Safety of Mobile Robot Systems in Industrial Applications

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***Abstract*— The fourth industrial revolution is in full swing and according to "BCC Research" a compound annual growth rate of 23.1 % will be expected on the global market for the period of 2018 to 2023. Leading new technologies as mobile robotics and manipulator systems will facilitate more flexible and efficient production processes. Unfortunately, mentioned in the latest "Statista" report, the complexity of mobile robotic systems and missing standards are one of the major obstacles for a broad rollout of mobile robot systems. This paper presents a selection of what is already possible in the field of mobile robots and mobile manipulation systems and gives an outlook on current and upcoming leading edge developments. We focus on the requirements of the industry and addresses the related barriers concerning the design and implementation of safe applications. As a result, we propose best practice, recommendations and first concepts to overcome the discussed challenges in implementation.**

I. INTRODUCTION

Mobile robot systems have become more and more embedded in modern industrial production systems in recent years. In Austria 99.7 % of all companies are small and medium-sized enterprises (SMEs), however they only account for 64 % of the net sales revenue shares [12]. Most of them could not afford the technologies needed for the fourth industrial revolution (Industry 4.0) according to their limited resources. This difference between SMEs and large enterprises is noticeable in their internal warehouse logistics and production lines. Mobile robots as used by large enterprises increase the efficiency and flexibility in logistic, assembly and production processes, whereby human resources will be relieved from monotonous work [3]. When talking about mobile robots different terms are used. The most common ones are autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) and up to now, there is no absolutely clear distinction established. In general, AGVs are, per definition, in-house, floor-bound conveyor systems with automatically controlled vehicles whose primary task is material handling. The guidance of the vehicle is realized by some infrastructure hardware (wires, black lines, etc.) placed in the surrounding environment of the moving robot. In contrast, an AMR can move around autonomously and performs a specific task (e.g., household vacuum cleaner robot). The navigation through its environment is given by sensors mounted on the robot [5]. Mobile robots are much more flexible in their use and allow features as dynamic customer specific modifications, situation aware movement planning, enhanced collaborative operation, etc. Thus, they are highly relevant for state of the art Industry 4.0 applications. However, using mobile robotics in industrial applications results in increased safety requirements and a well organized co-existence between moving machines and humans.

The remainder of this paper is organized in the following manner. First, we give some background information about existing types of mobile robots and how they are already used in industry. In Section III, we present existing safety-standards for mobile robot systems and discuss associated problems. Based on that, we match these safety problems to challenges occurring by integrating mobile robots into real-world applications. Finally, in Sections V and VI we generalize our results, propose some recommendations and concept for successful implementation and conclude the paper by a summary of lessons learned so far.

II. TYPES OF INDUSTRIAL MOBILE ROBOT SYSTEMS

As already introduced above there are different types of mobile robots. In this section, first we briefly describe two selected important components of mobile robot systems with respect to safety and second focus into two industrial-important types of mobile robots (wheeled robots and mobile manipulators) in more detail.

A. General Safety-Relevant System Components

A robot system consists of a large number of individual components, which in combination provide a high degree of flexibility and application variety. These include, among others, the human-machine interface, task allocation and scheduling, sensors, sensor fusion and perception, motion planning, actuators and robot control. We would like to take a brief look at the most safety-relevant components present in every mobile robot system.

a) Sensors: In the case of sensors that are mounted on a robot, safety instrumented systems must be separated from non-critical information sources. Safety-related sensors have high relevance for the overall safety of the system and must

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be components certified by standards (e.g., EN 61508) that guarantee a certain safety level.

b) Robust Navigation with Sensor Fusion: Robust navigation of mobile robots is necessary, especially if it does not move in a static manner steered by fixed tracks. The localization of the mobile robot, the mapping of the environment as well as the path planning from one station to another are important areas of the robust navigation [10]. Problems with sensor failures or inaccurate results can lead to misinterpretations of the current environmental situation or robot status, resulting in potential safety risks. Sensor fusion is a proven solution for this problem, as information of different types of sensors is used. Strictly speaking, a sensed value is validated by at least a second sensor using a different measuring method. This approach enables, that the failure of one sensor can be compensated by a set of other sensors built in. For example, a slipping wheel will not be detected by two or more odometry sensors but in combination with an accelerometer and gyro sensor or a global sensor such as Indoor-GPS [23].

c) Robot Control: The robot operating system (ROS) is an open source software framework, which enables an easy implementation of robot application [17] and control of a robot system. Most of the mobile robot systems today are working with ROS, because the framework delivers many useful packages for various different problems. Therefore, a problem does not have to be solved always from zero knowledge. Different sensors and actuators are preprogrammed in this framework, ready to use. Different localization and navigation methods for mobile robots were programmed with ROS hence, see [7], [1].

A major advantage of using ROS with mobile manipulators in terms of safety is that the two main hardware components (mobile base and robot arm) are controlled in one software framework. In case a safety-relevant situation occurs in one of these two components, it can be transferred directly and adequately to the other component.

B. Wheeled Mobile Robots

As already mentioned in the introduction we differentiate between automated guided vehicles (AGVs) and autonomous mobile robots (AMRs). AGVs are working with deterministic methods, which deliver a simple binary result. A line tracking sensor for example will decide whether it is on the line or not. However, fixed tracks are required for the navigation of such AGVs [20], [22], [6]. Concerning this guidance of AGVs there are three different types:

- Wire guidance uses wires embedded in the plant floor that are sensed inductively by the vehicle in order to determine its lateral position.
- Inertial guidance uses transponders, embedded in the floor, for verifying the course of the AGV and gyroscopes to identify and correct the inevitable drift of the system. Magnets can be placed in strategic locations for the AGV to read and to reset the system.
- Laser guidance uses a laser transmitter-receiver carried by the AGV. It senses retroreflective landmarks strategically placed throughout the plant. By sensing the landmarks, the vehicle can then triangulate its position.

Fig. 1. Mobile manipulator (compilation of an UR10 and MiR100) solving an assembly task in a prototype industrial application

On the other hand, researchers are working mostly on AMRs using probabilistic methods. They suit better for real world problems such as localization in dynamic environments, obstacle detection and collisions free navigation in real time according to the detected obstacles. Furthermore, AMRs do not need any kind of mechanical installation such as rails or guiding tracks, allowing more flexible movements of the mobile robots [9], [14], [16], [21].

C. Mobile Manipulation

A mobile manipulator as illustrated in Fig. 1 can be seen as a system that combines a mobile robot and a serial manipulator equipped with sensors and at least one actuator. The actuator usually corresponds to a gripper system in order to manipulate objects in the necessary manner. The combination of a mobile and a serial robot unites the advantages of both robot systems and has the potential to be used flexibly. Numerous handling tasks can be performed with such a system, regardless of a predefined location. Depending on the field of application or the task assigned to them, such robot systems are operated remotely, semi-automatically or completely autonomously.

In addition to remote-controlled exploration and rescue robots, which this article does not want to focus on, sensitive mobile manipulators are also used as service robots. Service tasks can be fulfilled in the public and private sectors. Examples of applicable platforms are Tiago from PAL Robotics [18] and Care-O-bot 4 from Fraunhofer IPA [11]. For the economical operation of a mobile manipulator in a production environment, the design differs from that of a service robot platform. Robustness, payload, adaptability, programmability are some of the important features and functions that such a system must provide. The implementation of these requirements is still the subject of research by numerous institutions and consortia. Within the EU project STAMINA [13], the company is working intensively on the collection and delivery of assembly-related components in the production halls of the car manufacturer Groupe PSA (formally PSA Peugeot Citroën). The intralogistics transport tasks are supported by a fleet of mobile manipulators.

Although a number of research and service platforms of this type of robot systems are available on the market, the variety of industrial solutions is limited. Examples: KUKA KMR, Stäubli HelMo; Compilation examples: OTTO 1500 and Yaskawa SDA20D, MiR100 and UR10. Research and development projects are currently aiming to make mobile manipulators usable for the picking of heavy or bulky components. By using mobile manipulators for this kind of tasks failures, which can cause high follow-up costs, should be prevented. In addition, human workers would be freed from long-term, highly repetitive and therefore unhealthy tasks, which becomes more and more relevant as the average age of the workforce increases further. The use of sensitive mobile manipulators in manufacturing environments (assembly, production and logistics) is currently reaching the limits of safety engineering. Especially when such a mobile robot system has to perform non-deterministic pick and place tasks [19].

III. SAFETY STANDARDS FOR MOBILE ROBOT SYSTEMS

Before discussing selected standards for AGVs, AMRs and mobile manipulators in detail, we present a general overview of relevant documents for the standardization of mobile robotic applications. Fig. 2 illustrates selected laws, ISO and IEC standards as well as guidelines. At the head of all documents and thus most important are laws as the Machinery Directive and national laws for the protection of human safety. The main purpose of the Machinery Directive is to ensure an equal safety level for machines placed on the market or put into service in all European member states and to enable freedom of movement within the European Union. The second stage of the illustrated hierarchy contains international ISO and IEC standards. ISO Standards are categorized in A, B and C types, whereas type A are basic safety standards including general aspects and design principles, type B are generic safety standards covering aspects applicable for a wide range of machinery, and type C are safety standards dealing with requirements for particular machines. Standards highlighted by a green check mark are harmonized with the overriding importance Machine Directive. This means, using such a harmonized standard a developed product/application comply with the relevant legislation. Last, there are recommended guidelines and technical specifications (TS) which reflect the field's technological state of the art but are not obligatory for any standardization.

A. Standards for Wheeled Mobile Robots

AGVs operate on general in-house traffic routes while the demands on their safety are correspondingly high. The regulations for the usage of AGVs is nationally and at EU level mostly clearly regulated by the Machinery Directive 2006/42/EC. It obligates the manufacturer of a machine or plant to perform a risk assessment (according to EN ISO 12100:2010) and, if necessary, to take measures to decrease the risks for the operator [8]. Besides the machine directive, national and international standards are in place. The EN 1525:1997 (*Safety of industrial trucks - Driverless trucks and their systems*) is the main standard concerning AGVs. The present problem is that this standard no longer addresses the current state of the art technology (release date 1997) and is also not harmonized with the Machinery Directive. EN ISO 3691-4:2018-05 is currently in development and should replace EN 1525:1997. This means that manufacturers are currently obliged to fulfill the requirements of the Machinery Directive without a corresponding state of the art standard.

Similar to AGVs, a comprehensive applicable standard for autonomous mobile robots (AMRs) is still missing and the promised standard EN ISO 3691-4:2018-05 is still in development. Until this standard is published, there exists only one comparable standard called ISO 13482:2014-02 (*Robots and robotic devices - Safety requirements for personal care robots*) concerning personal care robots, which is not applicable to industrial applications.

B. Standards for Mobile Manipulators

For mobile manipulators, which are a combination of a movable platform and a robotic arm, different standards have to be applied, depending on the purpose of the robotic arm:

1) *Robot arm rests, when AGV is in motion:* The robot arm can be considered as a load and the risk assessment for the total hazard by analogy to regular AGV standards has to be assessed. A critical aspect is the clear definition of a safe position in which the robot will be transported. For the interfaces on which the report performs its task, robotic standards have to be considered.
2) *Robot arm does assembly or processing steps during motion:* All relevant (collaborative) robotic standards must be applied for the robot arm when performing the necessary risk assessment.

The corresponding standards are given by ISO TS 15066:2016 (*Robots and robotic devices - Collaborative robots*) and ISO 10218-1:2011 (*Robots and robotic devices - Safety requirements for industrial robots*) The core standard EN ISO 10218-1 is currently in revision as it no longer represents state of the art technology. The whole application, meaning the moving platform, robot arm and the surrounding environment (roads and work areas), must then be evaluated according to part 2 of the EN ISO 10218 standard, which is dealing with the integration of industrial robot applications.

There are currently no fully-compliant standards, guidelines or design proposals for this type of robot, so the potential legal consequences of injury or damage are difficult to predict. When interacting with human workers, completely new hazards arise that are currently not covered in the present standards. To avoid a severe limitation of the extent and flexibility of enforceable solutions compared to the already

LAW	Machinery Directive 2006/42/EG National Law for the Protection of Health and Safety (ASchG 1995)			
ISO STANDARD	Type A	EN ISO 12100 ✓ Safety of machinery- Integrated manufacturing systems- Risk assesment and risk reduction		
	Type B	EN ISO 11161 ✓ Safety of machinery- Integrated manufacturing systems- Basic requirements	EN ISO 13849 ✓ Safety of machinery- Safety-related parts of control systems	
	Type C	ISO 10218 ✓ Robots and robotic devices- Safety requirements for industrial robots	EN 1525 Safety of industrial trucks- Driverless trucks and their systems	EN ISO 3691-4 ✓ Industrial trucks- Driverless industrial trucks and their systems (draft)
IEC STANDARD	EN 61508 Functional safety of e/e/pe safety-related systems	EN 62061 ✓ Safety of machinery- Functional safety of safety-related e/e/pe control systems		
GUIDELINE	ISO TS 15066 Robots and robotic devices- Collaborative robots	VDI 2510 Automated guided vehicle systems	VDI 2710 Interdisciplinary design of automated guided vehicle systems	

Fig. 2. Overview over relevant laws, standards and guidelines for mobile robot systems (automated guided vehicles and mobile manipulators). Standards highlighted by a green tick are harmonized with the machinery directive.

technically feasible ones, new approaches and safety models are highly needed.

In the USA the Robotic Industries Association (RIA) in cooperation with the American National Standards Institute (ANSI) are working on a conjunct national standard for mobile robotic systems called ANSI/RIA R15.08 (Draft). This proposed standard tries to bridge any gaps between regulations for AGVs, AMRs and mobile manipulators. ANSI/RIA R15.08 is in draft state since 2017 and is announced to be published in the early 2019 [2].

IV. CHALLENGES AND OPTIONS IN PRACTICAL APPLICATION DOMAINS

Implementing any kind of mobile robot or mobile manipulator for practical applications will lead to different problems. We discuss selected challenges within this section considering the present situation of missing applicable standards.

A. Challenges Associated with Wheeled Mobile Robots

A common drawback for authorities implementing a mobile robot application is the lack of know-how in the form of missing standards and guidelines. Talks with industrial partners have shown that most of the SMEs do not know which robot they need, and which criteria are important to differentiate between available products on the market.

A significant structural challenge is a required safety distance as required by the standard. For example, a minimum distance of 500 mm besides the robot track has to remain free to enable potential escape possibilities for humans. Industrial experiences showed that this minimum safety-distance is difficult to reach, especially when AGVs are integrated into existing systems where space requirements are not planned for their usage and paths are not intended to be utilized for mixed man-machine usage.

Additionally, the standard requires a limitation of velocities (0.3 m/s in linear/driving direction and 0.7 m/s in angular direction). This strict velocity constraints lead to the (erroneous) assumption that safe and certified components could be omitted by strictly limiting the velocities to the mentioned borders or that a risk assessment in consideration of the whole work system and the interfering inner-factory traffic is not necessary. On the contrary, a risk assessment might even help to allow higher velocities in some cases to increase the overall productivity of the implemented application.

Furthermore, employees in production environments are afraid of getting replaced by mobile robots (however, this is not the only fear). A survey resulted that the probabilistic navigation and autonomous obstacle avoidance with dynamic plan reconfiguration at high speed leads to a skeptical attitude of the workers. Deterministic navigation, on the other hand, results to a less scary feeling, because employees know exactly where the mobile robot is moving and do not have to be afraid of any unexpected movement behavior. Slower and ”relaxed” movements of the mobile robot resulted also positive in this survey. However, the production time will increase according to the slower driving mobile robots. Therefore, a compromise including the production time and the employees’ opinion has to be made [15].

B. Challenges Associated with Mobile Manipulators

The practical application opportunities for the use of sensitive mobile manipulators are extensive. Handling tasks of all kinds dominate, especially in the industrial context. The tasks in the production areas are usually assigned to intralogistics or internal goods handling. Transporting crates, removing and inserting components from and into machines or shelves, simple positioning tasks for work preparation, are the main assignments. Sensitive mobile manipulators are basically capable of carrying out these activities during normal operation with humans in the transport area. Nevertheless, the currently customary transport speeds of around 4 km/h do not compete with those of, e.g., motorized industrial trucks. In so-called ghost shifts, undisrupted progress of work is possible and is less critical in terms of cycle time. In addition, risks for humans are largely reduced during this period. However, if the above operations are to be performed during normal operation, the safety assessment of the robot system comes to the fore again.

V. RECOMMENDATIONS AND CONCEPTS TO OVERCOME THESE CHALLENGES

Many of the previously mentioned problems were solved already by different companies successfully implementing mobile robots in industrial environments. Therefore, recommendations are mentioned in the following as lessons learned and a concept to overcome the safety issue for mobile manipulation are introduced.

A. Recommendations for Wheeled Mobile Robots

The UAS Technikum Vienna is currently working on a research project named ”SIP 4.0 - Sicherheit in intelligenten Produktionsumgebungen” funded by Vienna City Administration. One output of this project will be a best practice guiding document, which should enable a low effort implementation of mobile robots in intelligent production systems, considering the small budget and know-how of SMEs. Most important, every robot application has to pass a risk assessment and has to prove that potential hazards are tolerable. As defined in ISO 12100:2010 a group of several people have to line up different risks in touch with the robotic system demarcated to the predefined system boundaries.

Environment: The perfect mobile robot for an enterprise depends on the needs and cannot be generalized. Most of the enterprises do already have a given infrastructure making it difficult to integrate mobile robots. Regardless, if an infrastructure is already given or a new one has to be built, it is important to include safety experts and labour inspectors from beginning to avoid problems in the final implementation state. In addition, different non-safety-certified components could be considered to provide a more comfortable feeling for the employees with mobile robots. Furthermore, rules for human-machine-collaboration with defined routes for mobile robots, traffic light systems at intersections and priority rules can accomplish this. All mentioned measures are applicable regardless of the implemented navigation method.

Sensor systems: Additional sensors for detecting humans are highly recommended. As seen at the LogiMAT 2019, all manufacturer of AMRs had safety-certified laser scanners implemented for detecting hindrances/humans in their products, independent of any velocity constraints given in the standards. Even most of the AGVs at the LogiMAT had safety laser scanners installed, apart of AGVs working in human free areas. In addition to human safety, the safety of mobile robots itself should also be considered especially for industrial environments. For instance, a mobile robot may destroy itself at low passages or dropping objects leading to an economical damage.

Tradeoff between AGVs and AMRs: An established technology might be a better option even if a newer technology is available. As seen at the LogiMAT the ratio between AGVs compared to AMRs was still 50:50. Probabilistic robotics used in AMRs is often preferred because of its flexibility. However, the paths of the mobile robot will not change daily in industrial environments and employees do not completely trust the automatically dodging mobile robots.

B. Concept to Overcome the Safety Issue for Mobile Manipulation

Especially in collaborative robotic applications, it must be ensured that forces and pressures remain below defined limits before being taking them into operation. However, the robot system or plant must not be modified without restarting this process. This circumstance poses a major challenge for applications with mobile manipulators because the robot system operates in a dynamic and therefore mostly non-deterministic environment.

We propose an alternative approach to partially solve this practically highly relevant problem. Not only a specific robot application is to be approved in terms of safety, but also a kind of class of an application. This means that, for example, a pick location is not considered explicitly, but a space as generous as possible in which an object can be picked up safely. The challenge is (a) to define reasonable limits of the space and (b) to demonstrate that all picking points within the defined limits are safe. This space is a so-called modification dimension, in which the application can be modified without the need for a new risk assessment. Other modification dimensions can be, for instance, a geometrical dimension of the workpiece, the position of the robot base or the manipulation velocity.

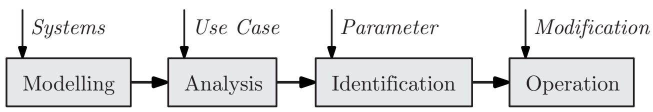

Fig. 3. Simplified structure of the proposed approach; the main action blocks and their input information.

To enable a permitted modification on one or more dimensions some steps are required to show that safety guaranteed. Fig. 3 shows a simplified structure of the proposed task sequence that can lead to this goal. Based on a set of mathematical models of different robots and safety devices (*Systems*) the actual application is analyzed and modeled (*Use Case*). An important next step is the identification of specific parameters that characterize the application and the system in use (*Parameter*). The decisive step is the merging of all system and application describing models into one overall model [4]. It is able to assess whether a variation within a modification dimension is actually admissible during operation (*Modification*). This is achieved by (a) assigning limits to a modification dimension, (b) performing selected biofidelic measurements at the edge and within the range, and (c) demonstrating through the mathematical models that all points within the range can be declared safe. With this method, the practical application flexibility of collaborative robots can be significantly increased. In its full extension stage, to be counted as future work, safe mobile manipulation can thus be achieved.

VI. CONCLUSIONS AND OUTLOOK

Each company has to choose between an AGV or AMR implementation. This depends on their personal needs such as production time, transportation tasks and the number of employees working in the expected mobile robot environment. Depending on this choice, the complexity of the implementation and the potential problems vary. No matter which decision is made the usage of additional safety measures for human safety like sensors are essential. Organizational measures such as taped lines for demarcations and traffic light systems at intersections for a more comfortable feeling with the mobile robots can have a major impact on the acceptance by the employees, which in the end is crucial for a successful application. Applicable standards are currently missing or in revision and the industry is in high need for technical support and new models in this regard so that new technologies can be still be used and applied safely without harming productivity. Apart from that, another major constraint using mobile robots and manipulators is the lack of flexibility when adjusting or changing workplaces or tasks. The aim of up and running research and development projects is to build up (software-) systems to (semi-) automatize the evaluating scenarios concerning their hazards. Still, it is not certain that a system like that can actually guarantee that all necessary safety aspects for the relevant modification dimensions are identified and addressed. To be a relevant support system this software would also have to evaluate the external and internal safety equipment and models accordingly and as an overall system, with all existing overlaps and interconnections. Technical feasibility is still uncertain.

In the need for quicker adoption to new requirements and more flexibility, safety topics and issues will become highly relevant during the planning and design phase. Therefore, methods and tools have to be created to enable virtual enhanced testing methods for flexible work-systems. In the future, sensor systems will become more advanced and cheaper. This will make it possible to equip the facility in a bigger manner and to bring the safety from the device itself into the surrounding space. In addition, Machine Learning algorithms for an autonomous configuration of machine new evaluation, testing and verification methods will have to be developed and applied. Summarized, the future will not bring a "cookbook standard" that addresses all issues and needs. The standards that are currently in development show a trend towards more individual responsibility of the user in regards to the (still) required risk assessment.

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