Towards Mobile Manipulator Safety Standards

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***Abstract* — We present an overview of the current (as of Spring, 2013) safety standards for industrial robots and automated guided vehicles (AGVs). We also describe how they relate to the safety concerns of mobile manipulators (robot arms mounted on mobile bases) in modern manufacturing. Provisions for the capabilities of mobile manipulators are provided in relationship to the current standards. Several scenarios are presented for which the behavior of a mobile manipulator may be unpredictable or otherwise contrary to the current safety requirements. We also discuss the needs for a new class of test artifacts for verifying and validating the functionality of mobile manipulator safety systems in collaborative working environments.**

Keywords—mobile manipulators; AGV safety; robot safety; safety standards; human-robot collaboration

I. Introduction

The utilization of robot technologies is rapidly growing globally and across a myriad of industrial domains to accommodate the need for increasingly flexible automation in modern manufacturing [1]. Such technologies include advances in dexterous robot grippers [2], safe collaborative robot design [3], and pervasive use of robot sensing [4]. A consequence of this rapid growth is that the development and integration of technologies in manufacturing environments is outpacing the evolution of standards and test methods that are used to ensure the safety of humans in these environments.

As an example of this rapid growth, mobile manipulators (robot arms mounted on mobile bases) are becoming more common as a means of expanding the utility of manufacturing automation. Safety standards for industrial robot arms and automated guided vehicles (AGVs) are written to reduce the risk to humans in industrial environments, but only with regard to their respective platforms. The marriage of mobility and dexterity enables truly flexible factory environments for lean manufacturing. However, it also presents an increase in capabilities for which the existing robot and AGV standards do not provide sufficient provisions for safeguarding.

The U.S. National Institute of Standards and Technology (NIST) helps promote the economic viability of U.S. manufacturing by developing test methods and metrics for system developers and users to evaluate the performance of new technologies. NIST is also aiding the development and validation of safety standards for both AGVs and industrial robots [5]. Adherence to such standards is voluntary, but compliance may be required by national safety organizations or for global distribution of robot technologies. This paper describes these standards and how they relate to mobile manipulators. This paper also illustrates the safety challenges with the integration of mobile manipulators into human-occupied settings. Section II outlines the mobile manipulator concept, and introduces the need for new safety standards for agile manufacturing. Section III describes the current standards for AGV safety, while Section IV discusses the standards for industrial robot safety. Section V presents the standards for human presence detection. Section VI highlights some conditions under which mobile manipulators are not properly covered by the AGV and industrial robot standards. Section VII details the need for new test piece designs for verifying and validating AGV, industrial robot, and mobile manipulator safety.

II. Mobile Manipulators

The arm-on-mobile-base paradigm has been around since the 1970s (e.g., [6]). It is commonplace for teleoperated and semi-autonomous platforms to be used for purposes such as bomb disposal [7], search-and-rescue [8], medical assistance [9], and residential service [10]. Such solutions are single-purpose with targeted applications. General-purpose mobile manipulators are less common, and tend toward proof-of-concept platforms that focus more on the aesthetic (e.g., [11]) and academic (e.g., [12]) functions of robotics, and less on the utilitarian. Following the 2011 disaster at the Fukushima Daiichi nuclear facility in Japan, there has been renewed efforts in researching, developing, and repurposing teleoperated mobile manipulators (e.g., [13]) to address practical needs in environments too dangerous for humans.

Few autonomous mobile manipulators are available as commercial, off-the-shelf solutions. Those systems that do exist (e.g., [14]) are intended for research rather than industrial purposes. Mobile manipulators for manufacturing tend toward one-off solutions with little exposure to research publication venues. Due to the requirements for reliability, manufacturing mobile manipulators are not as technologically innovative as their research counterparts. Early mobile manipulators, like AGVs, were separated from human traffic, had primitive sensing and control functions, and were limited to constrained tasks. Frequently, the mobile base and the robot arm are treated as separate components, with the base being used to cart and park the robot arm to task-relevant locations.

III. AGV Standards

The American National Standards Institute/Industrial Truck Standards Development Foundation (ANSI/ITSDF) B56.5

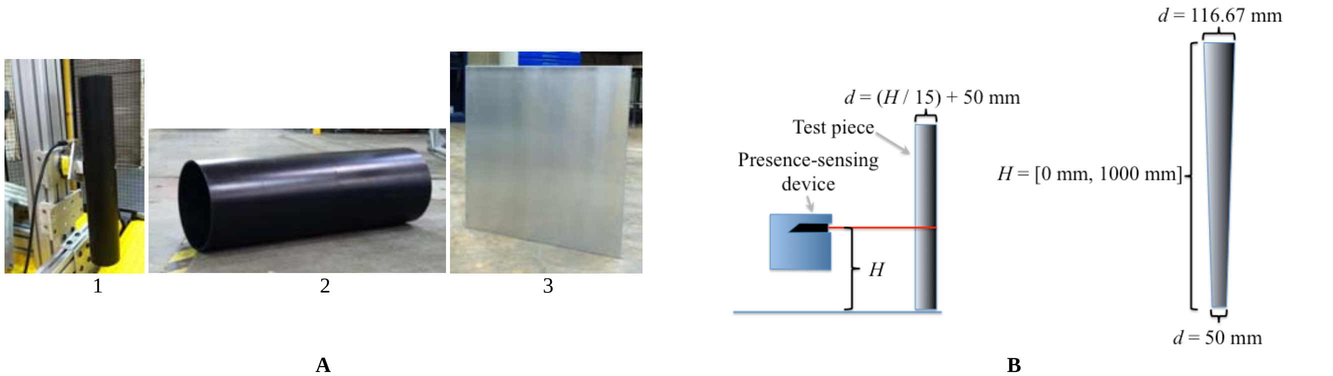

Fig. 1. Current test pieces used by the AGV (A) and industrial robot (B) standards. (A) shows the 1) vertical (shown being used for measuring bumper force), 2) horizontal, and 3) flat plate test pieces with thir proper coatings. (B) shows the range of artifact radii as a function of the detection zone height.

standard for AGVs [15] specifies the safety requirements for the design and use of AGVs and automated functions of manned industrial vehicles. In Europe, the AGV must comply with the Machinery Directive 98/37/EC [17], among other emission and power standards. There is also a standard that is normally used, EN1525 [18], which is a harmonized standard used to conform to the safety requirement of the Machinery Directive. Attempting to further harmonize safety standards, the International Organization for Standardization, Draft International Standard (ISO/DIS) 3691-4.2 [16] was developed over many years but not finished, and was recently deleted because AGV technology state-of-the-art surpassed the draft standard. Harmonization would require, for example, including both users and vendors sections with their safety roles and providing the same maximum allowable bumper forces in all standards.

Safety standards use artifacts for evaluating how well systems detect and respond to static obstacles. Artifacts shared by the U.S. and European AGV standards are a vertical cylinder 70 mm in diameter and 400 mm in length, representing the lower portion of a human leg, and a horizontal cylinder 200 mm in diameter and 600 mm in length representing the profile of a person lying down (see Fig. 1-A). The U.S. standard also includes a 500 mm square flat plate to represent highly reflective materials in a manufacturing environment. The ANSI/ITSDF B56.5 non-contact, sensor-based test methods utilize the three artifacts standing or laying down (depending on the test piece) at 0º and 45º to the path of the vehicle, at a range equivalent to the vehicle safe stopping distance and positioned at the center and the left-most and right-most boundaries of the vehicle path.

The next generation of AGV safety standards are expected to include criteria for 1) measurement of dynamic obstacles and obstacles appearing in the “Exception” or stop zone, 2) three dimensional (3D) imaging from an AGV to detect overhanging obstacles, 3) manned vehicles with automated functions when operators cannot see pedestrians, 4) detection of humans (in line-of-sight or occluded) and located near AGVs [19], and 5) robot arms onboard AGVs. A new AGV performance standard is also proposed to standards bodies to provide AGV users and vendors test methods for AGV applications. The performance standard may also cover robot arms onboard AGVs.

IV. Industrial Robot Standards

Internationally, ISO provides guidelines for the safety of industrial robots in the two parts of ISO 10218 [20, 21]. ISO 10218-1 outlines the requirements for the construction and control of the robots, and includes provisions for connections, axis limiting, actuation, etc. In contrast, ISO 10218-2 establishes the safety requirements for integrated robot systems, inluding safeguards and the integration of multiple robots and tools. Together, they ensure the safety for the entire robot workcell. ANSI and the Robotics Industries Association (RIA) adopted both parts of ISO 10218 in 2012 for the joint ANSI/RIA R15.06 [22] U.S. standard for robot safety. We refer to the two parts of ISO 10218 collectively as the industrial robot safety standards for simplicity.

Artifacts for the functional validation of presence-sensing for industrial robots are based on the mandated vertical and horizontal detection capability of the protective sensors, given in ISO 13855 [23]. This detection capability, d, is defined as

$$d = (H / 15) + 50 \text{ mm} \qquad (1)$$

where H = [0 mm, 1000 mm] is the height of the detection zone. The artifact is a cylinder of variable diameter based on the height of the detection zone (see Fig. 1-B), and is representative of a human arm or leg. Presense-sensing devices should be placed such that they can detect the intrusion of a foreign body before entering the robot’s protected working volume.

Historically, the safety of humans working close to robot systems was maintained by the strict separation of man and machine by physical safeguards. However, the 2011 revision of ISO 10218 added language that supports limited human-robot collaboration. The new wording enables the physical interaction between humans and robots per the guidelines of ISO Technical Specification (TS) 15066 [24]. NIST is helping draft ISO TS 15066, and is developing evaluation methods and metrics for the provisions of maintaining safe speeds and separation distances (“speed and separation monitoring,” SSM) of the robot while humans are nearby [25], and of reducing the potential for injury by limiting the transfer of forces and pressures from robots to humans (“power and force limiting,” PFL) in the possible event of collisions [26].

TABLE I: EXAMPLE OPERATIONAL CONDITIONS THAT HAVE LIMITED OR NO COVERAGE IN EITHER THE AGV (A) OR ROBOT (R) SAFETY STANDARDS USING EITHER A SINGLE- OR DUAL-CONTROLLER MOBILE MANIPULATOR CONFIGURATION. CONDITIONS MARKED WITH "A/R" ARE COVERED BY BOTH THE AGV AND ROBOT STANDARDS, WHILE CELLS MARKED WITH "--" ARE NOT COVERED BY EITHER.

		Moving AGV + Stationary Robot		Stationary AGV + Moving Robot		Moving AGV + Moving Robot	
		Single	Dual	Single	Dual	Single	Dual
a	Unexpected startup of robot or AGV	A/R	A/R	A/R	A/R	A/R	A/R
b	Robot/AGV hardware safety interlock	A/R	A/R	A/R	A/R	A/R	A/R
c	Human approach angle other than current direction of AGV travel, human is… …in robot work volume, in AGV path …out of robot work volume, in AGV path …in robot work volume, out of AGV path	 A/R A R	 A/R A R	 A/R A R	 A/R A R	 A/R A R	 A/R A R
d	AGV position uncertainty	A[1]	A[1]	A[1]	A[1]	A[1]	A[1]
e	Robot position uncertainty	R[2]	R[2]	R[2]	R[2]	R[2]	R[2]
f	Conflicting emergency stop situations	A	A	A	A	A	A
g	Robot sensing within the restricted space	A	A	A/R[3]	A/R[3]	A	A
h	Mobile manipulator stability	A[4]	A[4]	A[4]	A[4]	A[4]	A[4]
i	Overhanging obstacle extends into robot or AGV path	A[5]	A[5]	A[5]	A[5]	A[5]	A[5]
j	Reporting joint configuration of robot	A/R	A	A/R	A	A/R	A
k	Robot/AGV inhibiting motion of the other	A/R[6]	A	A/R[6]	A	A/R[6]	A
l	Planned/automatic restart from pause/stop	A/R	A	A/R	A	A/R	A
m	Sensing beyond vehicle path	A/R	R	A/R	R	A/R	R
n	Competing/incompatible safety protocols	A/R	--	A/R	--	A/R	--
o	Human carrying large load into AGV/robot path and vice versa	--	--	--	--	--	--
p	Velocity of any point greater than that of AGV/robot	Not Applicable				R	--
q	Unplanned restart from pause/stop	A/R	--	A/R	--	A/R	--
r	Error recovery startup	R	--	R	--	R	--
s	AGV/robot software safety interlock	R	--	R	--	R	--
t	AGV/robot position/configuration update and verification	A/R	--	A/R	--	A/R	--
u	AGV/robot assumes master control during a pause event	A[7]	--	A[7]	--	A[7]	--

[1] ANSI/ITSDF B56.5 requires detection of obstacles only within the planned AGV path
[2] per ISO 9283 [33]
[3] ISO10218-2 requires sensing within a restricted, safeguarded spaces, possible only if the AGV is not moving
[4] Partial. Per ANSI/ITSDF B56.5, 4.2.5, 9.2.2: "Only stable or safely arranged loads shall be handled"
[5] ANSI/ITSDF B56.5 requires only standard test pieces to be detected within the contour area
[6] ANSI/ITSDF B56.5 and ISO 10218-2 each cover part of the motion inhibition requirements, neither covers both separately
[7] ANSI/ITSDF B56.5 is not specific to onboard equipment causing a fault

V. HUMAN PRESENCE DETECTION STANDARDS

A prerequisite to providing safe collaborative working environments is the capacity to detect humans in the shared space. Recall that ANSI/ITSDF B56.5 specifies sensing and testing requirements for human presence detection. For industrial robots, ISO TS 15066 assumes that presence-sensing sensors for SSM meet the requirements of ISO 10218-2. These requirements specify that electro-sensitive protective equipment (ESPE) is compliant with International Electrotechnical Commission (IEC) standards (specifically, IEC 61496-1 [27]), with special attention to compliance with IEC/TS 62046 [28] for human presence detection. IEC/TS 62046 enumerates the technologies for human detection as being active opto-electronic protective devices (AOPDs; e.g., light curtains, standardized in IEC 61496-2 [29]), AOPDs responsive to diffuse reflection (AOPDDRs; e.g., laser detection and ranging devices, standardized in IEC 61496-3 [30]), pressure-sensitive mats and floors (standardized in ISO 13856-1 [31]), and passive infrared protective devices (PIPDs, not standardized). Because PIPDs do not have associated performance standards, they are not considered reliable, nor, consequently, "suitable as the sole means of protection."

For detection systems for industrial robots, the position and configuration of person-detecting devices are based on the requirements of ISO 13855, which also provides the basis for SSM in ISO TS 15066. Approved sole-protective ESPE technologies are either 1-dimensional (1D; e.g., AOPDs and pressure-sensitive mats) or 2D (e.g., AOPDDRs). PIPDs have a 3D detection zone, as do some camera-based systems (e.g., [32]). However, as mentioned previously, these are unacceptable as sole protective devices. AGV standards assume the existence and reliability of 3D technologies if used as non-contact obstacle detection devices, but do not contain performance requirements or evaluation methods of such sensors.

In addition to specifying acceptable devices for presence detection, IEC/TS 62046 details test methods and devices. The test method is a basic pass/fail evaluation that is routinely run to verify functionality. The test device is the cylinder discussed in Section IV. The AGV test method is specified in ANSI/ ITSDF B56.5, as mentioned in Section III. It is worth noting that, for both the AGV and industrial robot standards, the test methods and acceptable ESPE technologies are not specific to humans. However, these systems are expected to discern 'what is a human and what is not,' even though they can, in general, only detect intrusions of objects.

VI. STANDARDS AND MOBILE MANIPULATORS

As part of NIST's efforts in supporting the development of safety standards, we are working to extend and consolidate the existing industrial robot arm and AGV standards to provide safety provisions for mobile manipulators. This is not trivial, however, because mobile manipulators are not limited merely to robot arms mounted on AGVs. Mobile manipulators may include novel articulations, distributed and complex control structures, and as-yet unknown mobility technologies. To address the needs of mobile manipulator safety, we first evaluated the robot arm and AGV standards to discern the considerations for which there is sufficient coverage, and where there is little to no provision for risk minimization. These results are summarized in Table I.

Table I lists several risk scenarios involving mobile manipulators, and the relevant standard(s) that provide language for maintaining a safe operating environment. For each scenario, we consider whether or not the robot arm and AGV are active, and whether or not each is controlled separately or by a single controller. The single versus dual controller distinction is critical in that heterogeneous robot coordination and control is neither well-defined nor officially supported by the existing standards. The scenarios listed in Table I are not exhaustive, and are provided here for illustrative purposes only based on a risk assessment for the NIST testbed. A more targeted list of safety-related scenarios for the user's specific configuration will result from a risk assessment of the hazards of the user's environmental and operational conditions.

Table I shows considerable overlap between the industrial robot and AGV safety standards as they apply to mobile manipulators. Both the industrial robot and AGV standards, for instance, contain language to minimize the risks associated with the unexpected enabling of AGV and robot arm drive motors (***a***). When the entire system is driven by a single controller, the language in both the industrial robot and AGV standards provides adequate provision for human safety (e.g., the inhibition of all motion in the event of an error, ***k***).

In many cases, the risks associated with the operational conditions are specific to either the robot arm or the AGV, and one standard or the other may provide suitable coverage for the entire mobile manipulator system, alone. For example, language for handling the robot arm position uncertainty, ***e***, and gravitational stability of the mobile manipulator, ***h***, is provided in the industrial robot and AGV safety standards, respectively. This generally holds true for the dual-controller condition, but in cases where there is inconsistent or conflicting handling of conditions, the language of the existing safety standards is insufficient. In the following subsections, we discuss conditions ***n*** through ***u*** from Table I in greater detail. These were selected because they each contain configuration options for which there is no coverage of existing safety standards.

A. Competing/Incompatible Safety Protocols (n)

Contradictory safety standards pose a significant risk to the human operators those standards are meant to protect. When protocols mandate a pause or stop for an industrial robot, while the related protocols for AGVs require a completely different response, the resulting conflicting state may cause unpredictable behaviors for mobile manipulators. For instance, the ANSI/ITSDF B56.5 standard mandates that emergency stop braking cause the AGV to halt prior to impact between the AGV structure and other mounted equipment — including its load — and an obstruction. Hence, the AGV provides base motion stop for a robot arm mounted on the AGV. However, ANSI/ITSDF B56.5 is not clear on the case when an onboard robot is also moving. Also, ANSI/ITSDF B56.5 does not consider onboard equipment informing the AGV of emergency conditions, such as when a robot arm senses an obstacle in its work volume while the AGV is moving. Alternatively, these same functions are true in the industrial robot safety standards where there is no discussion for a robot onboard an AGV including how a robot arm stops AGV motion. Having a single controller for both the arm and the mobile base may circumvent this issue, whereas dual-controller setups are likely to result in motion control incompatibilities.

Ideally, there would be no conflict between the standards for the robot arm and the AGV base. Until then, however, the preferred response to such conflicts is to fail safe, and test methods should be designed to identify such conflict states. For instance, one such test method could verify whether a robot arm senses a hazard while the AGV base is moving, and whether the arm is able to automatically reconfigure itself to avoid said hazard.

B. Human/AGV/Robot Carrying Large Loads (o)

The extent of a system's ESPE sensing capabilities is limited by its underlying sensing technology. Although an AGV and an industrial robot are both expected to detect intrusions into their respective protected zones, there are numerous common conditions in which the safety guarantees may be circumvented. A model example of this includes large workpieces being carried by a human operator that may extend well into the protected regions of the robot arm or AGV, or conversely, large pieces carried by the mobile manipulator that extend beyond the sensing capabilitiy of the protective sensing system. Mobile manipulators pose an additional risk with their nearly limitless (and largely unpredictable) work volume, complicating attempts to monitor all conditions.

The prefered handling of this large load condition would be to treat such workloads as exensions of the human or mobile manipulator carrying them. Appropriate test methods would subsequently evaluate the capabilities of a mobile manipulator to correctly identify large payload conditions regardless of the angle of approach. The test method would also evaluate the capacity of the safety system to pause the motion of the robot arm and mobile base commensurately.

C. Velocity of Any Point Greater Than That of AGV/Robot (p)

Both the industrial robot and AGV safety standards are dependent on their respective velocities to provide safe stopping functionality. However, with the added dexterity of an arm mounted on a mobile base, it is possible for the velocity of any given point moving through Cartesian space to be greater than that of the AGV and robot arm separately. As such, the equations for specifying stopping distances may be perpetually wrong without accurate, real-time knowledge of both the arm and the mobile base. Moreover, measuring the velocity of a robot arm is somewhat ambiguous in that parts of the robot may move at different speeds. Common practice, however, assigns the robot arm's velocity to that of the tool flange. When combining the dynamics of a robot arm with a mobile base, the actual velocity of a mobile manipulator is unclear, and warrants specifying unambiguous language for measuring velocity.

Ideally, the Cartesian velocities of all actuated joints and attached components on a mobile manipulator would be known at all times. This is, of course, an infeasible requirement. As a bare minimum, however, the Cartesian velocities of rigid parts nearest to detected obstacles should be approximated as they move toward potential collisions. Acceptable test methods would demonstrate appropriate responses of the mobile base and robot arm during a coordinated motion where the combined closing velocity of the robot arm and AGV is greater than that of either separately. This includes determining whether the mobile manipulator can recognize the combined velocity hazard, and whether it can remove the hazard fast enough to avoid collision.

D. Unplanned Restart from Pause/Stop (q)

When recovering from a pause or stop state, restarting motion of a mobile manipulator may trigger an emergency response from either the robot arm or the mobile base in the dual-controller configuration. If one component starts moving while the other is stopped, the stationary component may interpret said motion as a failure to maintain the inactive state, and respond with an emergency stop. Different circumstances may require an emergency response whenever the robot arm or AGV base moves unexpectedly, and a suitable test method would reflect this appropriately.

E. Error Recovery Startup (r)

Assume either the AGV or the robot arm is in an error state. To safely restart the mobile manipulator to continue work, an error recovery procedure is required; otherwise the robot arm, when coming back online and seeing that the AGV is in an error state, immediately goes back into an error state, itself. Similarly, when the AGV comes back online, seeing that the robot arm is in an error state, the AGV immediately reverts to an error state. The effect is that error recovery is caught in a perpetual error-inducing loop in which an order of exception handling is required to restart functionality without automatically reverting to an error state. As a bare minimum, a mobile manipulator standard must specify error recovery requirements and procedures to determine precedence.

F. AGV/Robot Software Safety Interlock (s)

As a requirement of robot systems, controllers will be interlocked to reduce the risk of injury associated with the accidenttal activation of components. While such interlocks are typically implemented in hardware, additional component interlocks may be software-based (e.g., dynamic axis limiting or safety rated monitored stops) such that a manual reset is not required for the robot to resume operation.

In instances where such software interlocks are required for safe operation, both the AGV base and the robot arm are expected to respond accordingly based on two-way signal communications. A suitable test method must be developed that can quantitatively validate whether the AGV and robot arm respond according to software-based interlocks. This will require the development of standardized guidelines for both software interlocks and communication interfaces or protocols.

G. AGV/Robot Configuration Update and Verification (t)

To provide a safe, functional system, the position uncertainty of a mobile manipulator must be minimized. A key aspect of this is the capacity to update and verify joint and motor torque values in real time. Inconsistent update rates or deviations from what is expected result in an error. The mobile manipulator configuration poses a challenge in that protocols for sharing and guaranteeing configuration measurements are neither standardized nor mandatory. Neither the industrial robot nor AGV standards provide language to enable either controller to validate such information. This shortcoming must be remedied such that both the robot arm and AGV are aware of the configuration of the mobile manipulator as a whole.

H. AGV/Robot Master Control during Pause Events (u)

The current industrial robot safety standards require a manual restart from the disabled state following an error or a safeguard violation. With the adoption of ISO TS 15066, robot arms will be able to respond to hazardous conditions by initiating a safety-rated controlled stop. From this, the robot arm may restart automatically when a safety-relevant condition has been remedied. The AGV safety standards currently allow this automatic restart. However, from this stems a condition related to the issue discussed in Section VI-E: which element of the mobile manipulator, the arm or the mobile base, assumes master control for initiating a motion restart?

The prefered response of a mobile manipulator would be to use contextual clues to accurately determine which pause/stop responses are heeded and which may safely be ignored. However, an equally acceptable response would be to pause the mobile manipulator until all potential hazard states have been cleared. Contextual authority may be assigned following a risk assessment.

VII. Standard Test Pieces

Recall from Section III and Section IV the test artifacts used for validating AGV and industrial robot safety (Fig. 1). While the AGV artifact changes depending on the anticipated orientation of a human approached by the AGV, the artifact for industrial robots is intended to represent extended limbs as the human approaches the robot. In both cases, the artifact must be detected by ESPE, and the AGV or robot arm stopped prior to the point of contact. However, the large working volumes of the mobile manipulators and the complexity of the collaborative environments confound matters. Distinguishing between humans and task-relevant workpieces is difficult without also adversely impacting task performance.

New standard test methods for human-specific detection and localization have been discussed within various standards organizations. To date, no action has been taken toward such standardization. Biomimetic artifacts will be critical to the verification and validation of safe operations of industrial mobile manipulators in human-occupied spaces, and will enable new classes of sensors to be accepted as ESPE. Suitable artifact types would include the integration of various human profiles such as standing, bending, and kneeling. Also included are biomimetic devices for measuring impact force and pressure, and biosimulant systems that may mimic heat signatures, CO_2 release, and sound.

Also worth considering are artifacts that test for possible limitations of the sensing technologies, or may otherwise be difficult to discern. Such artifact categories extend beyond mimicking humans for safety purposes and include non-standard pieces such as walls, tooling, machinery, debris, and work materials. The flat, square, shiny test piece in the AGV safety standard only begins to address this manufacturing test piece need. Negative obstacles (e.g., trenches and inward-facing edges) are a regular focus for off-road systems, and would pose similar hazards to AGVs and mobile manipulators.

VIII. Discussion: A New Age for Industrial Robotics

In this report we provided an overview of the current safety standards efforts for industrial robot arms and AGVs, and how these relate to the use of autonomous mobile manipulators in industrial settings. We also present shortcomings in the existing requirements for test pieces and human presence sensing systems. From these discussions, it is clear that new standardized test methods and artifacts are required to ensure the safety of humans working in next-generation manufacturing environments. NIST is coordinating with the RIA and ANSI communities to address the needs for performance and safety standards for mobile manipulators. We are also working with industry partners in developing sets of test methods to accommodate the scenarios discussed in Section VI, new artifact designs for safety evaluations, and evaluative metrics for emerging 3D and human-specific presence detection systems.

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