Paper presented at the Workshop on Design, Learning, and control for safe human-robot collaboration
20th International Conference on Advanced Robotics (ICAR 2021)
Online, Dec. 7, 2021

From Safety Standards to Safe Operation with Mobile Robotic Systems Deployment*

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***Abstract*— Mobile robotic systems are increasingly used in various work environments to support productivity. However, deploying robots in workplaces crowded by human workers and interacting with them results in safety challenges and concerns, namely robot-worker collisions and worker distractions in hazardous environments. Moreover, the literature on risk assessment as well as the safety standard specific to mobile platforms are rather limited. In this context, this short paper first includes a brief review of the relevant standards and methodologies. We then proposes a risk assessment for the safe deployment of mobile robots on construction sites. The approach extends relevant existing safety standards to encompass uncovered scenarios. Safety recommendations are made based on the framework, after its validation by field experts.**

I. Introduction

The safety of robotic systems is a core aspect of most deployments, especially in regard to human-robot collaboration in shared workplaces. The various approaches proposed can be regrouped following the type of locomotion: Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs). For instance, UAV safety has been vastly studied outdoor [1]. Still, the direct/indirect common classification of risk for UAV can be transferred to other locomotion: direct hazards occur when the platform collides with obstacles, such as equipment and labor, while indirect hazards encompass the environmental circumstances affecting the robot functionality, such as noise and wind, as well as the distraction the robot represents to the workers. A model to assess the safety of mobile robot deployment with respect to its physical characteristics and its environment was proposed by Moud, Hashem Izadi, et al. [2]. Along the same line, Augustsson et al. [3] proposed the use of defined safety zones around the robot. The safety zone geometries are flexible and adapt to the work carried out by the robot, which can provide a safe human-robot interaction. Truong et al. [4] proposed another approach for safe collaboration between human and robots. They emphasize on human safety while robots and humans are navigating in a shared environment. When individuals are detected through the robot's sensors, the robotic system generates itself a safe zone for navigation. Shin et al. [5] proposed a framework compliant with ISO/TS 15066 [6] to assess the *collision peak pressure* of cobots close to humans. Their study emphasis the importance of the safety aspects in a shared work space.

Fig. 1. Clearpath Jackal in action on a construction site

The construction industry has been known to be one of the most dangerous for human workers [7] and using robots in construction sites has many foreseen advantages for tedious and repetitive tasks (site surveys, material transport, etc.). Therefore, we trust this context to be one of the most challenging environments for safety issues with autonomous mobile robots and we select it for our deployment use case. Kim et al. [8] already stressed that many security concerns regarding the deployment of robots on construction sites remained unanswered, particularly regarding human-robot collisions (direct or indirect injuries), an issue exacerbated with mobiles robots. Early works on human-robot collaborative tasks in construction sites show the increase of efficiency it can provide, but also the complexity of keeping both that level of efficiency and the safety of the operators [9]. Brosque et al. [10] follow this approach by implementing several collaborative unit tasks, such as bolting and welding, required to assemble a spatial structure in a simulated environment. Moreover, virtual environments were shown to be helpful to identify and mitigate the risks before conducting the real operations [11]. Their results are used for the development of a framework for safety analysis of human-robot collaboration. Despite the meaningful contributions of these studies and others, none of them provides a complete assessment of the risks for a mobile robot validated in field deployment (as opposed to simulation). Ideally, we should be able to flip the situation and, instead of a threat, robots navigating a construction site could be leveraged to enhance the workers safety. For instance, Wang et al. [12] proposed UAV aerial images to help with offline and offsite analysis of safety issues.

In this short paper, we propose a framework to assess potential safety risks regarding the deployment of mobile

*This work was not supported by any organization

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robots on construction sites with a quantifiable index. The paper is divided in the following sections: we detail the framework in Section III, then, in Section IV, we conduct a case study on the deployment of a Clearpath Jackal rover, depicted in Fig. 1, on a real construction site with the purpose to validate the framework, and to be able to define safety recommendations.

II. Relevant Standards and Technical Specifications

Several standards and technical specifications must be considered regarding the deployment of mobile robots in workplaces. While none of them are both specific to mobile robotic systems and applicable to various deployment scenarios, many elements are transferable. Most of the current applicable documents target manufacturing robots, eg., fixed (and recently some industrial mobile robots), collaborative devices, automated guided vehicles (AGV), automated agricultural machines, etc. ISO/TS 15066 is of particular interest, because it focuses on cobots, however not yet in the form of a standard but rather as guidelines. It details the following four collaborative operating modes: 1) safety-rated monitored stop; 2) hand guiding; 3) speed and separation monitoring; 4) power and force limiting. This classification of collaborative tasks, or combination of these, with regards to the safety requirements can be translated to mobile robots deployed alongside workers. The most recent standard, ANSI/RIA R15.08, focuses on industrial mobile robots (IMR). Both autonomous mobile robots (AMR) and AGVs are considered IMRs if deployed in an industrial facility, thus they are covered by this standard. However, AGVs and AMRs have different scopes: the former follows fixed routes, while the latter uses sensors to avoid and go around obstacles. The ANSI/RIA R15.08 is based on relevant guidance from ANSI/RIA R15.06 and ANSI/ITSDF B56.5, which focus on industrial robot safety and guided industrial vehicles, respectively. ANSI/RIA R15.08 includes general requirements for IMRs and their attachment, notably modes of operations, control functions, presence-sensing devices, etc.

III. Ensuring Safe Operation

The strategy applied here is divided into four steps, i.e., preliminary planning, data collection, risk assessment, and risk mitigation. The terminology used is inspired by the standards considered above.

A. Preliminary Planning and Data Collection

In the preliminary planning phase, several contextual elements must be identified and taken into account: the legal aspects affected by the deployment of a robot on a construction site, the objectives motivating the deployment of a robotic solution, and potential management changes resulting from these new working methods. When this administrative process is completed, some information must then be collected in order to carry out a risk analysis. This is notably done with a survey of the workers involved with the robot's deployment. Semistructured interviews with the same individuals and on-site visits complete the information gathering. Taking photos and videos is intrinsic to the last step and is particularly useful to identify potential hazards.

B. Risk Assessment

The risk assessment is divided in three steps: 1) Determination of the parameters and the limits of the robot and the environment; 2) Identification of potential dangerous phenomena; 3) Risk evaluation. First of all, the robot parameters are selected and characterized, including the type of locomotion, the robot's shape, its functions, the onboard sensors (which will be used for risk mitigation), the battery's parameters, and any other relevant information. The environment's parameters where the robot will be deployed must also be established, i.e., indoor or outdoor, as well as the type and configuration of the ground, the available space to move, presence of obstacles, etc. Combining the two set of information (robot and environment), we must evaluate elements such as visibility, which depends on both. Then, the working conditions of the robot are determined. This includes the typical and maximum duration of use, the frequency and the materials with which the rover will interact, etc. The complete life cycle of the robot must also be considered, i.e. commissioning, use, troubleshooting and servicing. Potential consequences of bad use and reasonably foreseeable failures must also be known. Finally, the minimum experience needed to operate the robot has to be established beforehand and validated with non experienced users.

Once the operation parameters of the robot are known, we get to the critical step of potential dangerous phenomena identification: they must be meticulously listed to minimize the risks. These can be mobile and moving parts (mechanical phenomena), live wires (electrical phenomena), too hot/cold machine parts (thermal phenomena), noise/vibrations, visible (laser) and invisible electromagnetic phenomena, dangerous substances and noncompliance with ergonomic principles. These potential hazards are then classified based on the entities facing the potential dangerous phenomenon, namely workers, the robotic platform itself, and the environment.

The next step is to evaluate and conduct a relative comparison between the potential risks posed by every dangerous phenomenon identified, in order to establish a priority order for the actions to be taken. The risk is defined as the combination of the probability of damage and its gravity according to ISO 14121. This definition is central to our framework and the risk index used. The latter can be divided into four parts, i.e., (1) gravity/severity of potential injury (G); (2) frequency and exposure time (F); (3) probability of occurrence (O); (4) possibility of avoiding or limiting damage (P). Together, these four parameters form the risk quadruplet set, with one additional parameter compared to the risk triplet set proposed by Prassinos and Lyver [13]:

$$RISK = \{< G, F, O, P >\} \tag{1}$$

The flow chart to select a value for these four parameters and

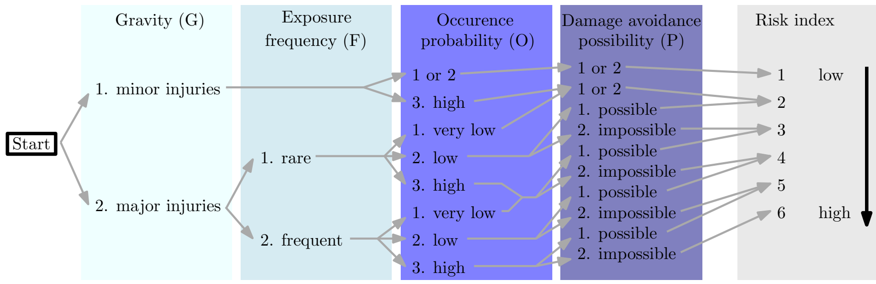

Fig. 2. Flow chart of the risk assessment (adapted from [14])

the final risk index was designed by Bourbonnière et al. [14], and is illustrated in Fig 2. The final stage is to make a judgment on the estimated level of risk. It is at this stage that we determine whether the risk is tolerable or not. When the risk is considered intolerable (high risk index), risk mitigation measures must be chosen and implemented. To ensure that the solutions chosen make it possible to achieve the risk reduction objectives without creating new potential dangers, the risk assessment procedure must be repeated once the solutions have been implemented. Furthermore, this last step is particularly important and cannot be overlooked, as corrective measures to reduce the risk posed by a particular phenomenon can also generate or increase the probability of other dangerous phenomena.

C. *Risk Mitigation*

The last step of risk ensuring safe operation with a new robotic system, as per the ANSI/RIA R15.06, is minimizing the risk index for all dangerous phenomena identified in the previous section, and eliminating them if possible. Preventive and corrective measures must be put in place and the risk index must then be reevaluated accordingly. These measures are classified into three categories: 1) intrinsic prevention; 2) organizational; 3) guards and detection devices. Examples of intrinsic prevention and mitigation measures at the source are given below:

- Separation distance between the robot and obstacles, workers and equipment (from ANSI B56.5);
- Keeping the batteries at a good level of charge or else completely change the battery (from ANSI B56.5);
- Adequate ground surface for the robot (from ANSI/RIA 15.08);
- Reducing speed and force/torque capabilities of the robot (from ISO/TS 15066).

Similarly, these are some organizational-type measures:

- Training of workers (from ISO 10218);
- Compliance with the manufacturer's instructions (from ISO 10218);
- Preventive maintenance of the robot (from ISO 10218);
- Pedestrian traffic plan indicating traffic lanes, road markings (from ISO 12100).

Finally, here is a short list of potential mitigation measures related to guards and detection devices:

- Audible alarms (from ISO 10218);
- Emergency stop devices (from ISO 13850);
- Proximity sensors (from ISO/TS 15066).

IV. Case Study

The case study presented here focuses on the intended deployment of a Clearpath Jackal, an autonomous rover depicted on-site in Fig. 1, on a building construction site managed by the company Pomerleau Construction in Montreal, Canada. Based on the needs identified, namely a large research payload and robustness, Pomerleau chose the Jackal by Clearpath. Before reaching the site, we recommended a methodical risk assessment to deploy it safely. We recommended the following steps, tailored to a worker without any prior experience with robots.

Step 1: Ensure compliance with robot safety standards ISO 10218-1 and 2 and ANSI / RIA R15.08.

Step 2: Present the Jackal to the various stakeholders (workers, supervisors) on the site in order for them to get to know the new mobile system that will now share their workspace. This step is critical to make sure they know the risks and how to behave in some specific situations with this AGV to reduce the probability of incidents.

Step 3: Make a presentation to be the local safety regulator (*CNESST* in the case at hand). The *CNESST* and worker unions must be aware of the presence of the AGV on the site and if necessary, validate its installation.

Step 4: Mapping the construction site; validating the ground is completely flat and where obstacles are located, which will facilitate the movement of the Jackal. It is essential to verify the data acquisition system on the Jackal with its sensors is functional and adapted to the environment.

Step 5: Undertaking a risk assessment procedure; This step consists of respecting two essential points: identifying the risks associated with the Jackal, then estimating and evaluating these risks in order to define the priorities.

Step 6: Identifying risk mitigation measures, partially detailed for this use case in Table I.

Step 7: Validating the risk mitigation measures through on-site simulated scenarios with the Jackal. Identify shortcomings and make adjustments if necessary.

Step 8: Validating the measures put in place while the robot is in operation by tests and feedback from the workers and experts in the field.

V. Conclusion

Work environments, including construction sites, are environments with a significant number of safety hazards; the introduction of AGVs to increase productivity creates additional concerns regarding safety. While a range of standards and regulations exists, there is no clear roadmap for the safe deployment of mobile robots on construction sites. Therefore, in this short paper, we proposed a framework to assess the risks and to identify measures of mitigation. The framework was validated through a case study in a real construction site context. Future work is planned for further detailing and risk predictability.

ACKNOWLEDGMENT

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada for the financial support through its CRD program 543867-2019, to Mitacs for the support of this field study as well as Pomerleau; the industrial partner of the ÉTS Industrial Chair on the Integration of Digital Technology in Construction.

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TABLE I

PARTIAL JACKAL RISK ANALYSIS (RRI: RESIDUAL RISK INDEX)

Identification	Risk index estimation					Mitigation	
Dangers / Dangerous Phenomena	Severity	Frequencies	Probability	Possibility	Risk index	Preventive and/or corrective measures	RRI
1 Collision / Contact during displacement of the robot	G2	F2	O3	P1	5	Integrate obstacle detection sensors, security distance between the worker and the robot	1
2 Robot overturning (loss of balance)	G1	F1	O3	P1	3	The state of the floor surface must be adequate for the robot (no openings)	1
3 Objects falling on the robot	G1	F2	O3	P1	5	Provide a protective cage in light metal covering the robot	2
4 Robot's battery low	G1	F1	O1	P1, 2	5	Charge in advance or change the battery	1
5 Robot's noise level	G1	F1	O2	P1	2	Reduce / eliminate as much as possible the level of noise	1
6 Crushing of the robot by a vehicle or worker	G1	F2	O3	P2	6	Define traffic lanes for the robot	1
7 Unexpected failure of the mechanical and electrical components of the robot (e.g. security device)	G1	F2	O3	P2	6	Preventive maintenance	1
8 Inability for the robot to stop during its use	G1	F1	O3	P1	3	Install an emergency stop button	1
9 Strength and speed of the robot	G1	F1	O2	P1	4	Decrease the speed of the robot	2
10 Irregular start-up procedure (false alarm)	G1	F1	O2	P1	2	Preventive maintenance	1
11 Loading an incorrect program	G1	F1	O2	P1	2	Automatic actuation of the brakes	1
12 Obstacles on the ground preventing the robot from deploying correctly	G1	F2	O3	P2	6	Improve the ground surface to facilitate the robot's access and free up intended paths	1
13 Devices or equipment on the ground	G1	F1	O1	P1, 2	2	Establish a good layout plan	1
14 Personnel arriving from all directions	G1	F1	O2	P1	2	Establish a good pedestrian circulation plan	1