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A Taxonomy for Mobile Robots: Types, Applications, Capabilities, Implementations, Requirements, and Challenges

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Abstract: Mobile robotics is a widespread field of research, whose differentiation from general robotics is often based only on the ability to move. However, mobile robots need unique capabilities, such as the function of navigation. Also, there are limiting factors, such as the typically limited energy, which must be considered when developing a mobile robot. This article deals with the definition of an archetypal robot, which is represented in the form of a taxonomy. Types and fields of application are defined. A systematic literature review is carried out for the definition of typical capabilities and implementations, where reference systems, textbooks, and literature references are considered.

Keywords: robotics; mobile robot; taxonomy; requirements; challenges; capabilities; implementations; literature review; survey

1. Introduction

Robotics has become a popular research field over recent decades. The digital library IEEE Xplore (*IEEE Xplore* [1] is a relevant source for systematic literature searches in the field of computer science and engineering. All publications that have been published in connection with the IEEE are searched. The library includes conference, journal, magazine, books, courses and standards publications.) achieves about 240,000 search hits when searching for *"robot OR robotics"* in the metadata. Approximately 77,000 search hits were found in the search for mobile robots (*"mobile AND (robot OR robotics)"*).

Figure 1 shows that the popularity of robotics has been increasing almost constantly over the last ten years. The relevance of mobile robotics in scientific publications, on the other hand, remained almost constant between 2009 and 2016, and has been increasing rapidly every year since then. On the one hand, this shows that the research area *mobile robotics* is more relevant than ever before and on the other hand that there are more and more solutions and research results in this area in the form of publications.

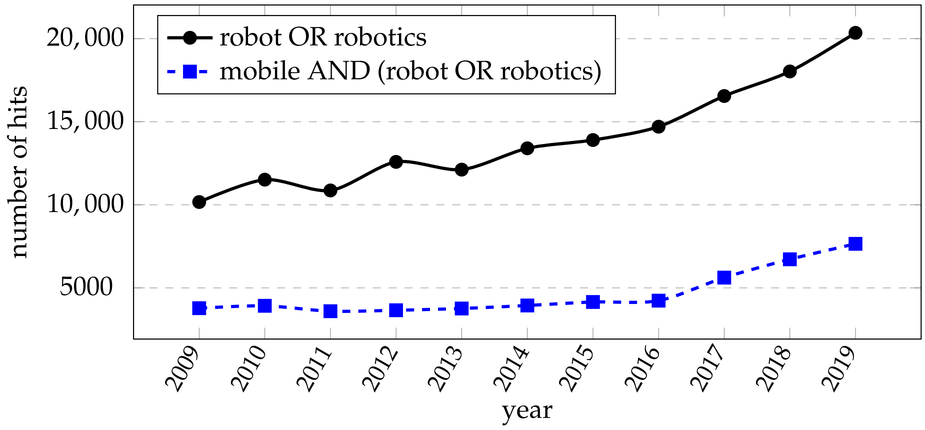

Figure 1. Development of search hits for *robotics* and *mobile robotics* (All search queries have been executed in IEEE Xplore in August 2020.)

The group of mobile robots that can move through its environment, is a carrier for many research topics within robotics, e.g., navigation or autonomy. Often researchers reference to the mobile robot. This article discussed how a typical mobile robot could be described by answering the following questions: What are the capabilities of a typical mobile robot? What technologies are topically used to implement its capabilities? What requirements and challenges result from these capabilities and implementations?

This research's primary goal is to define a taxonomy of mobile robots that describes the classes, applications, capabilities, and implementations of a typical mobile robot. The definition of a taxonomy was initially invented with biology. A taxonomy describes a method to classify objects. A taxonomy is often used to put individual cases into a unified and more generic context to handle those cases with standard methods. With the creation of a taxonomy, structures are established in which an object or structure can be sorted. This research uses taxonomy to define an archetypal mobile robot, whereas the indication "archetypal" means a generally valid definition of a device, here the archetypal definition of a mobile robot.

The taxonomy is mostly based on a systematic literature review, which is shown in Section 2, including the state of the art of taxonomies for mobile robots in Section 2.2. In Section 3 types of mobile robots, in Section 4 applications, in Section 5 capabilities, and in Section 6 implementations are analysed. The derivation of the taxonomy is shown in Section 7 before this article concludes with Section 8.

2. Literature Review

The basis of the definition of a mobile robot is created by running a systematic literature review [2,3]. The first step in the literature review is the definition of search terms. Those search terms are created by reviewing references of three types of literature. Those references will be described briefly in the next sections and will be compared and collected in Tables 3 and 4. First, books from the field of robotics will be examined in Section 2.1. Then, a selection of survey papers will be reviewed, which outlines the state of the art of (mobile) robotics (see Section 2.2). Last, other search terms will be searched by examining some reference systems from mobile robotics (see Section 2.3). The relevance of the selected references are shown in Table 1, which shows the number of citations with the exception of the *reference systems* where the number of search hits of references using this systems are listed. The quantification of the relevance is done by evaluating the search hits and number of citations using search engines for scientific references, namely *Google Scholar* (*Google Scholar* [4] runs its search queries independent from the publisher.) and *IEEE Xplore*. The selection of the survey papers and publications is not only done by pure number of citations and search hits. To minimize the chance to miss new or non popular research terms within mobile robotics, a mixture of old to new and few- to often-cited references are chosen. Reference systems that are known to the authors were selected, as well as randomly selected systems from search results. The quantification of each term will be done later by analyzing the relevance of each term in the literature (see Sections 5 and 6).

Table 1. Relevance of the selected references

Reference			Number of Citations/Search Hits	
Type	**Title** [source]	**Year**	**Google Scholar**	**IEEE Xplore**
Books see Section 2.1	Artificial Intelligence [5]	2009	35,011	N/A
	Probabilistic Robotics [6]	2005	10,226	N/A
	Springer Handbook of Robotics [7]	2016	3974	N/A
	Intro. to Auton. Mobile Robots [8]	2011	3665	N/A
	Robotics, Vision and Control [9]	2016	1545	N/A
	Embedded Robotics [10]	2008	568	N/A
Surveys see Section 2.2	Modular Reconfigurable Robots [11]	2007	813	N/A
	Challenges of Science Robotics [12]	2018	303	N/A
	Multi-Robot Taxonomy [13]	2016	126	N/A
	Challenges for Mars Expl. [14]	2000	86	N/A
	Robot Teleop, Taxonomy [15]	2015	33	N/A
	Review of Mobile Robots [16]	2019	20	N/A
	ANR Requirements [17]	2018	3	N/A
	Challenges of Mobile Robots [18]	2020	1	N/A
Reference systems see Section 2.3	Spot [19]	2019	945	70
	Khepera IV [20]	2015	187	46
	TurtleBot3 [21]	2017	180	35
	AMiRo [22]	2018	105	15
	WolfBot [23]	2014	80	10
	e-puck2 [24]	2018	75	8
	OmniMan [25]	2020	32	1
	ArEduBot [26]	2011	24	1
	Savvy [27]	2017	6	2
	Arduino Robot [28]	2018	5	1
	Omnidirectional Mobile Robot [29]	2016	4	0

All search queries have been executed in July and August 2020.

2.1. Books

Artificial Intelligence: A Modern Approach [5] by Russell and Norvig is one of the most popular books in the field of Artificial Intelligence (AI) and robotics. The book was quoted more than 35,000 times since its release in 2009 (see Table 1) and is often used as a textbook in study programs. The book's focus is on AI and its applications, e.g., in robotics. Detailed backgrounds are given on problem-solving, planning, reasoning, learning, and perception with or due to AI. Although the chapter on robotics is comparatively short, an overview of the hardware, software architecture and robot applications is given.

Probabilistic Robotics [6] by Thrun et al. is another indispensable book for research in the field of robotics, especially if the mathematical background of its algorithms and methods are required. In the beginning, the books explain the mathematical theories, e.g., for the Gaussian filter. This filter and many other algorithms and filters are explained in chapters such as localization, mapping, or planning and control in a high level of detail. Some practical examples are also described. The popularity of

Probabilistic Robotics is also recognizable with the high relevance in the scientific literature with more than 10.050 quotes.

Springer Handbook of Robotics [7] is, with about 2.200 pages, a good overview of robotics at a deep level. In the second version from 2016, the authors describe the current state of robotic systems' art. The book shows all basic robotics, including the design of robots, sensors and perception, manipulation and interfaces, moving in the environment, robots at work and robots and humans. Siciliano and Khatib claims to address topics with high topicality. In summary, both editions of this book have been quoted about 4000 times.

Introduction to Autonomous Mobile Robots [8] focuses, in comparison to the three already presented books, on mobile robots. Siegwart et al. start with an overview of classes of robots, following a detailed explanation of mobile robots' kinematic. Perception, localization, planning, and navigation are also shown. Helpful are the numerous examples from mobile robots, e.g., the introduction to sensors typically used with mobile robots.

Robotics, Vision and Control: Fundamental Algorithms in MATLAB [9] simplifies the work with robots if one has the intention to use Mathworks MATLAB [30] for the development of a robot. Corke shows many algorithms and functions which should be ready to be used in MATLAB. Examples are printed with MATLAB code, which helps new developers with entering the complex field of robotics. A big part of the book focuses on Computer Vision (CV) and how its applications are well supported with MATLAB. Modeling reactive systems, such as mobile robots, with MATLAB Simulink [31], is also described with practical examples.

Embedded Robotics [10] by Bräunl shows the combination of embedded systems and mobile robots. At first, the field of embedded systems is explained. Then, the design of mobile robots using embedded systems is described. The last chapter shows the applications of mobile robots. In *Embedded Robots*, the focus is always on hardware-near programming, whereas the other presented books mainly focus on algorithms or mathematical backgrounds. Here, Bräunl explains embedded development with robots up to the bit- and logic-level.

2.2. Surveys

In [11], the challenges and chances of robots are presented. The paper from 2007 was quoted about 800 times and is not explicit for mobile robots, but shows some trends in the research field of robots which can be adapted to mobile robotics. The focus of the publication lies on modular and reconfigurable systems. According to Yim et al., modular and reconfigurable systems are flexible to use and future-proof for future use-cases of mobile robots. The authors also describe the challenge of creating robust robots, both on the hardware and software level. Also, robots should be able to repair themselves independently, e.g., if used in unreachable terrain, e.g., on Mars. Algorithms to calculate the optimal configuration of robots and efficient and scaleable communications between robots in a big group are also defined as necessary preparations for future robots by Yim et al.

In [12], trends for robotics in education and research are shown. With (1) new materials, (2) bio-hybrid and bio-inspired robots, (3) energy, (4) swarm robotic, (5) navigation and exploration, (6) AI for robots, (7) brain-computer interfaces, (8) social interaction, (9) medical robots and (10) ethnic and safety ten trends are defined. The publication from 2018 shows a wide range of high-level trends, which can be adapted for mobile robotics. Despite the comparatively short availability of about two years, the publication has already been cited more than 300 times.

Ref. [13] gives an overview of target detection and tracking in multi-robot systems as a taxonomy. Even though the survey does not examine mobile robotics from a higher perspective, some aspects can be unified and adopted. Robin and Lacroix describes the necessity of decentralized algorithms to perform target detection and tracking with mobile robots. Besides, it is claimed that the target system needs to be monitored. This monitoring should be done directly on the target system and not only in simulations.

The requirements on the hardware within the development of mobile robots to explore Mars is shown in [14]. Huntsberger et al. describe the challenge on the mobile robot's hardware, without explaining the software's challenges. The focus is on the development of a suitable energy supply for the mobile robot. Also, the necessity of the robot's capability to recognize faulty parts on its hardware is described. The robot must also be able to repair those broken parts on its own.

In [15], a taxonomy for guidelines for the development of teleoperations with robots is shown. Furthermore, one focus of the publication is on integrating (human) users with the robots by giving usability guidelines. Adamides et al. define eight categories in the presented taxonomy. (1) Platform architecture and scalability, (2) error prevention and recovery, (3) visual design, (4) information presentation, (5) robot state awareness, (6) interaction effectiveness and efficiency, (7) robot environment/ surroundings awareness, and (8) cognitive factors.

Rubio et al. published a survey in 2019 on concepts, methods, frameworks, and applications of mobile robots [16]. Besides the classification into Wheeled Mobile Robots (WMR), Unmanned Arial Vehicle (UAV), and Unmanned Underwater Vehicle (UUV), the application field *navigation* is described in detail, e.g., the authors differentiate between localization and path planning. Besides, typical sensors for mobile robots are described, divided into two categories: (1) internal sensors, which measure internal data such as the velocity of the motors or the battery state, (2) passive and active sensors that measure the environment the robot.

In [17], concepts and requirements on Autonomous Networked Robots (ANR) are shown, and architectural patterns are compared. Therefore, centralized architectures are, according to Chukwuemeka and Habib, inferior to hybrid architectures of layered and decentralised approaches, especially in terms of reliability, robustness, and scalability. On the contrary, centralized architectures are more efficient than decentralized structures. The authors explain that the use of mobile robots in ANR are suitable for exploration and observation use-cases, where single robots are distributed into zones, which must not leave due to communication issues of each robot to the other mobile robots in the ANR system.

Alatise and Hancke show in [18] current challenges on autonomous mobile robots and its sensor data fusion. Mobile robots need to handle navigation in each application field. According to Alatise and Hancke other challenges are path planning, collision avoidance, and localization. Sensor data fusion is vital to gain reliable data from the sensors. Faulty data sets can be detected and corrected with sensor data fusion methods. Also, the authors described the state of the art methods for some popular sensors.

2.3. Reference Systems

As state of the art in mobile robotics the company *Boston Dynamics* stands out, e.g., with the robots *Atlas* or *Spot* [19]. *Spot* is the first of the *Boston Dynamics* mobile robots which is commercially available [32]. *Spot's* movement is highly inspired by natural role models, namely dogs. *Spot* has four legs, which helps the robot move robustly, e.g., to move in difficult terrain or climb stairs or past obstacles. The hardware can be individualized, e.g., it is possible to attach a manipulator or a moving camera on the robot's back. The robot can be controlled via a game-pad, like a remote controller, whereby the kinematics are calculated internally on the robot. Developers and users are provided with a high-level Application Programming Interface (API) and Software Development Kit (SDK) to implement their software (and hardware) for their use-cases. According to *Boston Dynamics*, *Spot* can be used in many scenarios, from transportation to observation of critical infrastructures.

Another popular robot is the *Khepera IV* mini robot, whose first version has been published in 1991. The current version is evaluated in detail by Soares et al. in [20]. The mobile robot processing unit runs an ARM Cortex-A8 CPU, which processes various sensors, e.g., infrared and ultrasonic sensors for collision avoidance and an RGB camera for object detection. Besides, the *Khepera IV* uses two microphones to localize sound sources such as voices. The mobile robot uses a modular approach and is extensible with extension-boards. The robot is mainly used in education and research.

Popular, especially as a demonstrator for the Robot Operation System (ROS), is the mobile robot *Turtlebot*, whose third generation, the *Turtlebot 3* [21] is currently available. The open-source robot has initially been developed by *Willow Garage*, who is also the core developer of ROS. The robot uses a modular approach and as standard a 360° Light Detection and Ranging (LiDAR) scanner, an ARM-based control unit, which controls, e.g., an Inertial Measurement Unit (IMU). A camera can be attached as an official extension. The control unit is a Raspberry Pi 3 Single-Board Computer (SBC). Noteworthy is the integration of ROS and ROS2, which makes the *Turtlebot* popular among new developers and beginners in the field of robotics. The *Turtlebot* is used in many use-cases, e.g., for Simultaneous Localization and Mapping (SLAM) applications to hardware extension to handle objects.

The *Autonomous Mini Robot (AMiRo)* is developed at Center for Cognitive Interaction Technology (CITEC) of Bielefeld University [22]. The mobile robots is implemented as a distributed and modular system with three main modules. Those modules, the *Di Wheel Drive*, the *Power Management*- and the *Light Ring* are each equipped with a Micro Controller Unit (MCU) which processes sensor- and actuator information under real-time conditions. The *Cognition*-module, which is an extension board for the *AMiRo*, hosts an ARM-CPU, which is more powerful than the MCUs of the basic modules. ROS [33] or Robotics Service Bus (RSB) [34] interfaces are provided for the *Cognition* extension. Another module for the modular approach of the *AMiRo* is the FPGA-based *Image Processing* module, which is typically used to proceed CV algorithms in a ultra-parallel approach. For communication within the distributed system the system provides e.g., a Controler Area Network (CAN) bus. The mobile robot is mainly used in education and research, e.g., in multi-robot applications using the color of the *Light Rings* to identify each *AMiRo*.

The *WolfBot* [23] is another mobile robot that is available as an open-source project. The robot uses an omnidirectional drive with three mecanum wheels. Sensors, e.g., infrared sensors, a camera, and a microphone, are handled by a BeagleBone [35] SBC, which is equipped with an ARM Cortex-A8 CPU. The robot can navigate via SLAM. Betthauser et al. emphasis the low energy consumption from 3.47 W to 6.27 W. Besides the hardware, the software of the *WolfBot* is also available as open-source. The mobile robot has been developed for research and education.

The robots *e-puck* [24] and *e-puck2* [36] are commercial mini robots which can be extended with various modules. The base of the *e-puck2* uses a STM32F4 MCU, an IMU, a simple camera and sensors for obstacle detection. The robot can be extended with more powerful computers, other cameras ans self-developed hardware. The mobile robot hosts several internal interfaces for communications. Many research projects can be found in the literature (see Table 1).

OmniMan is the name of another robot system, which is presented by Röhrig and Heß in [25]. The robot uses an omnidirectional drive with four mecanum wheels and a mechanical arm with a gripper to handle, e.g., organizer boxes. *OmniMan* is controlled by a PC. A laser scanner is used to avoid collisions to fulfill safety requirements and to map the environment. Besides, the real-time synchronization between the robot's movement with the PC is shown, and kinematic calculations are described in detail. The mobile robot is developed to study the cooperation of humans and robots.

Gartseev et al. introduce the *ArEduBot* in [26]. This mobile robot is based on the *iRobot Create* [37] platform, a hardware development kit by iRobot, one of the leading manufactures of robotic vacuum cleaners. In addition to the *iRobot Create* hardware, an Arduino board is installed. The focus of the publication is the development of a toolbox for Model-based development (MBD) using Mathworks MATLAB [30]. MATLAB's code generation produces real-time capable code, although the software is comparatively simple as the application only controls the mobile robot's driving and the avoidance of collisions. The sensor data can be analyzed and visualized after the application has stopped. The *ArEduBot* is used in education and research contexts.

The mobile robot *Savvy* [27] implements an omnidirectional drive via mecanum wheels. Due to its modular approach, the robot is prepared for future applications. New modules can easily be adapted into the robot's base. The architecture of the robot is distributed into a local real-time layer and a higher performance layer. The local real-time layer uses an STM32-based MCU and a mini-PC. The top layer runs ROS and provides functions for localization, SLAM, CV and a Human Machine Interface (HMI). This top layer is also used to coordinate a multi-robot scenario. According to Wu et al. *Savvy* is used to map unknown environments or follow pedestrians with a 3D-depth camera.

Meghana et al. introduce in [28] a mobile robot, which is mainly used to observe an outdoor area. For this purpose, the robots are equipped with a camera that can be turned around in 360°. The robot is especially useful in dark conditions, where it can detect movements with its infrared sensors within the camera. Those movements are used to send notifications; authorized persons can identify themselves with Radio-Frequency Identification (RFID) cards. An Arduino Uno board controls the movement of the robot and the camera. The camera data is transmitted via GSM mobile communications, where the number of objects is limited due to the low bandwidth of GSM.

Yaseen Ismael and Hedley from Newcastle University describes the development of an omnidirectional robot in [29]. The mobile robot is controlled by an Arduino board [38], which calculates the kinematic of the omnidirectional motors, the information from the ultrasonic sensors, and the path planning onboard and sends data for further analysis to a PC. Technical details about software implementations are not included in the publication. The robot is used for internal research projects.

3. Analysis of Types

The definition of the types of mobile robots is mostly done be the type of movement, the environment, the mobile robot is used in, or special characteristics of the mobile robot. In *Springer Handbook of Robotics* [7] five types of mobile robots are defined, which encompass these characteristics.

Mobile robots can be roughly categorized into three different modes of locomotion. A classical type of mobile robot, on which this work focuses, is the so-called Wheeled Mobile Robots (WMR). Siciliano and Khatib describes in [7] (p. 575 ff.) the group of WMR as widely spread mobile robots, which have many advantages, such as their simple structure, energy efficiency, high speed and low production costs.

The second group, the underwater robots or Unmanned Underwater Vehicle (UUV) are described in [7] (p. 595 ff.), which are mainly used to investigate environmental issues and to combat pollution of the seas. Underwater robots tend to be implemented as Remotly Operated Vehicle (ROV) and are therefore operated remotely. The data transfer to the robot is often done by wire. In addition to ROV, there are autonomously acting robots, so-called Autonomous Mobile Robot (AMR). These navigate autonomously and perform their task underwater autonomously. The group of AMR is also increasingly found in other areas of robotics, for example the group of WMR.

Flying robots, on the other hand, have to manage without any external cables at all. Here the autonomy has an even larger portion, than with underwater robots, since the carrying along of a cable for remote control is usually not wanted or technically not feasible. Flying robots belong to the group of Unmanned Arial Vehicle (UAV). Together with the infrastructure, system and human-machine interfaces, they are also called Unmanned Aircraft System (UAS). In [7] (p. 623 ff.) it is explained that especially the group of flying robots are complex systems, since they have six degrees of freedom, for example in comparison to WMR, and the processing of navigation itself is a complex task for a flying mobile robot. Furthermore, flying robots are strictly limited in terms of flight duration, payload and size. A major advantage is the ability to reach long distances, for example with fixed wing aircraft. Multicopters are inexpensive alternatives for lower altitudes and are suitable, for example, for monitoring critical infrastructures [39] or transporting cargo such as medical articles [40]. Multicopters are also more agile than fixed-wing aircraft and can, among other things, “stand still” at one point in the air due to their rotors.

Biomimetic robots can be described as another class of mobile robots [7] (p. 543 ff.). Biomimetic systems, or bionics, describes the transfer of models from nature to technical systems. In the case of mobile robots, bionics often refers to the mode of locomotion. For example, there are mobile robots in the form of worms or snakes that copy the way these animals move. Humanoid robots can also be called bionic robots, such as the NAO robot already presented, which are modeled after the human body. Humanoid robots are used especially in cooperation with humans, because according to [41] the acceptance of the robot by the human partner can be promoted by the familiar form.

The class of micro- and nano-robots refers to the compact design of the robots [7] (p. 671 ff). Typically, the size of robots in the micro/nano class is in the range of nanometers to millimeters. Mobile micro/nano robots are being researched for use in medicine, for example, where these robots are used in living organisms [42].

4. Analysis of Applications

For the category of applications of mobile robots the IEEE definition [43] is considered and checked by means of two already presented sources (see Table 2). It is shown that although the naming and the level of detail of the individual categories of application areas differ, this generally holds little potential for discussion. For example, ref. [5] (p. 1006 ff.) distinguishes between *transportation* and *self-driving cars*, while these two terms are summarized as *transportation* in [18]. Similarly, *telepresence* can be counted as part of the *Service* area. The area *Health care* is missing in [18], while *Education/ Teaching* is not listed in [5]. The application area *Military* is only listed in [43].

Table 2. Applications of mobile robots in the literature.

Reference	**Application**											
Source	**Industrial/ Agriculture**	**Transportation/ Logistics**	**Self-Driven Cars/ Autonomous Vehicles**	**Health Care**	**Disaster Response**	**Exploration**	**Service**	**Entertainment**	**Human Augmentation**	**Education/ Teaching**	**Military**	**Telepresence**
IEEE [43]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
AI [5]	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Review [18]		✓			✓	✓	✓			✓		

✓: Application listed.

5. Analysis of Capabilities

In the following section the capabilities of mobile robots are analyzed in the three steps. The capability of a mobile robot is the ability to fulfill that capability. For example, a mobile robot has the capability to navigate or is able to heal itself. First, search terms obtained from the three reference types are compared and evaluated. For this purpose capabilities (see Table 3) are noted, which are described or explained in the respective publications. The table shows which terms are used frequently and less frequently in the selected publications.

Table 3 shows that there must be a differentiated view on the individual terms, since the subjectively selected references do not allow for reliable statements about the relevance of the capabilities. The terms *Navigation* and *Autonomy* are undisputed, since they are addressed in almost all sources. *Self-healing*, on the other hand, is presented in the overviews and explained in a book, but the reference systems under consideration do not implement it.

Table 3. Capabilities of mobile robots in the literature

Type	Title [source]	Navigation	Autonomy	Optimization/ Learning	Multi-Robot Cooperation	Safety	Human-Robot Interaction	Security	Reliability	Energy Efficiency	Usability	Self-Healing
Books see Section 2.1	Artificial Intelligence [5]	✓	✓	✓	✓		✓					
	Probabilistic Robotics [6]	✓	✓	✓								
	Springer Handbook of Robotics [7]	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
	Intro. to Auton. Mobile Robots [8]	✓	✓		✓		✓			✓		
	Robotics, Vision and Control [9]	✓	✓		✓		✓		✓		✓	
	Embedded Robotics [10]	✓	✓	✓	✓		✓			✓		
Surveys see Section 2.2	Modular Reconfigurable Robots [11]			✓					✓	✓		✓
	Challenges of Science Robotics [12]	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
	Multi-Robot Taxonomy [13]	✓	✓	✓	✓	✓		✓	✓	✓		
	Challenges for Mars Expl. [14]	✓	✓		✓		✓		✓	✓		✓
	Robot Teleop, Taxonomy [15]	✓	✓	✓	✓		✓		✓		✓	
	Review of Mobile Robots [16]	✓	✓	✓	✓	✓	✓			✓		
	ANR Requirements [17]	✓	✓	✓	✓		✓		✓	✓		
	Challenges of Mobile Robots [18]	✓	✓	✓						✓		
Reference systems see Section 2.3	Spot [19]	✓	◷	◷	◷	✓	✓				✓	
	Khepera IV [20]	✓	✓	✓	✓					✓		
	TurtleBot3 [21]	✓	✓		✓		✓					
	AMiRo [22]	✓	✓		✓						✓	
	WolfBot [23]	✓	✓		✓					✓		
	e-puck2 [24]	✓	✓		✓		✓				✓	
	OmniMan [25]	✓					✓			✓	✓	
	ArEduBot [26]	✓	✓								✓	
	Savvy [27]	✓	✓		✓		✓					
	Arduino Robot [28]	✓	✓				✓					
	Omnidirectional Mobile Robot [29]	✓	✓		◷		✓			✓		

✓: Capability addressed/ described. ◷: As future capability addressed/ described.

The next step in the analysis of the capabilities of mobile robots is therefore the systematic application of the already defined search terms with the digital library IEEE Xplore to get the total number of search hits to compare all defined search terms to each other. The syntax and search matrix of the search query in IEEE Xplore and the number of hits can be looked up in the Appendix (see Table A1). In analogy to Table 3, it can be stated that the classical capabilities of mobile robots, such as the *Navigation*, provide a particularly large number of search hits. The *Usability*, on the other hand, has little relevance in scientific publications.

To analyze the trend of the search terms in more detail, each search term is explained and analyzed individually in the following and last step of the analysis. The search covers the years from 2009 to 2019, so that a good impression of the development and relevance of the individual topics can be shown. Tables 3 and A1 are used to classify the individual capabilities and compare them with each other.

5.1. Navigation

Navigation is the search term with the most search hits (All search queries have been executed in IEEE Xplore in August 2020) witch about 34.400 hits (see Table A1) in connection with mobile robotics. The term navigation, i.e., a mobile robot's ability to maneuver independently in unknown terrain, includes localization, mapping, collision avoidance, and path planning. Figure 2 shows a high number of search hits over the years 2009 to 2016 and a strong increase since 2017, which is not due to the popularity of mobile robotics in scientific publications, since the increase is almost linear (see Figure 1). Rather, the increase shows the high importance of navigation in mobile robotics and the progress in this field, especially since 2016. Paden et al. gives an overview of the state of the art, and the methods and algorithms of navigation and cartography using the example of self-propelled cars [44]. The course of autonomous navigation, from route planning to steering and engine control, and the current limitations in accuracy are explained.

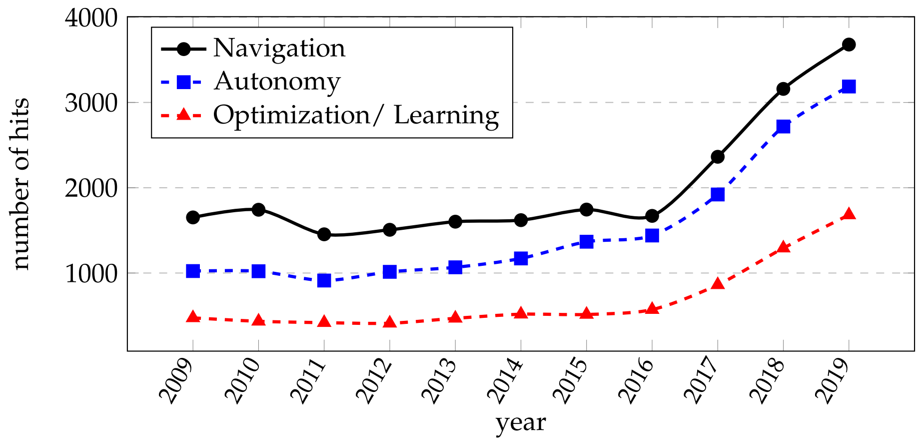

Figure 2. Development of search hits for *navigation*, *autonomy* and *optimization/ learning*.

5.2. Autonomy

Autonomy in mobile robotics refers to the ability to act autonomously, i.e., to make one's own decisions, for example, to perform a task. Similar to navigation, autonomous mobile robots have been on the scientific agenda for a long time. However, since 2016, the number of publications of the AMR has increased again (see Figure 2). The progress in the research of autonomy can be well illustrated with the development of the Mars Rovers [45]. Sojourner landed in 1997 and was the first mobile robot to operate autonomously on a foreign planet. With each successor (Spirit and Opportunity 2004 and Curiosity 2012), the degree of autonomy increased. This degree of autonomy can be measured, e.g., the SAE J3016 standard from the automotive industry is often used here [46]. SAE J3016 describes six categories from SAE Level 0 (no autonomy) to SAE Level 5 (full autonomy driving). There are also independent classifications of autonomy in robotics, which are compared, for example, in [47]. Furthermore, Beer et al. suggests a taxonomy from a gradation of 10 levels of autonomy.

5.3. Optimization/ Learning

Self-optimization and the capability of robots to learn new capabilities on their own is a research topic that appeared in scientific publications about 11,000 times (see Table A1). The development in the last ten years (see Figure 2), on the other hand, has been relatively constant. The almost linear increase from 2016 onward can be attributed to the increased number of scientific publications in mobile robotics. Although learning and optimization are summarized here, the optimization of existing functions and algorithms is more trivial than learning entirely new capabilities. The latter is considered a necessity to achieve real, complete, and lasting autonomy of technical systems. In [48], it is shown how mobile robots improve navigation in a known environment by learning routes. It is also interesting that although optimization and learning are addressed in the surveys and books, they are hardly implemented in the selected reference systems (see Table 3).

5.4. Multi-Robot Cooperation

The Multi-Robot Cooperation includes the cooperation of two robots and the interaction of whole swarms and the so-called ANR. Especially swarm robotics can be described as a trend of the last years, since search hits have more than tripled since 2016 (see Figure 3). In [49] heterogeneous swarms of robots are shown. A significant challenge in the development of multi-robot systems is the implementation of the capabilities of the distribution of the task(s) among each other and the Machine to Machine (M2M) interface, respectively the communication between the individual robots.

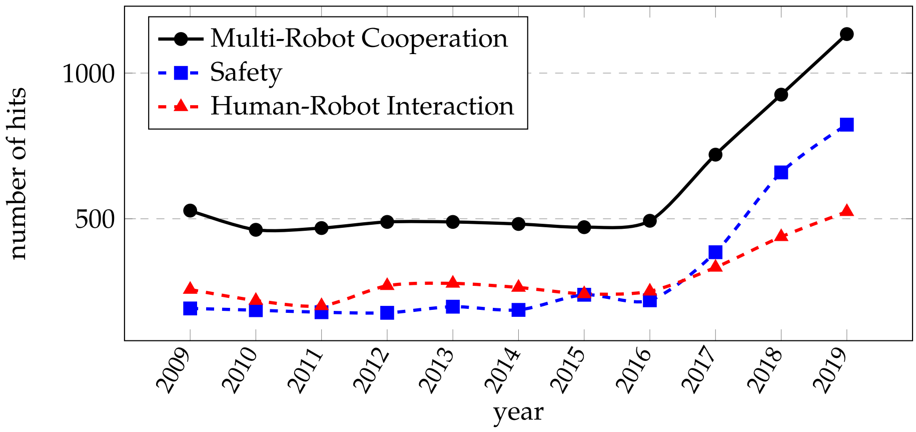

Figure 3. Development of search hits for *multi-robot cooperation*, *safety* and *human-robot interaction*.

5.5. Safety

Robots are to be classified as safety-critical systems because they are a potential danger for the users, the environment, and themselves, as Guiochet et al. explains in [50]. A safe mobile robot has the ability not to harm others, others, or itself. For this purpose, algorithms are implemented on the software side, and special material is used on the hardware side to protect the system and its environment. For the observance of the safety, it requires extensive tests [51]. Vasic and Billard show risk factors in the interaction of robots and humans [52]. The safety considered here can be described as a trend since the search hits are almost constant until 2016 and have quadrupled since then (see Figure 3).

5.6. Human-Robot Interaction

The search hits for Human-Robot Interaction are around 200 hits and increased from 2016 onward in line with the popularity of mobile robotics in scientific publications. Compared to the Multi-Robot Cooperation, the search hits are about half. However, the interaction between robots and humans is addressed in almost all selected references (see Table 3). The capability or the challenges of the interaction between humans and robots often lies in communication (HMI). The communication direction can also play a role here since the human-robot interaction is not necessarily bidirectional. In the literature, the terms Machine to Human (M2H) or Human to Machine (H2M) are also used. In [53], the necessity of Human-Robot Interaction and its implementation problems are described. Riek and Member explain in [54] methods for the coordination of movements of humans and mobile robots.

5.7. Security

While *safety* is generally concerned with harm the machine can potentially cause in its environment, *security* refers to the machine's resistance against attacks from outside—e.g., hacking attempts. The relevance in scientific publications has been increasing until 2017 (see Figure 4), although the search hits are a small part compared to navigation or autonomy (see Table A1). Also, the selected reference systems do not address this topic. In the surveys and the books, the topic is also not very present (see Table 3). Also, the number of search hits decreases again in 2018 and 2019. Nevertheless, ref. [55], for example, explains the importance of protecting against external attacks, especially for mobile robots. On the one hand, mobile robots usually collect data that should not be tapped by third parties in order to protect data privacy. On the other hand, mobile robots, in particular, are potentially dangerous, as they could cause physical damage. For example, an externally controlled UAV can cause enormous damage if it is deliberately flown into humans.

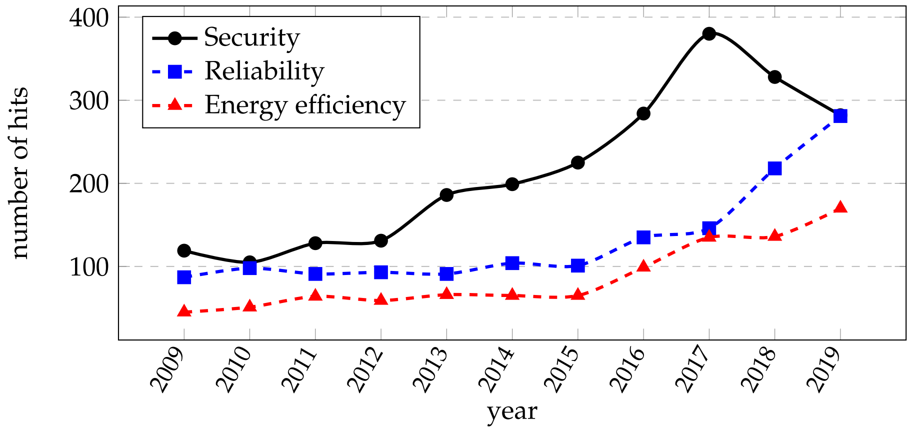

Figure 4. Development of search hits for *security*, *reliability* and *energy efficiency*.

5.8. Reliability

Reliability can be described as a trend in mobile robotics. The number of search hits increases from 2015 on, and in 2018 and 2019, there were massive leaps towards 300 search hits per year (see Figure 4). Similar to security, reliability is also meaningless for the selected reference systems (see Table 3). For example, Carlson and Murphy published an analysis of reliability in 2003, which clearly shows the need for improvements in this area [56]. The reliability of mobile robots has many positive and important aspects. For example, reliability contributes to mobile robots' acceptance and increases safety, which can be impaired by malfunctions.

5.9. Energy Efficiency

The ability to use energy effectively or to use Low Energy (LE) components is indispensable in many mobile robot applications. The number of search hits for this purpose is at a relatively constant low level (see Figure 4). The increase from 2015 onward is analogous to the increase in search hits for mobile robots. This topic is overrepresented in the selected references. Energy efficiency plays a comparatively large role, especially in the surveys (see Table 3). The increase in energy efficiency can be achieved in different areas. One possibility to use the available energy efficiency can be achieved by efficient use of the drive since it usually accounts for a large share of mobile robots' energy consumption. Künemund et al. show in [57] Methods and algorithms for efficient path planning.

5.10. Usability

Usability in mobile robots' use and development is almost irrelevant in scientific publications (see Figure 5). Although there have been isolated publications on this topic, the absolute number of publications is low, with a maximum of 50 search hits per year. In practice, usability plays a significant role, especially for such complex systems as robots. The need to present data in a simple form and make interaction with humans easy plays a significant role, especially in the interaction of mobile robots with elderly and sick people [58].

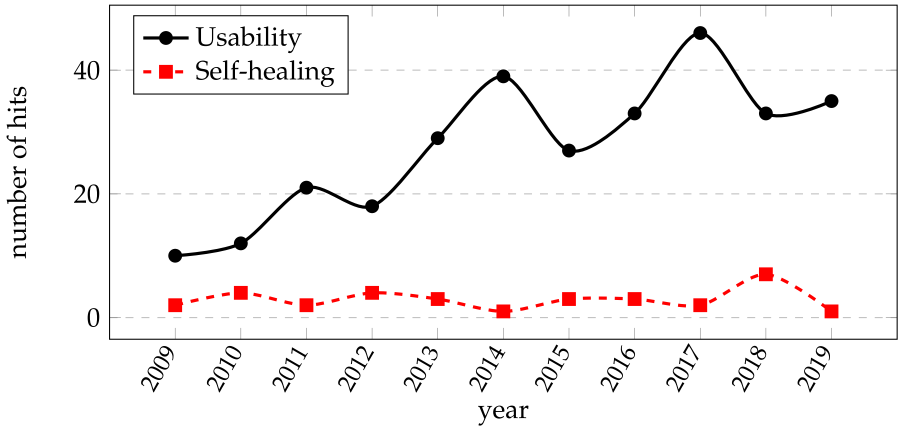

Figure 5. Development of search hits for *usability* and *self-healing*.

5.11. Self-Healing

Self-healing or independent repair of mobile robots is a capability that is needed to develop a fully autonomous robot. A mobile robot must be able to replace defective hardware or compensate for the defect in some other way in order to be able to act autonomously in the long term. The relevance in scientific publications disappears only slightly (see Figure 5). This leads to the conclusion that there are only very few solutions for this field of research. This research area seems to be an open challenge within mobile robotics, as this topic is addressed in [7]. Some of the few publications of Self-healing/Self-Repair show the use of material that can be restored after damage [59].

6. Analysis of Implementations

An analysis of the implementations follows. The implementations of a mobile robot in this context means the realization or technology used. The differentiation to the capabilities of a mobile robot is not always easy. In principle, the implementations should serve the capability or implement it. The *system monitoring* is needed to ensure the reliability of the mobile robot, although the *system monitoring* itself could also be a capability. The same is true for the *real-time*, which obviously can be called a capability. Here, however, the *real-time capability* is assigned as implementation for the fulfillment of safety.

The technology used in technical devices changes frequently, especially since mobile robotics is a very popular field of research and therefore new research results and insights are gained quickly. The analysis is performed analogous to the analysis of capabilities (see Section 5). First, the implementations from the three reference types are compared. Table 4 shows which implementations were explained or described in which reference.

When looking at Table 4, it becomes clear that here, too, a more differentiated analysis of the individual topics is required. While the *real-time capability* is omnipresent, research areas such as *monitoring* or *reconfigurability* are mentioned only in a few cases. In the following, each search term is secured in a literature search. First the absolute search hits are collected (see Appendix A, Table A1 and later each search term is described individually and analyzed in its temporal development. The syntax and the search matrix of the search query in IEEE Xplore can be looked up in the Appendix A (see Table A1).

Table 4. Implementations of mobile robots in the literature.

Type	Title [source]	Real-Time capability	Machine Learning	Computer Vision	Cloud Computing	Monitoring	Modularity	Model-Based Development	Redundancy	Reconfigurability	Edge Computing
Books see Section 2.1	Artificial Intelligence [5]	✓	✓	✓	✓	✓	✓			✓	
	Probabilistic Robotics [6]	✓	✓	✓							
	Springer Handbook of Robotics [7]	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Intro. to Auton. Mobile Robots [8]	✓		✓			✓				
	Robotics, Vision and Control [9]	✓		✓			✓	✓	✓		
	Embedded Robotics [10]	✓		✓			✓				✓
Surveys see Section 2.2	Modular Reconfigurable Robots [11]						✓			✓	
	Challenges of Science Robotics [12]	✓	✓	✓	✓	✓	✓		✓	✓	
	Multi-Robot Taxonomy [13]			✓		✓	✓	✓			
	Challenges for Mars Expl. [14]										
	Robot Teleop, Taxonomy [15]				✓	✓					
	Review of Mobile Robots [16]	✓	✓	✓			✓		✓	✓	
	ANR Requirements [17]	✓			✓	✓	✓			✓	
	Challenges of Mobile Robots [18]	✓	✓	✓				✓	✓		
Reference systems see Section 2.3	Spot [19]	✓		✓			✓				
	Khepera IV [20]			✓			✓				
	TurtleBot3 [21]			✓			✓				
	AMiRo [22]	✓	✓	✓			✓				
	WolfBot [23]	✓		✓							
	e-puck2 [24]	✓		✓		✓	✓				
	OmniMan [25]	✓									
	ArEduBot [26]	✓						✓			
	Savvy [27]	✓		✓			✓				
	Arduino Robot [28]	✓		✓							
	Omnidirectional Mobile Robot [29]										

✓: Implementation addressed/described.

6.1. Real-Time Capability

As already mentioned, real-time capability is a requirement that is absolutely necessary in mobile robotics. By adhering to a defined time condition, the safety and also the reliability of the system can be increased [60]. For example, the immediate execution of an action, such as stopping the motors within a predefined time after detection of an obstacle, can prevent accidents, defects or dangerous situations. Looking at the development of search hits since 2009 (see Figure 6) shows a growth since 2006 and a strong increase since 2016. This trend is accompanied by many search terms related to mobile robotics, as the latter itself has also gained popularity (see Figure 1).

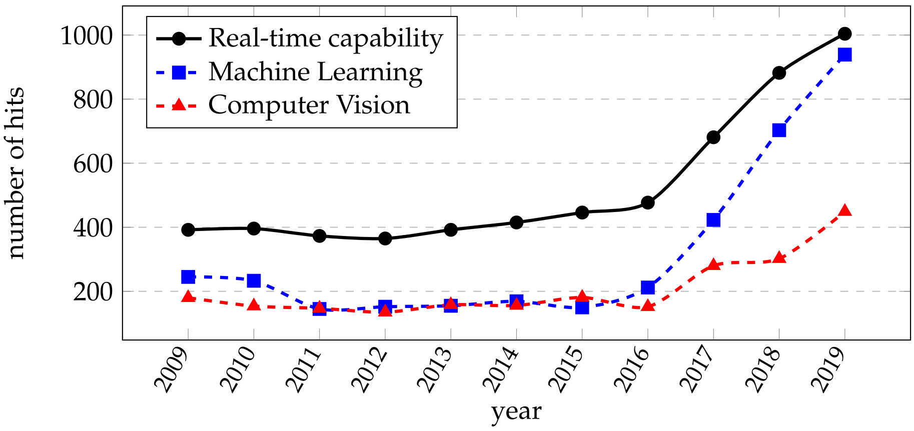

Figure 6. Development of search hits for *real-time capability*, *machine learning* and *computer vision*.

6.2. Machine Learning

The use or application of machine learning was addressed comparatively little in the selected sources (see Table 4). In the search hits, on the other hand, the topic is very present, with a slightly negative trend until 2015, but rising very strongly from 2015 onward (see Figure 6). Machine Learning can be used to evaluate large amounts of data, for example to recognize patterns in the data and to learn from them. The category and search matrix machine learning also includes *neural networks*, and *deep learning*. Neural networks are one of many ways to apply machine learning. Here, data is fed to a network of information, which is provided by various algorithms, for example for object recognition [61]. Deep Learning is a method which extends this information independently and thus extends its knowledge or the information base. Positive or negative weighting is calculated for each data input. The more data is processed, the better and more accurate the result will be, a deeper and broader network of information is formed. However, neural networks must first be trained by generating correct paths in the network. In robotics, this technology is used for example in navigation, but especially in object recognition [62].

6.3. Computer Vision

Object recognition also falls into the field of computer vision, but several technologies and methods can be used for this purpose. Accordingly, the course of search results is nearly congruent with the search results for neural networks (see Figure 6). For example, computer vision is used as an implementation to recognize objects whose position is needed for navigation. The computer vision has images as source, in mobile robotics usually as video stream(s), which are evaluated. Typical here is the checking for patterns, for which OpenCV [63] can be used. The source of the image material can be generated by various sensors, from classic 2D cameras to 360 degree LiDAR scanners. An overview of current hardware, methods and algorithms is given by Arnold et al. in [64].

6.4. Cloud Computing

With a few exceptions, research into cloud computing in combination with mobile robotics has only been underway since 2009. The trend since 2009 has been a sharp increase almost every year (see Figure 7). The search hits include not only the trend towards cloud computing, but also the approach of integrating servers into the technical implementation of mobile robots. Cloud computing or the use of servers can be used to add very large amounts of computing power and storage space to a technical system. This can be used to outsource algorithms and methods, such as neural networks, whose performance requirements can often not be provided locally on a mobile robot. In addition, cloud services in particular can be adapted if, for example, the performance requirements increase spontaneously. In [65] gives a short outline of the use of cloud computing in robotics. Ref. [66] explains in more detail the current state of the art and the open questions in the research area *cloud robotics*.

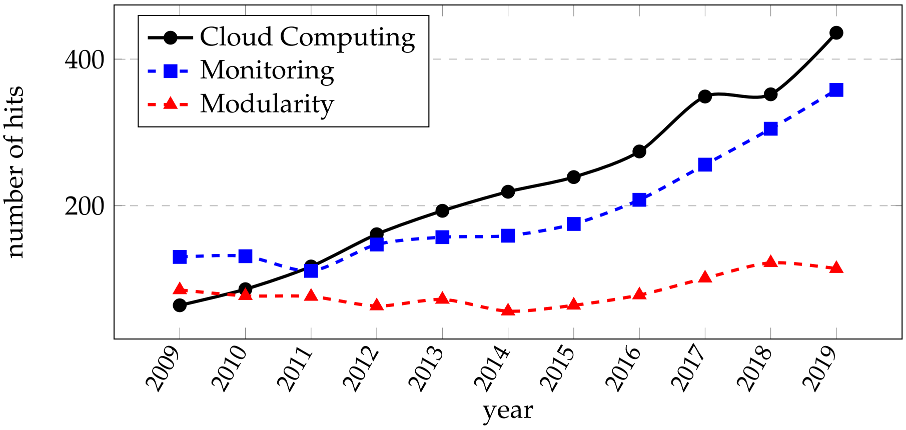

Figure 7. Development of search hits for *cloud computing*, *monitoring* and *modularity*.

6.5. Monitoring

The monitoring and verification of the system is a broad field of research, which is summarized here as *monitoring*. This includes the *validation* of the system, i.e., checking whether the system serves the defined purpose, as well as the *verification*, i.e., checking whether the system is implemented correctly, which is done for example by regular measurements. For example, it is possible to verify whether time schedules are adhered to in the system (*Time Verification*). The real-time compliance and the verification of other factors can be used to validate that the mobile robot meets the safety requirements. In addition to validation and verification, monitoring also includes the search term *diagnosis* of the system, as well as *self-awareness*. The search matrix also includes the research fields *monitoring* and *fault detection*, which also aim at monitoring and testing the system. The number of search hits for the research field of monitoring in mobile robotics is increasing almost linearly, and this increase will be even stronger from 2015 onward (see Figure 7). In [67] an example of monitoring the state of a mobile robot is shown, which shows users and developers with a Graphical User Interface (GUI) the current internal state. A model for the self-perception of robots is explained in [68], which detects internal errors and thus leads to a higher safety and reliability. The early detection of errors, especially in the drive of a WMR is shown in [69].

6.6. Modularity

Modular mobile robots are widely used, as seen in the selected reference systems (see Table 4). In the years 2009 to 2015, publications on modularity in mobile robotics are constant, from 2016 on there is a slight increase (see Figure 7), analogous to the increasing popularity of mobile robots in scientific publications. Modularity means that the technical system is built up in the form of a building set. The overall system is divided into individual smaller components. The subdivision is usually made according to service or function and in any case concerns the software, sometimes also the hardware. Modularity makes it much easier to adapt and expand the system than in a complete system without strictly defined interfaces between hardware and software components. In mobile robotics, a modular design is particularly in demand, since the location and the environment often change and new sensors or actuators may be required. The implementation of the modularity and expandability of the mobile robot AMiRo is presented by Herbrechtsmeier et al. in [70] and others., e.g., the structure of the ROS framework is also based on its modularity.

6.7. Model-Based Development

The development and maintenance of complex technical systems, such as mobile robots, is costly and a challenge for developers. The software is usually very extensive. In [71] (p. 46 ff.) it is explained that to cope with these requirements the MBD should be applied. By using these methods the developers are supported and the documentation is simplified. This leads for example to a higher usability for the developer. In [71] the author has already shown an implementation of methods for MBD, mainly by using MATLAB Simulink for the development of a mobile robot [72]. The MBD in scientific publications has a large increase in recent years (see Figure 8) and with about 1.400 search hits a comparatively relevant keyword for systematic literature search (see Table A1).

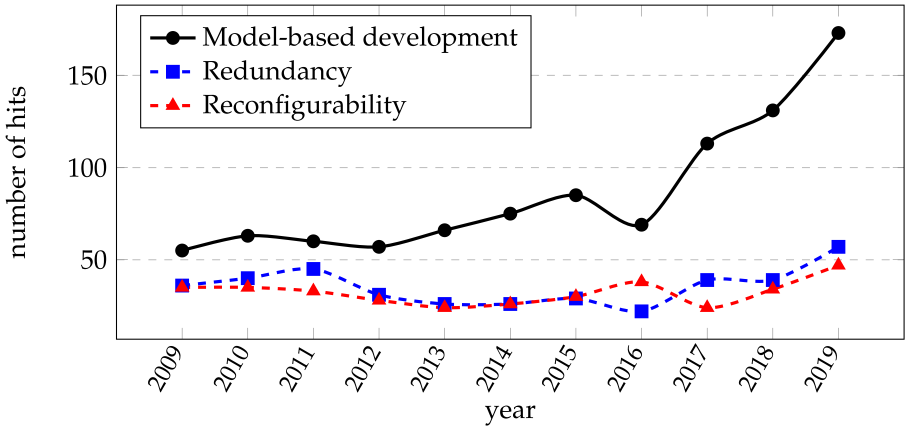

Figure 8. Development of search hits for *model-based development*, *redundancy* and *reconfigurability*.

6.8. Redundancy

Another implementation to increase the safety and reliability of a mobile robot is the use of redundancies. Redundancy describes the availability of information at more than one place in the software, or the availability of more than one part or component, the omission of which has no direct consequences. In the event of a failure, e.g., a defect, of a component or function, the redundant counterpart takes over. Redundancies can still be used to detect faulty sensors. In [73] it is shown how to use redundant sources to identify faulty data sets from the motor decoders. Redundancies are not addressed in the selected reference systems (see Table 4), but are mentioned in the surveys and books. The number of search hits is constantly below 50 search hits per year (see Figure 8).

6.9. Reconfigurability

The number of search hits for reconfigurability of mobile robots behaves analogously to the number of search hits for redundancy (see Figure 8). On the one hand, reconfigurability describes the hardware reconfigurability to adapt the configuration to the environmental conditions. According to [11] the development of these systems is a challenge for robots in general and describes mobile robots that can adapt their shape. The adaptation of the hardware can also be used to replace defective parts with existing hardware, which leads to self-healing of the robot [74]. However, the software of mobile robots can also be reconfigured, for example by changing the sequence of functions or by adjusting the timing conditions in the software. This software reconfiguration can also be used for the automated distribution of tasks in multi-robot cooperations [75].

6.10. Edge Computing

Edge and Fog Computing *(in the following only referred to as Edge Computing)* is a technology that will not achieve the first search hits in combination with mobile robotics until 2015 (see Figure 9). In 2016 and 2017, there are more isolated search hits. In 2018 and 2019, there is a clear trend. Edge computing is generally a trend that comes from the area of Internet of Things (IoT). It shifts the processing of applications or services from central nodes, such as the cloud, to the network's edges. This reduces the amount of data that needs to be sent to a server to analyze data and the cloud's dependence, as this analysis takes place on-site, and only the results are sent to the server. In [76] Edge Computing is used to reduce the SLAM algorithms between the local robots and the cloud in a so-called edge-fog layer.

This reduces the latency compared to processing the algorithms in the cloud and, thus, the application's reliability and security.

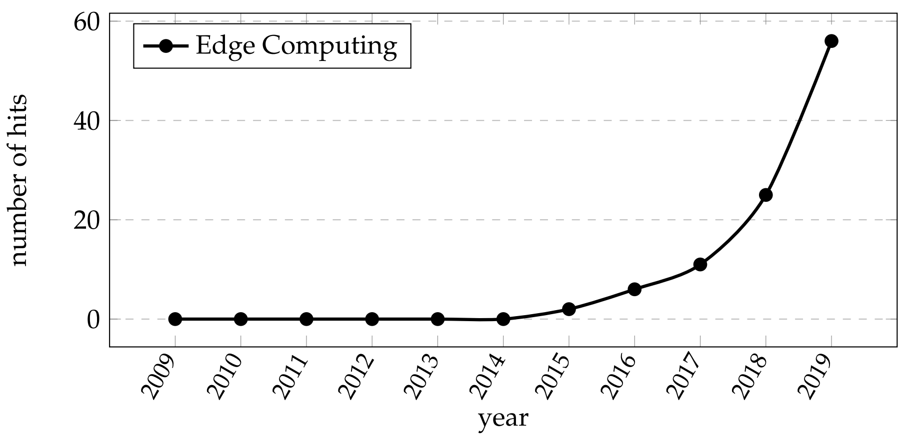

Figure 9. Development of search hits for *edge computing*.

7. Taxonomy

The taxonomy for mobile robots is divided into those four categories (types, applications, capabilities, and implementations) using the previous chapters to derive the taxonomy for mobile robots.

7.1. Types

The analysis of the types of mobile robots in Section 3 presents five types defined by *Springer Handbook of Robotics* [7] which are transferred into the taxonomy:

T1 Wheeled Mobile Robots (WMR)
T2 Unmanned Arial Vehicle (UAV)
T3 Unmanned Underwater Vehicle (UUV)
T4 Biomimetic
T5 Micro/ Nano

7.2. Applications

The analysis of the applications in Section 4 showed that mobile robots' application areas are not clearly defined. However, the differences lie largely in the level of detail of the listing. For the taxonomy of a mobile robot, the already presented applications from the IEEE are taken over from [43] into the taxonomy, since this provides the most complete listing of the shown ones:

A1 Industrial/ Agriculture
A2 Transportation/ Logistics
A3 Self-driven cars/ Autonomous vehicles
A4 Health care
A5 Disaster response
A6 Exploration
A7 Service
A8 Entertainment
A9 Human Augmentation
A10 Education/ Teaching
A11 Military
A12 Telepresence

7.3. Capabilities

The capabilities of mobile robots were explained in Section 5. From the analysis of these, capabilities can be derived, which today every robot should typically support. Not all of the shown capabilities are taken over from the selected sources, but only those whose relevance is justified by frequent search hits. Thus the capabilities *usability* and *self-healing* are not typical capabilities of mobile robots today. All other capabilities are transferred to the taxonomy:

C1 Navigation
C2 Autonomy
C3 Optimization/ Learning
C4 Multi-Robot Cooperation
C5 Safety
C6 Human-Robot Interaction
C7 Security
C8 Reliability
C9 Energy efficiency

7.4. Implementations

The implementations of mobile robots were examined in Section 6. This can be derived from current technologies and which implementations should be considered and supported in a mobile robot's design and development. Analogous to mobile robots' capabilities, only those implementations are included in the taxonomy, whose relevance is justified by the selected sources or the number of search hits. It was found that *redundancy*, *reconfigurability*, and *edge computing* are not found in a typical mobile robot today. All other implementations are taken over into the taxonomy:

I1 Real-time capability
I2 Machine Learning
I3 Computer Vision
I4 Cloud Computing
I5 Monitoring
I6 Modularity
I7 Model-based development

8. Conclusions

The complex field of mobile robotics was worked up in the form of a taxonomy. While the definition of the types and application areas of mobile robots can be determined with little effort, the elaboration of typical capabilities and implementations requires a comprehensive literature review. In particular, the trends of the last ten years are derived from search hits. Nine capabilities and seven implementations are defined, which the architecture of an archetypal mobile robot should support. This results in particular requirements for the robots' system and software architecture, such as integrating the cloud or compliance with real-time requirements. The realization of these capabilities and implementations are also a challenge for the developers of mobile robots. In the future, the list of capabilities and implementations is likely to be extended again. For example, integrating the current trend of using edge computing can be a challenge for future mobile robots.

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

Appendix A

Table A1. Search matrix and number of hits for capabilities and implementations of mobile robots.

Topic	Search Matrix	Hits
Navigation	("All Metadata":mobile AND robot AND (navigation OR mapping OR slam OR "collision avoidance" OR "path planning"))	little potential for
Autonomy	("All Metadata":mobile AND robot AND (autonomy OR autonomous))	24,626
Optimization/ Learning	("All Metadata":mobile AND robot AND (learning OR optimizing))	11,051
Multi-Robot Cooperation	("All Metadata":mobile AND robot AND (swarm OR "multi robot" OR "networked robots"))	9265
Safety	("All Metadata":mobile AND robot AND safety)	4617
Human-Robot Interaction	("All Metadata":mobile AND robot AND ("human machine" OR "machine human" OR "human robot" OR "robot human"))	4477
Security	("All Metadata":mobile AND robot AND security)	2907
Reliability	("All Metadata":mobile AND robot AND reliability)	2037
Energy efficiency	("All Metadata":mobile AND robot AND (energy AND (efficient OR efficiency)))	1237
Usability	("All Metadata":mobile AND robot AND usability)	379
Self-healing	("All Metadata":mobile AND robot AND ("self healing" OR "self repairing"))	45
Real-time capability	("All Metadata":mobile AND robot AND ("real time" OR realtime))	8874
Machine Learning	("All Metadata":mobile AND robot AND ("neural network" OR "neural networks" OR "machine learning" OR "deep learning"))	5768
Computer Vision	("All Metadata":mobile AND robot AND ("computer vision" OR cv OR "object recognition"))	4207
Cloud Computing	("All Metadata":mobile AND robot AND (cloud OR server))	2864
Monitoring	("All Metadata":mobile AND robot AND (verification OR validation OR diagnosis OR "self awareness" OR "system monitoring" OR "fault detection"))	2851
Modularity	("All Metadata":mobile AND robot AND modular)	1438
Model-based development	("All Metadata":mobile AND robot AND ("model based" OR "model driven"))	1346
Redundancy	("All Metadata":mobile AND robot AND redundancy)	739
Reconfigurability	("All Metadata":mobile AND robot AND (reconfiguration OR reconfigure))	581
Edge Computing	("All Metadata":mobile AND robot AND ("edge computing" OR "fog computing"))	130

All search queries have been executed in July and August 2020.

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