60. [CrossRef]
56. Rajeswaran, L.; Ehlers, V.J. Audits of emergency trolleys' contents in selected hospitals in Botswana. *Health SA Gesondheid* **2012**, *17*, a621. [CrossRef]
57. Poljak, M.; Šterbenc, A. Use of drones in clinical microbiology and infectious diseases: current status, challenges and barriers. *Clin. Microbiol. Infect.* **2020**, *26*, 425–430. [CrossRef] [PubMed]
58. Li, J.; Goh, W.; Jhanjhi, N. A design of IoT-based medicine case for the multi-user medication management using drone in elderly centre. *J. Eng. Sci. Technol.* **2021**, *16*, 1145–1166.
59. Mohd, S.A.; Gan, K.B.; Ariffin, A.K. Development of Medical Drone for Blood Product Delivery: A Technical Assessment. *Int. J. Online Biomed. Eng.* **2021**, *17*, 183–196. [CrossRef]
60. Shi, Y.; Lin, Y.; Li, B.; Li, R.Y.M. A bi-objective optimization model for the medical supplies' simultaneous pickup and delivery with drones. *Comput. Ind. Eng.* **2022**, *171*, 108389. [CrossRef]