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Literature Review of Mobile Robots for Manufacturing

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Abstract

Mobile robots are devices that can move autonomously to accomplish their goals. This paper provides a review of such robots oriented towards manufacturing applications. It describes the kinds of mobile robots that are used and what criteria are appropriate when deciding to make use of mobile robots. It also covers ways of localizing the robots, controlling them, and addresses their safe use in collaborative applications with humans. The standards covering mobile robots are described and the paper ends with a brief survey of more advanced vehicles and applications.

Table of Contents

Introduction

While there is no generally-accepted definition for the term “mobile robot,” it is often taken to mean a device that can move autonomously from place to place to achieve a set of goals (see, e.g., Tzafestas [1]). Mobile robots are used in a wide range of applications including in factories (e.g., automated guided vehicles or AGVs), for military operations (e.g., unmanned ground reconnaissance vehicles), in healthcare (e.g., pharmaceutical delivery), for search and rescue, as security guards, and in homes (e.g., floor cleaning and lawn mowing). Automated guided vehicles or automatic guided vehicles (AGVs) were invented in 1953 [2]. AGVs are most often used in industrial applications to move materials around a manufacturing facility or a warehouse [3]. Typical AGV types are, as shown in Figure 1, tuggers (AGVs that pull carts), unit loaders (AGVs with onboard roller tables for parts-tray transfers), and fork trucks (robots similar to manual fork trucks). Use of mobile robots, and AGVs in particular, is growing as the range of robot applications in factories, hospitals, office buildings, etc. increases. While mobile robots can use a range of locomotion techniques such as flying, swimming, crawling, walking, or rolling, this paper focuses mainly on rolling or wheeled mobile robots. More advanced mobile robots are briefly discussed and referenced in the sections on Localizing the Mobile Robot and Advanced Applications.

tugger unit load fork lift

Figure 1. Typical AGV types (tugger and unit load AGV photos courtesy of America In Motion)

This paper reviews research and applications on a range of topics of importance for implementing mobile robots and AGVs in manufacturing. These include planning, navigation, vehicle localization, and interactions between mobile robots and humans and between groups of mobile robots. It also covers a sampling of applications in real-world factories and provides a brief discussion of some advanced mobile robot concepts.

Mobile robots address the demand for flexible material handling, the desire for robots to be able to operate on large structures, and the need for rapid reconfiguration of work areas. Much of the earlier work on outdoor vehicles for defense, search and rescue, and bomb disposal is relevant to the manufacturing domain, as is work that has been done on personal care robots and robots for household and hospital applications. When a robot arm is added to the mobile robot, we term this a “mobile manipulator,” discussed briefly in the Advanced Applications section.

Two roadmaps provide predictions for future mobile robot systems. For material handling, the Material Handling Institute [4] expects new capabilities in autonomous control, artificial intelligence, and robotics, along with motion- and gesture-sensitive technologies that could lead to systems in which humans, machines, and computers interact freely and effectively in completely new ways. By 2025, it is expected that economical, high-speed automation for loading and unloading trucks should be available, both at the carton and pallet level. For mobile robots used in manufacturing, a recent roadmap for U.S.

robotics [5] predicts that by 2030, autonomous vehicles will be capable of driving in any environment in which humans can drive, and furthermore be safer and more predictable than a human driver. Vehicles will be able to learn on their own how to drive in previously unseen scenarios.

Criteria for Adoption

Mobile robots can be relatively expensive and may require significant expertise to install and operate. It is therefore important to ensure that their use in a particular application is appropriate. This need has led to the development of various criteria for evaluating the conditions under which mobile robots should be adopted. In their technology roadmap [6], Sabattini et al. first describe the process of installing and setting up AGVs in a factory. They then describe some of the barriers to greater adoption of the technology. These include cost, the fact that it is difficult to achieve the desired efficiency to make the introduction cost-effective and able to operate at the required task cadence, the lack of flexibility of current systems which makes changeovers expensive and time-consuming, and safety concerns. Cost also includes the need for an accurate localization system and developing routing plans and traffic management. Efficiency in using AGVs can be limited by poor routing, by having to reduce the speed of the vehicles (e.g., due to sharing the workspace with people), or by inadequate knowledge about the environment that causes poor paths to be selected or delays due to the vehicle having to react appropriately to changes (e.g., pallets of goods within the intended AGV path). Greater use of sensors can help to increase efficiency. Ways to increase the flexibility of the system are to reduce the need for infrastructure such as the targets needed for localization (e.g., by adopting alternative localization methods) and increasing the ability of the system to adapt to changes in its tasks (e.g., through models). Safety is of paramount importance but the means to assure it may impact efficiency and flexibility. Increasing the use of sensors and providing better semantic models of the task and environment can reduce these impacts.

Criteria for using mobile robots as assistants in industrial applications are provided in Angerer et al. [7]. The authors outline the required capabilities of a mobile robot (see Table 1). They also describe the characteristics of tasks that are suitable for their use. These include the presence of a frequently-changing environment, handling loads with a mass higher than 5 kg (which causes ergonomic problems for people), the need to move components between a storage area and the work space, a wide variety of parts, and the ability to work interactively with people. They propose four main areas where improvements would enhance adoption and make AGVs easier to use. The first is safety, for which they advocate the use of sensors to detect and track the people in the workspace and changes in the robot's behavior in response to the people's actions. Another area for improvement is to make it easier and faster to react to changes in the process or task. This currently requires substantial reprogramming which the authors' propose to replace with an automated approach described in Angerer et al. [8]. The third area they advocate is to provide substantially more information to the robot about its environment, both from *a priori* knowledge and from sensor inputs. The knowledge should include a model of the process and the interaction between the human and robot. The final requirement is that the human-robot collaboration feel natural and intuitive, which can be achieved with a model of the task and the use of sensors to help the robot understand the degree of completion.

The authors provide a methodology for introducing mobile robots into manufacturing applications and an example of a real implementation of multiple part feeding.

Table 1. Required capabilities for a mobile robot assistant in manufacturing environments (from [7]).

	Industrial requirements for assistive robotics
Navigation	Robustness in unstructured environment
Gripping technology (when used as a mobile manipulator)	Applicability for different part geometries
Hardware components	Economic components in compliance with industrial standards
Workload	20 kg (needed to help offload ergonomically undesirable tasks from people and to be able to handle typical loads)
Workspace	1.8 m square floor area (a typical size of a human-reachable work area)
Availability	99 %
Energy supply	24 hours
Safety	CE (European Commission) labeled application for man-machine interaction

Human-Robot Interaction

It is becoming more common for humans and robots to share a workspace. This has led to the need for improved human-robot communication and for awareness by the robot of what can be expected of the people around it and, similarly, by the people of what can be expected of the robots. An aspect of interaction with robots that is not unique to mobile robots is teaching them the tasks they are expected to accomplish. In Argall et al. [9], a method of teaching by demonstration is described, in which primitive components of motions are learned by a robot through teleoperation. The method is able to extrapolate from a set of basic motions to the development of a complete task without the user having to demonstrate all aspects of the task. Another approach is to use gestures to show the mobile manipulator what it should pick up or where it should go (Pedersen, et al. [10]). This requires the definition of gestures that are both easily communicated by humans and easily recognized and disambiguated by the sensors on the mobile robot. Some researchers have also investigated ways in which a robot can ask for help. Rosenthal and Veloso [11] describe a mobile robot that can navigate around an office environment but has no manipulator, so, for example, cannot push the elevator button. The robot has algorithms to enable it to find people and ask them for help, taking into account the imposition on the people it asks (the travel distance to the help location) and the robot's own need for a short task completion time. Another issue to consider when people are in the environment is addressed by Sisbot et al. [12]. Here a planner is developed that computes paths that take into account the comfort and expectations of people that may be near the robot. The plan assures that the robot both keeps a safe distance from all people and tries to keep the robot in the field of view of the people to prevent surprise appearances.

Personal care robots have developed into advanced human-robot interactive systems. For example, Care-O-bot (Graf et al. [13]) is now in its third generation with characteristics that are potentially very useful to the industrial mobile robot community. Navigation is via odometry (measurements of vehicle motion) improved by simultaneous localization and mapping (SLAM) based on front and rear laser scan data that is compared with a global map. A three-level hierarchical controller includes single wheel control, four wheel control, and a trajectory planner to enable path planning around obstacles and through narrow passageways. The omni-directional mobile manipulator includes a tray and robot arm and can compute collision-free manipulation paths based on data from a color camera and light detection and ranging (LIDAR) sensors. The system also implements spatial segmentation for obstacle learning and interpretation of the three-dimensional cloud of points detected by the LIDAR sensors for object recognition.

Navigation and Localization

Mobile robots often operate in large facilities and many different approaches have been taken for localization and navigation. They range from methods in which the entire facility is first mapped and routes are planned a priori to those in which sensors provide information about traversable areas and the vehicles determine their own current positions and plan their paths dynamically based on features recognized in the environment. There is typically a trade-off between a priori plans and dynamically-generated one. When there is not expected to be much change in the environment and cycle times are critical, a priori planning is usually preferred. When the workspace or the tasks change frequently it is often better to plan dynamically. Manufacturing facilities often take a middle road. Markers may be placed in the work area that are recognized by sensors on the vehicles and provide accurate localization through triangulation and thus simplify navigation. Other sensors on-board the vehicle look for obstacles or unexpected objects in the path of the vehicle and may be able to plan a way around them before returning to their pre-planned route. . It is also important to know the position and orientation (pose) of a mobile robot and many methods have been developed to provide this information. A commonly-used approach is to rely on odometry augmented by sensor-based measurements from lasers, radio-frequency identification (RFID) systems, two-dimensional bar codes (e.g., QR codes), cameras, etc. More advanced systems make use of algorithms that accomplish the localization and navigation tasks simultaneously. These systems are usually referred to as SLAM algorithms, for Simultaneous Localization And Mapping. By seeing the same features in multiple views using sensors that move with the vehicle, the algorithms can stitch together the sensor information. When this information is combined with the vehicle's estimates of the positions at which the information was gathered, a local map can be constructed. Over time, the whole facility can be mapped and the maps can be used to plan the vehicle's paths.

Localization and navigation of commercial AGVs is still commonly accomplished by wire guidance where induction is sensed from electrified wires embedded in the floor. It is now more common, however, to determine localization by laser triangulation methods, in which a spinning laser senses range and azimuth to wall-mounted reflectors. Several other localization methods are available on AGVs today as shown in Figure 3, including ceiling mounted bar codes, range or camera-based wall-following, using floor markers or magnets, and following magnetic tape. Azizi and Howard [14] describe some of the factors that reduce the effectiveness of odometry-based methods and ways of improving their performance using models of the errors and of the vehicle. Floor spots or magnets are an extension of wire guidance which use floor-embedded magnets to localize the AGV at the magnet and correct for odometry errors that accumulate between magnets. Wire guidance has been expanded to magnetic and chemical tape guidance. An example of mobile robots that use tape-based path sensing is discussed in Horan et al. [15]. These vehicles use cameras to view the floor tape. Similar research was performed at NIST to follow a lane having tape lines as boundary markers instead of a single center line. At the end of the lane, unique, temporary markers could be placed on the floor that would indicate to the vehicle that it should use its perception system to navigate through unstructured environments to a particular endpoint. Ceiling-mounted bar codes are available as an alternative to laser triangulation and are used in large warehouses where center supports for reflectors may not be available. The unique bar codes are two-dimensional patterns read by an onboard camera and the system can determine the position of the vehicle with an uncertainty of approximately 5 cm. Range-based wall-following is typically used in confined spaces, such as during truck loading applications.

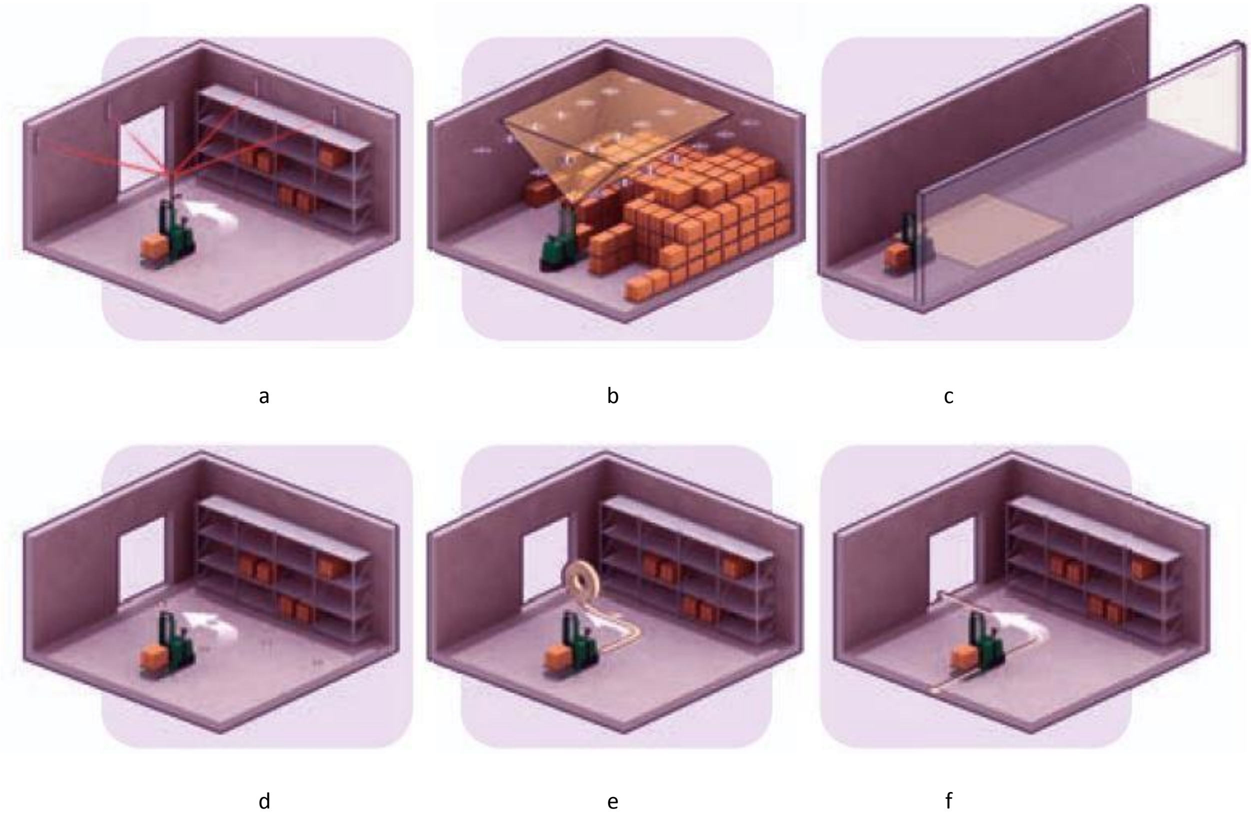

Figure 2. Various AGV localization methods in use today: a) laser triangulation, b) ceiling mounted bar codes, c) range or wall-following, d) floor spots/magnets, e) magnetic tape, and f) inductive wire (from [16]).

Biswas and Veloso [17] describe a fast algorithm for localizing a mobile robot using planes extracted from depth information that is projected into a 2D map of the environment. They make use of a Microsoft Kinect sensor that produces color images registered with range information. Since they are working indoors, they make use of the fact that there are typically many flat surfaces in the environment. Planes are extracted from the range data and matched with boundaries in the 2D map. The boundaries are typically places where walls meet or where the floor meets a wall. It is thus relatively easy to locate traversable regions including doors, corridors, etc. and to map the work area. Navigation is done by planning paths through the resulting map, with the three-dimensional information being used to check for and avoid obstacles. Creed and Lakaemper [18] also take advantage of the prevalence of planar regions in man-made environment. They project linear features into a two-dimensional map and use consistency to build a representation of the environment based on line segments. Moving objects are detected as obstacles and are not placed into the map. Their system is able to modify the map to deal with slow changes to the environment, such as when a door is opened and remains open for a significant time.

Another approach uses vision to localize the robot and, frequently to map the environment at the same time (SLAM). This allows navigation without needing an *a priori* map or known beacons in the environment (e.g., Davison and Murray [19], Liu and Thrun [20]). The Ford Motor Company implemented a SLAM application in which a camera was used for mapping floor patterns beneath the

AGV (Kelly, [21]). A related approach uses either bar-codes on the ceiling (TotalTrax [22]) or a mosaic image of the ceiling (Lucas et al. [23]) to determine the location of the vehicle and map the facility.

In yet another approach, Luimula et al. [24] use RFID tags in the environment for localization. Röhrig et al. [25]use a combination of laser and wireless ranging (using IEEE 802.15.4a network signals) to localize an omnidirectional vehicle using a particle filter (a type of sequential Monte-Carlo method). Bostelman et al. [26] applied GPS-like waypoint navigation to an indoor facility by using active RFID tags as waypoints placed at corners or where events were to occur. For example, at robot turns and door openings, the robot senses the tag upon approach. Once at the tag, the robot can, for example, turn the assigned amount to move along its new direction toward another tag while using stereo vision and 2D laser scanning for obstacle detection and avoidance. Since the vehicle can also place the sensed obstacles into a map, the same method could be used for mapping unstructured facilities when moving from one tag to another.

Röwekämper et al. [27] developed a method for localization using particle filters and two laser scanners. They also developed metrics for pose evaluation and evaluated the performance of their algorithm, showing that it is accurate to within an average of 5 mm and 0.15°. The performance metrics are useful for evaluating a wide range of algorithms. A different high-resolution localization approach is exemplified by Bartlett and Hvass [28] and Wang et al. [29]. These researchers independently developed the capability to localize a mobile manipulator by using a large-volume metrology instrument (Nikon iGPS). The authors of the first study used a manipulator mounted on an omnidirectional base to follow a path on an airplane wing with high accuracy. The second paper used a small robot to scan a turbine blade to inspect it or construct a 3D model. In each case, the external iGPS measurements were used to control the onboard robot motion with low errors (about 5 mm) in a large area (about 3 m^2).

Planning and Coordination

In a typical manufacturing environment there may be a large number of industrial vehicles moving material or in-process parts between workstations or, in more advanced operations, positioning tools or robots that operate directly on the parts. There are many aspects of the operation of such vehicles that must be planned and coordinated. They include ensuring that the paths of the vehicles do not intersect, that traffic does not become congested, that material is delivered to the right places at the right times and throughput is compatible with the work cadence of the factory, and that vehicles are given time to recharge. Planning includes determining more than just the paths that the vehicles will follow. It also may include ensuring that the vehicle avoids other equipment or people while enabling high precision docking with conveyors or other equipment.

The current practice in industry is to handle coordination as an offline problem to be solved when the vehicles are programmed. There are a number of reasons for this approach. They include safety concerns and the desire to maintain a constant rate of production. The offline approach breaks down in situations where there is the need for quick changeovers between tasks, and when people may share the workspace with the vehicles. As a result, there is a greater need for methods that try to maintain productivity and safety while still enabling the vehicles to modify their trajectories to enable coordinated motions and ensure obstacle avoidance. Such implementations rely on increasingly adaptive and intelligent control architectures with improved sensor feedback and situational awareness [36].

Much work has been done to try to plan and coordinate the actions of multiple mobile vehicles. For industrial AGVs, coordination is usually done centrally and the optimal routes can be computed offline because they do not change for long periods. Because AGVs and mobile robots are starting to be used in less structured environments and in situations where their tasks are not fully known in advance, the planning and coordination has become more difficult. While there are still methods that are based on centralized computation, distributed approaches are becoming more common because of the computational intractability of centralized methods. Decentralized methods tend to be agent based and may make use of a set of spatial and temporal zones in each of which plans are computed separately. An example of a zone-based approach is Digani et al. [37]. The authors define a two-layer architecture. The first layer breaks the work area into sectors and uses a topological search algorithm to find paths from sector to sector. The second layer is responsible for planning paths within each sector and computes the actual trajectories that each vehicle will follow, taking into account conflicts that may occur at intersections. Another approach that has some similarities is taken by Herrero-Perez and Martinez-Barbera [38]. Here, there are again two levels, but one is for decentralized navigation planning and the other for centralized task allocation and traffic control. The traffic control makes use of a zone-based decomposition of the work area, while the task allocation uses an auction mechanism to allow AGVs to bid on tasks. The AGV behaviors are modeled as Petri net plans. The system has been implemented and is operational in a real factory environment. While the paths that are planned in this system are not fixed, special care must be taken for high-accuracy docking maneuvers, which are planned and executed using a special procedure (Herrero et al. [39]). Another approach to task allocation and conflict resolution is to use time windows to find candidate paths and check their feasibility (Smolic-Rocak et al. [40]). This method uses a centralized algorithm to develop a dynamic routing plan for a facility that uses multiple AGVs and takes into account the number of active missions and their priorities. The algorithm resolves time window conflicts iteratively by inserting new time windows until there are no overlaps or the overlap is on the first segment of the path, which means that the candidate path is not feasible. The method has been implemented in several factories.

Predicting the movements of people and vehicles in the vicinity of mobile robots is important for safety and efficiency. Acuña et al. [42] developed a path-planning method called dynamic artificial potential fields, in which the planner allows the robot to navigate safely in highly dynamic environments even when obstacles move at higher velocities than the mobile robot. The method has been tested only in simulation and claims 100 % better results for the same scenarios than systems that do not incorporate prediction. Also, for dynamic environments, artificial potential field algorithms have been used to enable mobile robots to “repel” static and dynamic obstacles as if they were oppositely charged magnets and to dynamically adjust robot speed. Shehata and Schlattmann [43] researched a dynamic virtual obstacle representation that adjusts robot speed and steering angle. Again, this algorithm was only proven in simulation.

Angerer, Pooley, and Aylett [8] discuss the use of a hierarchical multi-agent system for dynamically reconfiguring mobile robots to accomplish a range of variations of tasks in an automobile factory that arise due to customizable feature of individual vehicles. Their system consists of a behavior-based backbone that operates at a fixed rate. It includes an ontology describing the objects and where they are located in the facility and a set of tasks that the system is able to carry out. The system can dynamically generate new agents to execute tasks that may arise when the environment changes. These agents are based on known capabilities of the system. Actions have both preconditions and post-conditions and this makes it possible to validate a new (planned) action before it is executed and during execution. While the system is in principle applicable to both stationary and mobile robot applications, it was developed and tested in an automotive application in which mobile robots move components between workstations and storage.

Performance Evaluation

Given the expense and risk involved in implementing mobile robots, it is important to evaluate how well they perform and to be able to determine ways in which their productivity can be improved. According to Berman et al. [31], evaluating the performance of AGVs should include both the capabilities of the vehicle itself and the role it plays in the manufacturing environment. The authors advocate a three-part evaluation strategy that covers the individual subcomponents of the AGV task (control, navigation, and load handling), a quantitative evaluation of the AGV system and its role, and a qualitative evaluation of the system. They provide a number of metrics and demonstrate their use in a two-vehicle system.

NIST has addressed performance evaluation of mobile robots in manufacturing by fostering challenges to promote academic research on AGV intelligence for factory environments. These challenges attempted to raise the AGV's level of intelligent performance on tasks that occur in real situations. Two such competitions were:

- Virtual Manufacturing Automation Competition (VMAC), 2007 - 2009 (Balakirsky and Madhavan [32]). This competition consisted of workshops and national and international AGV competitions based on real-world factory scenarios that demonstrated accurate path following and docking tasks. A feature of the competitions was that the software used enabled code to be moved without any changes from the simulation system in which it was developed to a real AGV for demonstration.
- Mobility and Task Completion Challenge, International Conference on Robotics and Automation (ICRA), 2012 [33]. This virtual challenge was designed to address the need for one or more factory AGVs to operate in unstructured environments amongst dynamic obstacles. Teams used the Unified System for Automation and Robot Simulation (USARSim) [34] framework to control simulated AGVs that delivered completed pallets by driving through a simulated warehouse environment, including loading and unloading of vehicles with a robotic arm.

Temple University and the University of Maryland, College Park, conducted research to test and evaluate the navigation capabilities of industrial mobile robots in industrial environments, such as modern dynamic warehouses. Their goal was to create and experimentally validate a framework by which AGVs and forklifts can automatically generate a sufficiently accurate internal map (world model) of their surroundings (Lakaemper and Madhavan [35]). Vendors who participated in the research received a quantitative, unbiased, third party assessment of their systems' capabilities.

Standards for Industrial Mobile Robots

Currently, there no performance standards for automatic industrial vehicles anywhere in the world. There are, however, safety standards both national and international. A key US standard for AGVs is the American National Standards Institute/ Industrial Truck Standards Development Foundation (ANSI/ITSDF) B56.5 for AGVs and manned vehicles with automated functions [44]. The scope of B56.5 is to define the safety requirements relating to the elements of design, operation, and maintenance of powered, not mechanically restrained, unmanned automatic guided industrial vehicles and the systems of which the vehicles are a part. It also applies to vehicles originally designed to operate exclusively in a manned mode but which are subsequently modified to operate in an unmanned, automatic mode, or in semiautomatic, manual, or maintenance modes. A list of other relevant mobile robot safety standards for both US and Europe is shown in Table 2.

A new ASTM International AGV performance standards-development task was formally approved by the ASTM main committee on May1, 2014. The effort forms a new committee, entitled: "Driverless Automatic Guided Industrial Vehicles," with the scope being to develop "standardized nomenclature and definitions of terms, recommended practices, guides, test methods, specifications, and performance standards for Driverless Automatic Guided Industrial Vehicles" while encouraging research and sponsoring symposia, workshops, and publications to facilitate the standards development in coordination with other ASTM technical committees. Five associated sub-committees will be structured to address Environmental Effects, Docking & Navigation, Object Detection & Protection, Communications & Integration, and Terminology.

Beyond industrial automatic guided vehicles, yet relevant to humans working close to mobile robots, ISO 13482 [45] crosses over from personal care mobile robots to industrial mobile robot risk assessment and mitigation. This standard includes safety of personal care robots designed to improve quality of life for people. Most of these robots are mobile and intended to directly interact with humans and obstacles in their environments.

Advanced Applications and AGVs

The range of applications that lend themselves to the use of mobile robots is growing as the capabilities of the robots and related sensors improve. This growth is also spurred by the overall demand by industry for greater automation and the development of safety standards that let humans and robots share a work area. As a result, a number of prototype mobile robots have been built for manufacturing applications. These range from vehicles that track materials, to mobile manipulators, to aerial drones used for material handling.

A novel application of AGVs to keep track of and optimize the locations of items in a warehouse is provided in Hildebrandt et al. [46]. The authors assume that stock items are equipped with radio frequency identification (RFID) tags and that a set of mobile robots can both localize their own positions in the facility and determine the locations of stock items using the RFID tags. The robots move about in the facility and, by tracking the movement of items, robots can identify preferred paths, find opportunities for optimizing storage locations and vehicle trajectories, and keep track of inventory.

The Kiva Mobile Fulfillment System [47] is one of several examples where a beneficial side-effect of the way that items are delivered from and returned to storage is the optimization of the placement of items in a warehouse. For example, items that are required frequently will, over time, be stored closer to the delivery area because the robots find convenient places to store them rather than relying on fixed locations.

Throughout this document, discussion of mobile manipulator research has been interspersed with mobile robot research as an extension of mobility. Mobile manipulators are being discussed in standards committees due to the gaps between AGV and robot arm safety standards and the possibility of opening new areas of research (Marvel and Bostelman [48]). Figure 3 shows a timeline from Bøgh, et al. [49] providing an example of the many mobile manipulator systems that have been or are being researched. Sophisticated vehicles that include robot arms for manipulation and sensors for navigation and handling components are discussed in Hvilshøj et al. [50].

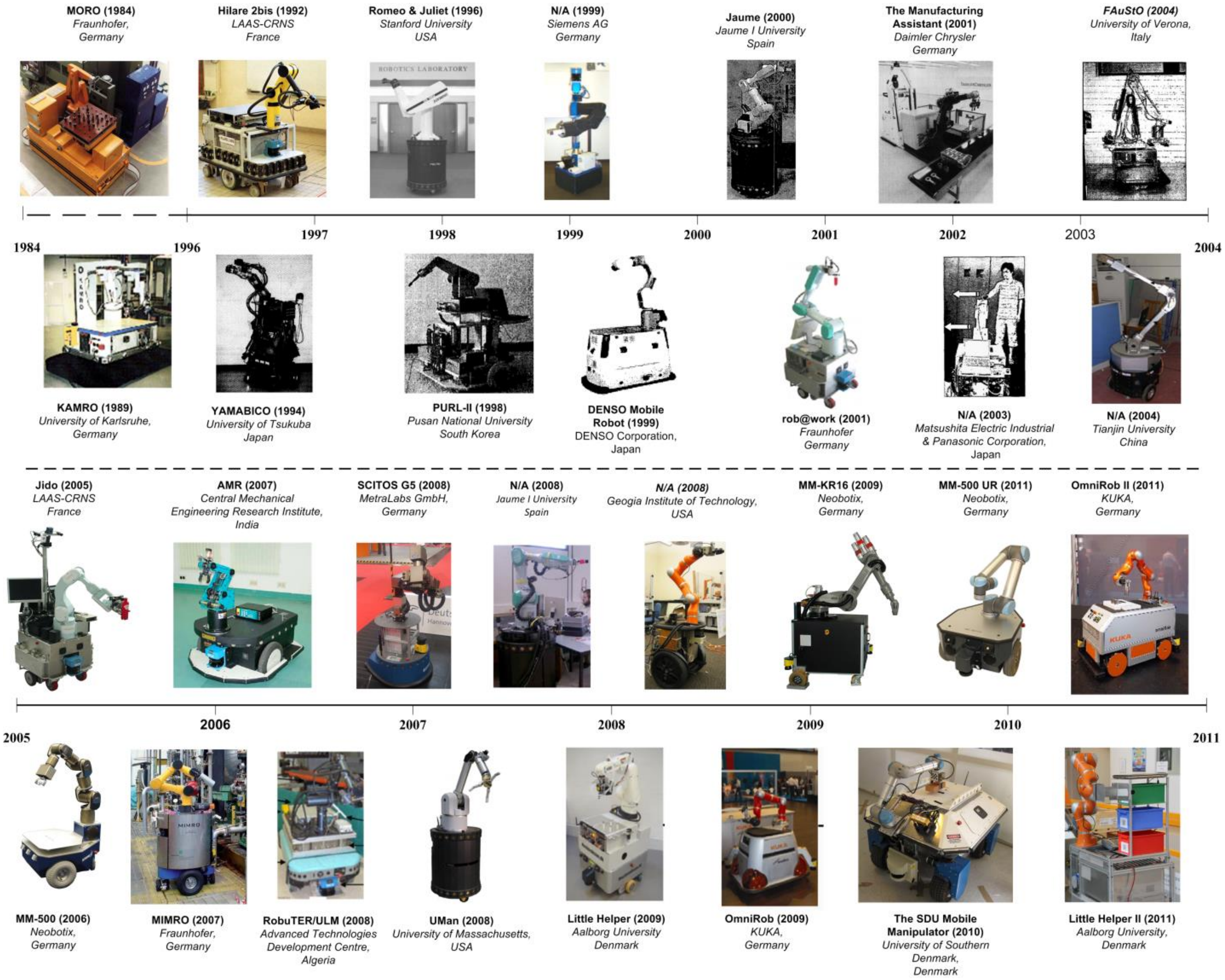

Figure 3. Timeline of mobile manipulator development (Photo courtesy of MTECH, Aalborg University, Denmark [49]).

Small drone multi-rotor copters are beginning to be explored for use in material handling with the recent concept of drone delivery of small packages weighing up to approximately 2.2 kg (5 lb) [51]. This concept (see Figure 4) from the Netherlands requires minimal infrastructure to install, enables rapid deployment, and is expected to maintain a relatively high sustained throughput. Interest from companies like Amazon will continue to drive battery and control development [52].

Figure 4. Snapshot of simulation video showing drones being used for palletizing (from [46]).

An example of a crawling mobile robot is described by Menegaldo et al. [53]. The robot is designed to inspect the outer surfaces of large oil ship hulls and floating production storage and offloading platforms. Locomotion over the hull is provided through magnetic tracks, and the system is controlled by two networked PCs and a set of custom hardware devices to drive motors, video cameras, ultrasound, inertial platform, and other devices. The navigation algorithm uses an extended-Kalman-filter (EKF) sensor-fusion formulation, integrating odometry and inertial sensors.

When the work area is cluttered or the floor is not level, combinations of mobility methods may be needed. For example, Michaud et al. [54] discuss a robot with legs for climbing over obstacles or changing robot height combined with tracks for mobility on hard or soft surfaces. Autonomous control for this type of tracked mobile robot is discussed by Mihankhah et al. [55] for navigating and traversing obstacles (e.g., stairs). These types of robots could provide material handling or mobile manipulation in highly unstructured environments, such as shipyard dry docks, aircraft manufacturing, or other large, small-batch manufacturing projects.

An alternative to a traditional mobile robot with onboard manipulator is described by Yang et al. in [30]. It consists of a four-legged, parallel robot with clamping devices at the end of each leg. A set of supporting pins is placed in the work environment at known locations. The robot moves by detaching a leg from one pin and attaching it to another, thus always accurately knowing its position. It is able to climb, so does not have to remain on a flat surface. The legs do not all have to be clamped and the platform mounted on the legs can carry and manipulate tools to perform work when reaching its destination.

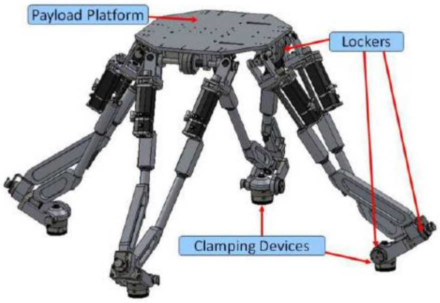

Figure 5. CAD model of a four-legged, parallel, walking robot with locking mechanisms (lockers) as needed for walking or load manipulation on some passive joints and clamping devices at the end of eachleg [29].

Summary and Conclusions

The field of mobile robotics is much larger than what has been described in this document. It covers autonomous driving on roads and across country, flying and water-based mobile robots, and a range of indoor applications that are not related to manufacturing. Historically, research in the United States has focused largely on areas of interest to the military and emergency services because that is where funding for research has been available. More recently, interest has been growing in mobile robots to assist people or provide services because there is a perception that robotic solutions might be commercially viable. Research in Europe has been more varied and has addressed more of the manufacturing needs, while Japan has focused, until recently, on humanoid robots and Australia has conducted substantial work in mining and agriculture. All of these strands of research are starting to be combined into systems with greater capabilities both for movement and autonomous action. As a result, it can be expected that the number of mobile robots in manufacturing will increase and the tasks that they will be expected to accomplish will become more complex. With a parallel increase in sensor processing capabilities and hardware robustness, it will become more common for people and robots to interact in a common workspace.

A range of manufacturing applications will be made possible that are currently very difficult or expensive to achieve. For example, instead of requiring large, custom machine tools to fabricate large components, it will be possible to move smaller, general-purpose tools around the component and fabricate it in a new way. This will require highly-accurate position measurements, but such tools already exist and have started to be applied in robotics applications. Another advantage of not requiring large “monument” machine tools is more flexibility in arranging the assembly line and, ultimately, enabling dynamic reconfiguration as the product mix changes. Other advantages of using mobile robots include the ability to offload dangerous or ergonomically-challenging tasks from people and to automate tedious tasks such as kitting and palletizing.

Before these capabilities can reach the marketplace, however, vendors will have to be able to guarantee the specifications and range of application areas of their products, and purchasers will want ways of comparing products and determining which are most suited to their needs. This will require performance metrics and procedures that are currently in their infancy. There will also be the need to program the tasks the robots will carry out in an easy and flexible manner, to be able to change tasks rapidly as the product mix changes, and to deal with the much less constrained work environments that inevitably accompany people working alongside robots. Standards will also have to be enhanced and harmonized, especially when mobile robots incorporate manipulators and dexterous end-effectors.

While progress is being made on all fronts, it is likely that introduction of new capabilities for manufacturing will be slow. There is a need for more focused research on manufacturing robotics and especially on mobile robots that can plan their own paths, localize themselves precisely, and have sufficient sensors and generic-enough manipulators to carry out human-like tasks in unstructured factories.

Table 2. Other AGV-Related Standards

ANSI B11.1-2010	Safety of Machinery – General Requirements and Risk Assessment
BS EN 1525: 1998	Safety of industrial trucks – Driverless trucks and their systems
BS EN ISO 3691-6:2013; BS EN ISO 3691-1:2012 (originally BS EN 1726-1:1999)	Safety of industrial trucks – Self-propelled trucks up to and including 10 000 kg capacity and industrial trucks with a drawbar pull up to and including 20 000 N
IEC/EN 60204-1: 2006	Safety of machinery – Electrical equipment of machines -- Part 1: General requirements (IEC 60204 -1:2005 (MOD))
BS EN 61496-1: 2010	Safety of machinery - Electro-sensitive protective equipment -- Part 1: General requirements and tests (IEC 61496 -1:2004 (MOD))
ISO EN 13849-1: 2008	Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design (ISO 13849-1:2006)
IEC 61508-1: 2010	Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 1: General Requirements
IEC 61508-2: 2010	Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 2: Requirements for electrical/electronic/programmable electronic safety-related systems
IEC 61508-3: 2010	Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 3: Software requirements
IEC 61508-6: 2010	Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 6: Guidelines on the application of IEC61508-2 and IEC61508-3
IEC 62061: 2005	Safety of machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems
IEC/TR 62061-1	Guidance on the application of ISO 13849-1 and IEC 62061 in the design of safety-related control systems for machinery
IEEE Std 1175: 1992	IEEE Trial-Use Standard Reference Model for Computing System Tool Interconnections
VDI 4451 Part 2:2000	AGVS Power Supply and Charging Technology (Lead acid and NiCd batteries), our batteries is LiFePO4 type

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