Development of Standard Test Methods for Unmanned and Manned Industrial Vehicles Used Near Humans

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ABSTRACT

The National Institute of Standards and Technology (NIST) has been researching human-robot-vehicle collaborative environments for automated guided vehicles (AGVs) and manned forklifts. Safety of AGVs and manned vehicles with automated functions (e.g., forklifts that slow/stop automatically in hazardous situations) are the focus of the American National Standards Institute/Industrial Truck Safety Development Foundation (ANSI/ITSDF) B56.5 safety standard. Recently, the NIST Mobile Autonomous Vehicle Obstacle Detection/Avoidance (MAVODA) Project began researching test methods to detect humans or other obstacles entering the vehicle's path. This causes potential safety hazards in manufacturing facilities where both line-of-sight and non-line-of-sight conditions are prevalent. The test methods described in this paper address both of these conditions. These methods will provide the B56.5 committee with the measurement science basis for sensing systems - both non-contact and contact - that may be used in manufacturing facilities.

Keywords: automated guided vehicles, ANSI/ITSDF B56.5 safety standard, force measurement, collaborative work spaces.

1. INTRODUCTION

In many situations, facility operations or forklift operators cannot ensure that every pedestrian carries an active detection device or wears clothing that is easily detected by drivers or sensors. Such pedestrians are *passive* in regard to the detection system. Systems used to detect the presence of passive pedestrians use vision, stereo vision, infra-red, or laser scanner technologies. To date, few such technologies have been implemented in industrial settings where humans are frequently either non-occluded or occluded from line-of-sight sensors onboard industrial vehicles.

Passive pedestrian detection can be separated into three application areas: path, area and point. In "path" applications, the detection is made at longer ranges and is generally associated with automotive safety systems. Radar systems combined with vision systems are often used in these applications [1, 2, 3]; but the efficiency and effectiveness of these systems are not known. In "area" applications, the detection is made at shorter ranges and is typically associated with pedestrian street crossings. Vision [4] or infra-red [5] detectors are commonly used here; an example provided in [6] shows error rates ranging from 9 % to 39 % for these systems. The third application area detects pedestrians at a specific "point" in tightly controlled environments. In industrial environments, for example, crosswalk gates are commonly used [7].

The National Institute of Standards and Technology (NIST) is researching human-robot collaborative environments for automated guided vehicles (AGVs) and manned vehicles such as forklifts. Safety of AGVs and manned vehicles with automated functions (e.g., forklifts that slow/stop automatically in hazardous situations) are the focus of the American National Standards Institute/Industrial Truck Safety Development Foundation (ANSI/ITSDF) B56.5:2012, Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles [8]. Recently, NIST researchers [9] began developing test methods to assess the safety of humans when entering or residing in the paths of such vehicles using the 2012 version of B56.5:2012. That version included changes that allow non-contact sensors to detect standard test pieces so long as the pieces are positioned within the path of the vehicle and beyond the stop zone of the vehicle. However, there remains an exception in the standard for addressing the sudden appearance of an obstacle within the vehicle stopping distance. Similarly, manned vehicles, such as forklifts, are

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currently allowed to include up to 20 % of regions where drivers may not see pedestrians enter the vehicle path. These situations are commonplace in manufacturing facilities and present significant potential liabilities [10].

We have focused our research on developing standard test methods for sensors integrated on both manned and unmanned vehicles to improve B56.5 and other supportive ANSI safety-related standards (see example in Figure 1). As sensors and algorithms become more capable, their application to industrial vehicles may improve pedestrian safety.

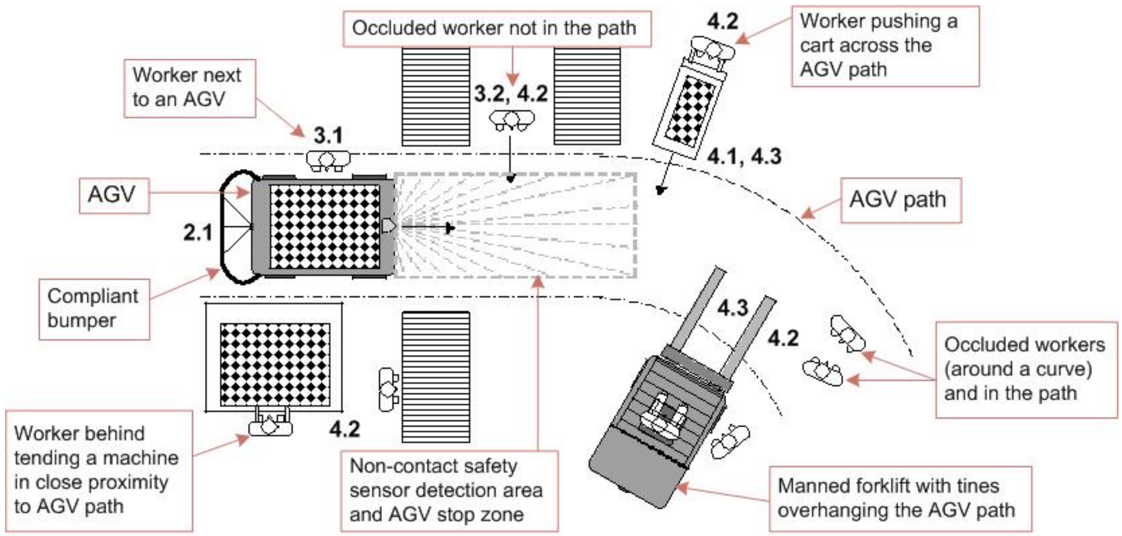


Figure 1 – Example of potential human and equipment impingements on the path of an AGV in human/AGV collaborative workspaces. The dashed line area in front of the AGV is the stop zone. The numbers represent the sections of this paper where the situation is addressed.

Our research on non-contact sensors includes development of test methods to address 1) standard test pieces and mannequins entering the vehicle's path and 2) non-line-of-sight sensing used to inform the vehicle of a pedestrian who may enter its path. Further, since the standards community is interested in standardizing the maximum allowed force that can be applied to humans by industrial vehicles, we are attempting to measure forces on humans, through use of test pieces, from contact with AGV bumpers. This becomes particularly important if a human is not detected by non-contact, onboard, safety sensing and/or they enter the vehicle stop zone. To make these measurements, we are developing a new force measurement apparatus based on an independent force measurement system for robots developed at NIST [11]. This earlier system was developed while also considering the Common Injury Criteria [12] that formed part of the background information on human injury for International Organization for Standardization (ISO) 10218 robot safety standard and ISO/Technical Specification (TS) 15066 on human/robot collaborative workspaces [13]. A similar force measurement system is currently being developed for measuring AGV bumper force.

Sections 2 and 3 discuss test method developments for detection of obstacles that are on the vehicle path using contact and no contact, respectively. Section 4 details test method developments for detection of humans or obstacles outside of the vehicle path. Currently, standards do not require sensing beyond the vehicle path, although accidents could be avoided if the vehicle were alerted prior to a path intrusion. Visible people or obstacles may be detected with imaging systems to alert vehicles. However, hidden people may require other technologies, such as radio frequency identification (RFID) or magnetics, for detecting humans wearing an associated detection device. Occluded obstacles moving into the vehicle path will most likely not have detection devices. If this happens, they would potentially be undetected outside the vehicle path but potentially detected within the stop zone - too late to avoid collision with the vehicle. Section 5 addresses additional planned research for standards development at NIST in both safety and performance areas. This planned research addresses safety associated with a combination of robots and AGVs where robots are typically within fenced areas and AGVs only address onboard equipment. Since this situation is not covered by the existing standards, it represents a gap. A new AGV performance standard is being proposed to fill this gap. It is briefly described in Section 5 of this paper.

2. DETECTING HUMANS/OBSTACLES ON THE VEHICLE PATH USING CONTACT

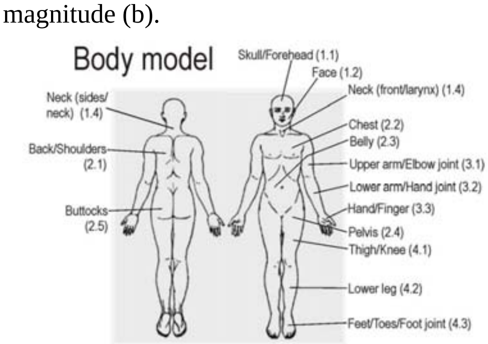
The original obstacle detection device on AGVs was a collapsible contact bumper. If the AGV cannot change its planned path, it will collide with the obstacle. B56.5 specifies that if used as a force sensing device, a bumper shall be fail-safe in its operation and mounting and shall not exert a force greater than 134 N (30 lbs.) applied parallel to the floor and opposing the direction of travel with respect to the bumper. Bumper activation shall cause a safety stop within the collapsible range of the bumper – hopefully before the vehicle strikes an obstacle [B56.5 clause 8.11.1.1]. British Standard EN1525 [14] specifies the use of test pieces and the associated maximum forces for each test piece as: 1) a horizontal test piece with 200 mm diameter and 600 mm length lying in the AGV path, maximum actuating force on test piece of 750 N (169 lbs.) and 2) a test piece with 70 mm diameter and 200 mm height positioned vertically along the cylinder axis in the AGV path, having maximum actuating force on test piece 250 N (56 lbs.). EN1525 also specifies that the force when the bumper is compressed to the position reached in a bumper stop from maximum speed and load shall not exceed 400 N (90 Lbs). The following sub-sections describe the test methods to validate that a system meets these requirements and a NIST designed test apparatus.

2.1 Contact Bumper Force Test Methods

Unfortunately, allowed AGV forces on standard test pieces using contact bumpers vary across U.S. and European standards. This causes serious problems for both AGV manufacturers and users about what appropriate bumper force can be applied to humans. Further, neither standard provides information associated with the origins of the specified force values. We make the assumptions that the horizontal test piece described in [8] and [14] represent the human torso or upper leg lying in the path of the AGV and the vertical test piece represents a vertical human's lower leg in the path of an AGV. In relation to the BGIA[1] injury criteria [12], the sustained forces during the collision between an AGV and a human would best be described as a clamping force because the time duration of contact is related to the response of the human. The maximum forces allowed in the BGIA document for clamping force on the torso regions occur at the back/shoulder and buttocks; while the maximum clamping force for the lower leg region is 140 N.

Table 1: Injury criteria and body models from early drafts of ISO TS 15066. Clamping/squeezing force (CSF) and impact force (IMF) values are provided for several regions of the body (a), with the distinctions between the two being characterized by duration and magnitude (b).

Body model Main and individual regions with codification [a]			**Maximum allowable Limit values of the injury severity criteria (CSF, IMF, PSP) and arranging factor (CC)** [b]			
Main body regions		**Individual body regions**	**CSF [N]**	**IMF [N]**	**PSP [N/cm²]**	**CC [N/mm]**
1. Head with neck	1.1	Skull/Forehead	130	175	30	150
	1.2	Face	65	90	20	75
	1.3	Neck (sides/neck)	145	190	50	50
	1.4	Neck (front/larynx)	35	35	10	10
2. Trunk	2.1	Back/Shoulders	210	250	70	35
	2.2	Chest	140	210	45	25
	2.3	Belly	110	160	35	10
	2.4	Pelvis	180	250	75	25
	2.5	Buttocks	210	250	80	15
3. Upper extremities	3.1	Upper arm/Elbow joint	150	190	50	30
	3.2	Lower arm/Hand joint	160	220	50	40
	3.3	Hand/Finger	135	180	60	75
4. Lower extremities	4.1	Thigh/Knee	220	250	80	50
	4.2	Lower leg	140	170	45	60
	4.3	Feet/Toes/Joint	125	160	45	75
[a] BR - Body region with codification Regions - Name of the individual body region			[b] CSF - Clamping/Squeezing force IMF - Impact force PSP - Pressure/Surface pressing CC - Compression constant			



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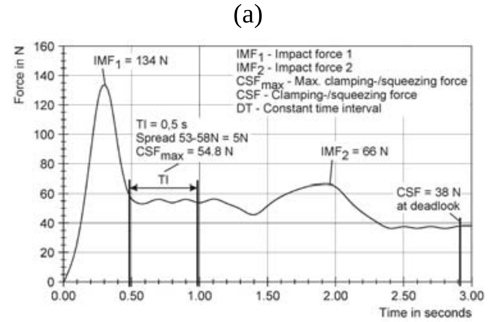

(b)

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[1] Berufsgenossenschaftliche Institut für Arbeitssicherheit - BG Institute for Occupational Safety and Health, abbreviated to BGIA in German, now IFA (German translation: Institute for Occupational Safety and Health)

In comparison, the industrial robot arm safety standards have integrated more explicit biomechanical principles towards limiting contact forces and pressures. Early drafts of ISO TS 15066, for example, contained limits to clamping and instantaneous impact forces, minimum areas of contact, and compression constants based on an extensive literature review [13]. These Power and Force Limiting (PFL) maximum allowable "injury criteria" values varied according to different regions of the body as shown in Table 1. These values are considered by many to be overly conservative [15] in order to avoid injury severities exceeding category 1 of the Abbreviated Injury Scale [16] or "surface injuries" as codified by ICD-10-GM 20062 [17]. More recently however, development of ISO TS 15066 has moved away from the injury criteria; its values will be based on a scientific study of pain thresholds at the Johannes Gutenberg University in Mainz, Germany. Using the same body regions as the injury criteria, the pain threshold study uses a custom-built algometer to measure the forces and pressures incurred by applying ramped force behind a plastic plunger pushing against the clamped body parts. The resulting values of both studies are expected to be integrated into ISO TS 15066. A simultaneous study at Fraunhofer Institute for Factory Operation and Automation (IFF), Magdeburg, Germany is measuring pain thresholds based on instantaneous impacts of free and constrained body regions. That study is developing models in the form of transfer functions to relate direct clamping force measurement to free body collisions.

To evaluate and validate the PFL capabilities of a collaborative robot, the original injury criteria literature review gave specifications of a test device capable of approximating the biomechanical properties of different parts of the human body. NIST designed and built such a measurement device (Figure 2) based on these specifications, and then verified and validated the specifications based on metrological analyses and empirical evaluations using two different robot systems [4].

This device measures force and displacement and supports both fixed and free space collisions along a single axis. The injury criteria compression constants are incorporated into the device through the use of ten custom compression springs with the same outer dimensions that are easily interchangeable by removing the strike plate cap. Force measurements are made using a piezoelectric force transducer which is housed between the base of the force/displacement assembly and the base support for the spring. To support performance evaluations of the device, the design also incorporates a linear variable displacement transducer (LVDT) coincident with the device axis.

A series of weights can be added to the linear slide carriage assembly during free space collisions to replicate the mass of the human body regions being struck by the robot. Also shown in Figure 2 as transparent components is the concept of incorporating future spring/damper parameters to replicate response of the human body during free body collisions. Currently there is no guidance provided for free body collisions and this is a topic of discussion within the TS 15066 working group. This work parallels IFA and Fraunhofer IFF efforts to develop transfer functions to avoid the complexities associated with mechanical modeling of free space collisions.

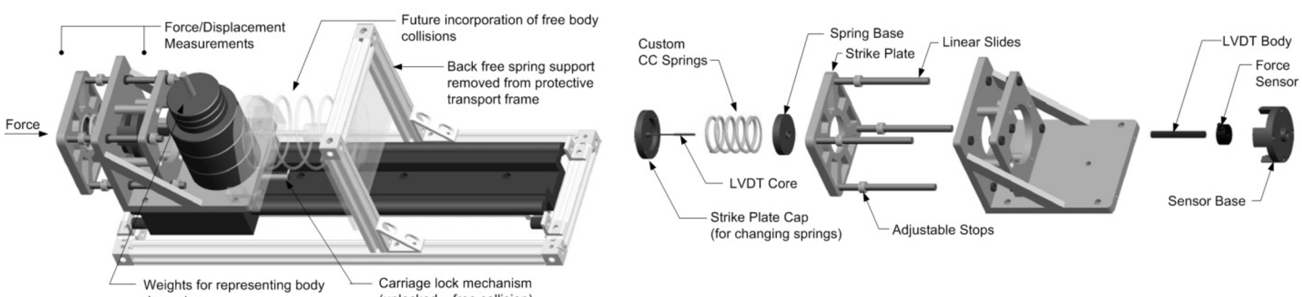

Figure 2 - NIST designed and built force and displacement measurement device.

2.2 NIST-Designed AGV Bumper/Stop Distance Test Apparatus

NIST has developed an apparatus for testing the forces and associated stop distance of an AGV bumper incorporating the BS EN1525 test pieces. The device as shown in Figure 3 consists of a weighted base and adjustable force sensors; it can be configured for the 200 mm by 600 mm test piece (left) and the 70 mm by 400 mm test piece (right). Each test piece is constrained to move in one direction: the measurement direction of the load cell. The load cell can be positioned along the axial direction of each test piece for centering on the bumper strike point. In the case of the horizontal test piece configuration, the height of the test piece can be adjusted to the AGV bumper height. In addition, the force measurement assembly, which includes the test piece and load cell, can be removed from the base for hand-held force tests on an AGV bumper.

Test methods are being developed to ensure that forces stay below maximum specified forces on a bumper along a series of collision directions associated with a human as positioned relative to vehicle motion. Candidate bumper collision vectors are shown in Figure 4, and can be performed statically via hand-held force testing or dynamically via an AGV driving against the apparatus.

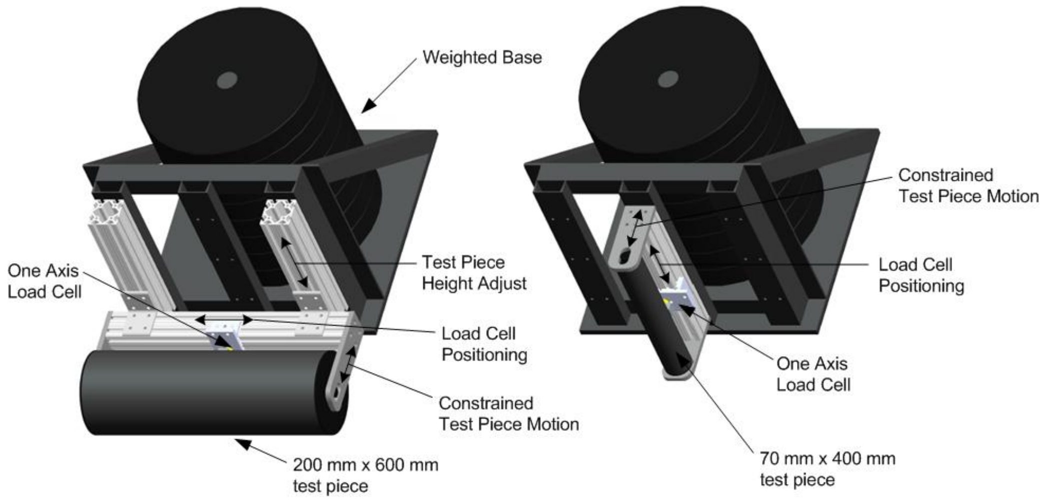

Figure 3: NIST Test Apparatus configured with horizontal test piece (left) and vertical test piece (right)

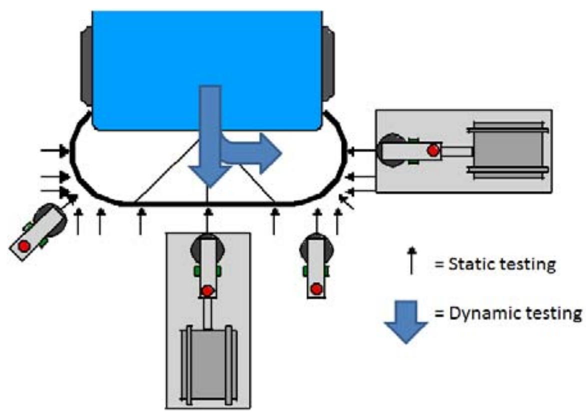

Figure 4: Static and Dynamic bumper force measurement apparatus application.

Additional bumper-collision test methods are being developed to test the ability of an AGV to stop before contact of the vehicle structure and installed equipment with people or objects appearing in the path of the vehicle in the main direction of travel. This stopping distance is defined by the geometry of the bumper design and is the distance between the bumper position at the point that a collision is detected and the point at which the bumper makes contact with the vehicle body or at the bumper position where the maximum collision force is detected. Section 2.1 Contact Bumper Force Test Methods described a compliant test apparatus that could potentially be adapted to the AGV bumper force test apparatus and used to measure forces when AGVs do not have compliant bumpers.

3. DETECTING HUMANS/OBSTACLES ON THE VEHICLE PATH WITH NO CONTACT

3.1 Beyond the Stop Zone

In 2012, a revised ANSI/ITSDF B56.5 standard was published that allows noncontact sensing devices to be used as safety devices in addition to bumper-based safety systems. The revision includes NIST-researched test methods using static test pieces detected using a variety of sensors: 2D scanning laser detection and ranging (LADAR), stereo vision, ultrasonic, and 3D flash light detection and ranging (LIDAR)). B56.5 section 8.11.1.2, Noncontact Sensing Devices, specified new test pieces, coatings for test pieces, and a test procedure including vehicle speeds and a description of where and how the test pieces are to be placed in the vehicle path. Test pieces are to be detected by non-contact sensors that resemble 1) a human leg "with a diameter of 70 mm and a height of 400 mm set vertically" and 2) a human profile lying down "with a diameter of 200 mm and a length of 600 mm," as well as a flat surface test piece "measuring 500 mm square set vertically." Test pieces are to be colored a flat black when optical sensors are used and the flat surface test piece is to be highly reflective if ultrasonic (sonar) sensors are used. All test pieces are to be detected by the vehicle's "primary sensing device" when the vehicle is at "0 %, 50 %, and 100 % of vehicle speed in the main direction of travel and be positioned to be within the contour area of the vehicle (including onboard payload, equipment, towed trailer, and/or trailer payload)." The sensors "shall cause a safety stop of the vehicle prior to contact between the vehicle structure and the people or objects." The test method includes statically positioning the human profile and flat surface test pieces at "0º and 45º to the path of the vehicle." All test pieces are to be placed "at a range equivalent to the vehicle safe stopping distance and positioned at the left-most, right-most, and center of the vehicle path." Figure 5 is included in the B56.5:2012 standard and depicts the test method and sensing area.

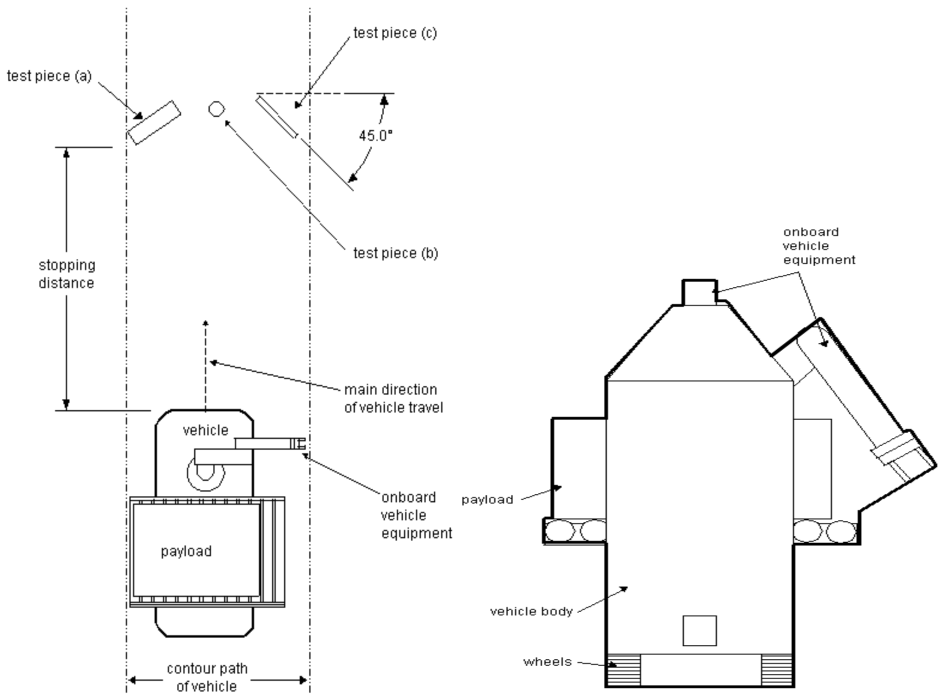

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Figure 5 - B56.5:2012 figure showing (a) the test method configuration showing the top view of the vehicle path and test pieces and (b) the front view of the vehicle contour (bold outline) around vehicle, overhanging payload, equipment, trailer and/or trailer payload. The vehicle contour is the area that must be detected by noncontact sensing devices.

Although the B56.5:2012 revision made dramatic improvements to the previous version, further improvements are needed, including

- Test methods for sensing and reacting to humans or obstacles that dynamically appear beyond the vehicle stop zone and beside the vehicle

- Test methods for sensing and reacting to humans or obstacles that statically or dynamically appear within the vehicle stop zone
- Reference and test method for measuring the force that a bumper can place on humans should the vehicle make contact with them
- Test methods for sensing beyond the vehicle path to prevent contact with or minimize potential risks to humans
- Test methods for the safety of robot arms mounted on vehicles

These improvements, which are also being researched at NIST, are explained below.

3.2 Within the Stop Zone

Assuming the vehicle stays on its path and an obstacle appears within the stop zone, the vehicle will collide with the obstacle. Even within the stop zone, obstacle detection should cause the vehicle to slow down as early as possible using non-contact sensing or contact bumpers. B56.5:2012 discusses a test method to detect standard test pieces beyond the minimum vehicle stopping distance with vehicle speeds at 50 % and 100 %. B56.5 also includes an exception for obstacles suddenly appearing at less than the minimum AGV stopping distance. The exception states: “Although the vehicle braking system may be performing correctly and as designed, it cannot be expected to function as designed should an object suddenly appear in the path of the vehicle and within the designed safe stopping distance. Examples include, but are not limited to, an object falling from overhead or a pedestrian stepping into the path of a vehicle at the last instant.” An interpretation of the exception could be that, if the vehicle does not detect an obstacle within the minimum safe stopping distance, the vehicle could potentially continue moving at the 50 % or 100 % speeds.

In recent experiments, NIST researchers used 2D LADAR sensors mounted to an AGV. In contrast to the earlier experiments where the test piece was static, in these experiments the AGV and the test piece were both moving. The 2D sensor was mounted to the NIST AGV to scan horizontally, with the beam approximately 10 cm (4 in) above and parallel to the floor and confined to detecting the vehicle path (vehicle width) at the maximum coast-to-stop distance. Note, that the sensor scan width can be set to any width, including the B56.5 standard, non-hazard zone vehicle path width of the vehicle plus 0.5 m. The test piece entered the AGV path within the exception zone, was detected by the safety sensor, and the distance of the test piece to the AGV and the AGV stopping distance measurements were calculated and analyzed.

Initially, onboard AGV sensor systems provided data representing vehicle position and simultaneously provided the test piece detection position as it entered the vehicle path [18]. However, results of these tests showed that onboard vehicle position sensor and test-piece, sensor-detection data did not compare well to ground truth data. Hence, a different test method that does not include onboard measurement systems was required. The Grid-Video test method was therefore, developed (see Figure 6) where the NIST AGV moves from right to left at 1 m/s and (a) a test piece is pushed into the stop (exception) zone outlined in red, (b) the test piece is hit by the AGV, and, (c) the vehicle coasts or is controlled to a stop depending on the test. Ground truth (reference) is provided by the paper grid on the floor. A laser line is positioned along the AGV path and is connected to the red light shown in the (a) image to indicate when the test piece enters the

a b c

Figure 6 – AGV being tested using the Grid-Video method where: (a) a test piece is pushed into the stop (exception) zone outlined in red; (b) the test piece is hit by the AGV; and (c) the vehicle coasts or is controlled to a stop depending on the test. Ground truth (reference) is provided by the paper grid.

vehicle path and should be detected by onboard vehicle sensors. The 30 frame-per-second video can be viewed frame-by-frame during post processing of the test to determine vehicle stopping distance which is expected to show that reduced kinetic energy occurred. This simple method is being recommended to the B56.5 committee.

4. DETECTING HUMANS/OBSTACLES BEYOND THE VEHICLE STOP ZONE

4.1 Non-Occluded Humans/Obstacles

As described in sections 3.1 and 3.2, 2D scanning LADAR safety sensors were used at NIST to detect obstacles that were placed beyond and in front of the vehicle stop zone or moved into the stop zone of the vehicle, respectively. In both cases, the test piece was within the vehicle path when detected by onboard safety or other sensors. However, implementations where humans or other obstacles are detected outside the vehicle path prove beneficial to worker safety since they allow more time for vehicles to react appropriately (slow, drive around, or stop). AGVs used in B56.5 - designated hazardous environments or paths with less than 0.5 m clearance are required to move at 30 % of their maximum speed. AGV safety sensors are typically programmed with slow zones surrounding stop zones. Slow zones typically measure beyond the AGV width and in front of the stop zone and are designed specifically for the environment, vehicle, payload, stability, etc. As an AGV moves through narrow areas or turns near obstacles that are outside of the stop zone, the AGVs slow zone behaviors are activated.

However, as shown in Figure 1, lower right, two workers are hidden from the AGV due to the curvature of the path. Typically, the AGV would account for possible hazards by always moving slowly around the curve, potentially and consistently slowing production. Alternatively, if the AGV is programmed to move at higher production speeds, it must detect the hazard in time and control the vehicle accordingly without slowing and stopping for any other off-path obstacles around the curve. Three modes of vehicle braking are mandatory according to the B56.5 standard: emergency, parking, and service braking. However, an additional controlled braking may be used in this case which allows “for an orderly slowing or stopping of the vehicle (that) may be accomplished by electrical or mechanical means.” For paths restricted only to vehicles, the safety sensor will detect in-path obstacles when the AGV gets closer to them and apply an emergency brake. However, this reaction may be too slow for next generation unstructured environments where paths and the line-of-sight to obstacles will be changing frequently. With controlled braking, continuous sensing of the environment occurs while the vehicle speed is also controlled for planned AGV movements. This allows the AGV to control speed continuously based on a changing path and situation. This path-measurement concept was researched in [18] demonstrating a continuously safe approach to flexible manufacturing environments where humans may be present. Beyond safety, this function could also provide additional vehicle path planning and situation awareness.

Figure 1, lower right, also shows an example scenario of forklift tines that cross the AGV path. Forklift tines are not B56.5 standard test pieces, although they fall within the AGV and payload contour area; and, therefore, they are not required to be sensed by the AGV safety sensors. Current AGVs typically have one to several 2D line scanning LADAR safety sensors onboard that sense the 3D environment. As shown in [18], this sensor configuration has limits for 3D environment sensing. NIST tested the scenario of the Figure 1 example to ensure that dynamic forks entering the AGV path could be detected by current 2D scanning LADAR sensors mounted vertically and on the AGV edge and that the vehicle could stop without collision using controlled braking. However, what could not be tested with this sensor configuration is perhaps the worst case when overhanging obstacles are within the path, such as a forklift carrying a load in the AGV path with the fork tines and payload pointed directly at the AGV. Current scanners will potentially detect the overhanging load too late to stop the AGV. Instead, 3D imagers are ideal for this and other cases, such as ladders overhanging the AGV path, crane hooks, or any overhanging load in front of its lift support, within the path, and above the ground. Figure 7 shows this scenario for a standard ANSI/ITSDF B56.5 plate overhanging, yet within the AGV path and also a ladder overhanging the path.

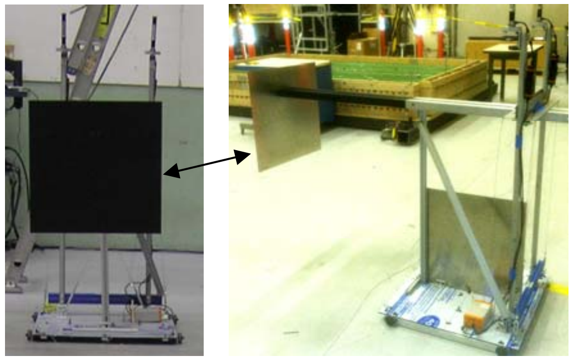

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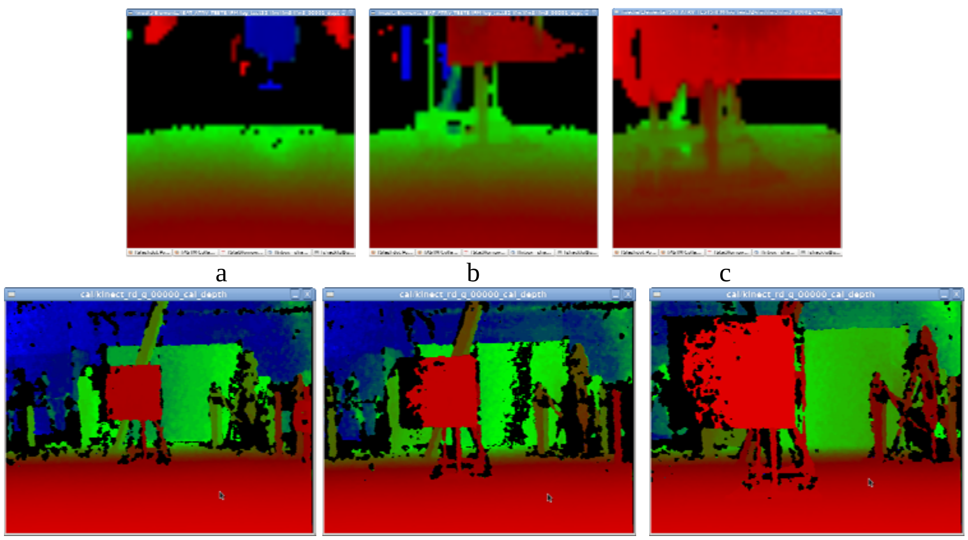
Figure 7 – View of (a) standard flat plate from the front and (b) from the side within and overhanging the AGV path.

Two different types of 3D imaging sensors were mounted on the AGV. Flash LIDAR 3D imaging sensors were positioned to detect regions in front and sides of the vehicle. The other type of 3D imaging sensor was an RGB-D (red, green, blue - depth) camera using structured light for range detection. None of the 3D sensors were connected to the vehicle controller; they were only used to collect data.



a b c

d e f

Figure 8 – Snapshots of data collected with (a, b, c) the 3D LIDAR sensor and (d, e, f) the RGB-D sensor of an overhanging black plate (see Figure 7) statically positioned in the AGV path. Note the overhanging ladder in the background across the AGV path in the RGB-D data.

The illustrations in Figure 8 (a – c) show results from the flash LIDAR, and Figure 8 (d – f) show results from a RGB-D sensor detecting the static overhanging plate. For these experiments, the AGV was moving at 1 m/s. Figure 8 also shows that obstacles on the floor can be detected. In Figure 8 (a - c), the results showed that the plate was detected by the sensor as the AGV approached it. Figure 8 (a) shows the plate as a blue rectangle and Figures 8 (b and c) show the plate as a red rectangle; the color in Figure 7 is based on range with red indicating objects closer to the vehicle. The RGB-D sensor results in Figure 8 (d - f) also detected the plate and even the ladder behind the plate. Given their limited fields of view, neither sensor was sufficient for detecting the entire NIST AGV contour region when obstacles are within approximately 1.2 m of the vehicle. Therefore, a combination of these sensors was required.

The experimental data collected from 3D sensors on an AGV show that these devices could be useful for detecting obstacles in the AGV's path, on the ground, or overhanging the path. They were also useful for detecting humans, as shown in Figure 9. However, further research is needed on the use of 3D sensors to detect obstacles and to signal the AGV to slow or stop. The 3D imaging sensor technology used may also prove useful for manned industrial vehicles by providing the operator with alerts to slow or stop the vehicle when obstacles are located in occluded regions from the vehicle operator.

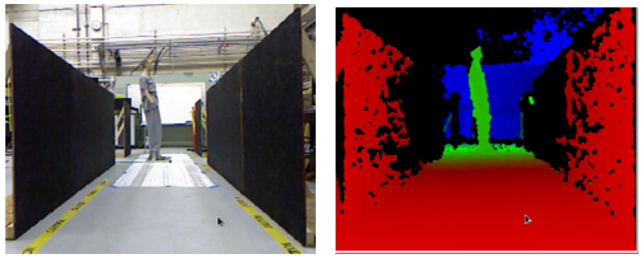


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Figure 9 – (a) Photo of a static mannequin and (b) RGB-D snapshot of the mannequin in the AGV path.

Although these sensors are not safety rated, they show potential for use on AGVs and manned vehicles. It would thus be expedient for the ANSI/ITSDF B56.5 standard committee to develop test methods that can be used by all AGV manufacturers and users in anticipation of the time when these sensors are safety rated and broadly used. Some suggested modifications to the ANSI/ITSDF B56.5 language to include 3D sensors include:

- static, overhanging, standard test pieces must be detected at the same distance as the current static, ground-based test pieces
- dynamic standard test pieces must also be detected when they enter the contour area of the vehicle path, regardless of whether they are overhanging or not, and prior to contact with the vehicle
- although 3D sensors are not yet safety rated, AGV non-contact safety sensors may be augmented by 3D sensors to provide improved obstacle detection

The ideal situation would be if 3D imaging sensors were safety rated. Therefore, it would be advantageous if the sensor industry could provide 3D safety-rated sensors for the AGV industry since it would expand the market for such sensors.

4.2 Occluded Humans

Detecting humans hidden from onboard AGV or manned industrial vehicle sensors typically requires workers to wear identification or tracking devices. Examples include tags or pedestrian alert devices associated with radio frequency identification (RFID) or magnetic technology systems. Because there is no guarantee that workers will wear ID devices detectable by these vehicles, workers are typically cordoned-off from vehicle paths. Next generation agile manufacturing facilities, with changing vehicle paths and human/AGV collaboration, may not allow dedicated vehicle paths and therefore, increase the danger to humans from vehicles. Alternatives to workers wearing tags may be cameras (see [19]) or infrared motion-detection systems such as those mounted from above the work area and currently used in security and surveillance applications. However, these systems require line-of-sight from the sensors to workers; and, therefore, they may require a large sensor network for proper area coverage. In facilities with unattended machine motion, or pedestrian paths or spaces occluded from the sensors, these technologies may not be ideal. No matter which occluded human detection system is used or may evolve, a test method is required to prove its performance in detecting humans near hazards of industrial vehicles and other equipment.

NIST has been developing test methods for pedestrian detection systems that can locate humans that are hidden from industrial vehicles. Technologies measured and used for test method development are RFID-based systems marketed for the forklift industry and magnetic systems mainly marketed for the mining industry; but which are also being developed for pedestrian safety near forklifts. Both of these technologies may have the potential to detect humans during non-line-of-sight conditions and predict that a pedestrian is either in or moving towards a forklift path. This will allow the operator time to slow or stop the vehicle or avoid a collision with the pedestrian. The manned or automated vehicle could potentially be controlled automatically by the sensing system to slow or stop the vehicle prior to a collision.

Both RFID and magnetic systems include a transceiver mounted to the vehicle, and tags (battery assisted - powered or active) or pedestrian alert devices (PADs), respectively, worn by pedestrians in the vicinity of the vehicle. NIST tests included both indoor and outdoor test space environments and provided a series of system characterization tests for: antenna and tag power, configurations, and orientations. Additionally, a series of test scenarios was set up and tests conducted, including blocked or gapped line-of-sight to the transceiver, and same or adjacent space scenarios for occluded sight testing. The Same Space Scenario setup is shown in Figure 10 and the Adjacent Space Scenario setup is shown in Figure 11.

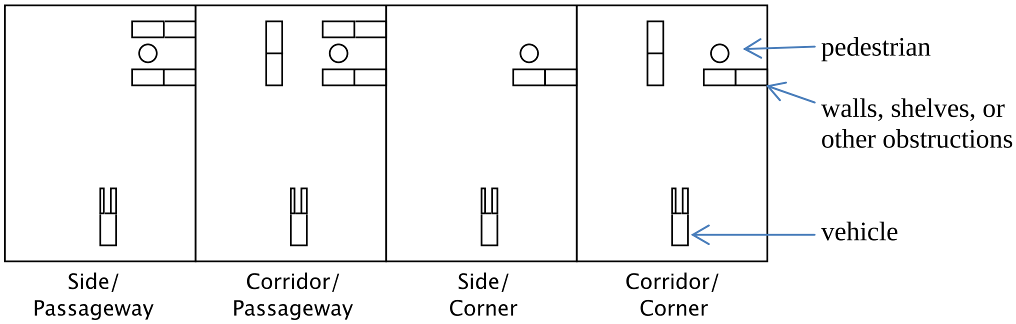

Figure 10 - Top views of Same Space Scenarios showing the pedestrian (circle) approaching the vehicle path and the forklift (bottom of each figure) in various conditions. The rectangles represent obstructions.

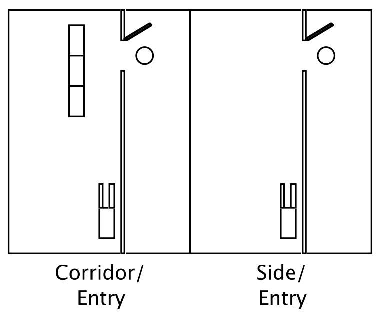

Figure 11 - Top view of Adjacent Space Scenarios.

Same Space Scenarios consider situations where the vehicle and intruder are in the same room or space. These scenarios offered multiple paths for the radio signals to travel between the antennae and RFID tags. We collected data for two approaches under two conditions for a total of four situations. The approaches, shown in Figure 10, refer to the location of the intruder. A “corner” is where there is an obstruction between the intruder and the forklift. A “passageway” is where the intruder is between two objects allowing access to the vehicle path. The conditions refer to the location of the forklift. A “side” is where the intruder approach is to one side of the forklift’s path and the opposing side is open. A “corridor” is where the opposing side is not open. The forklift was always positioned 0.5 m from the approach side, the forklift path is at the edge of the obstruction and was 0.5 m wider than the forklift. The corners, passageways, and corridors were assembled from metal cabinets.

The following procedure was developed towards a standard test method for occluded pedestrian detection systems and includes the scenarios shown in Figures 10 and 11.

Pedestrian Detection System Test Method

A Pedestrian Detection System (PDS) initiates an alarm on an industrial vehicle (AGV, forklift, or other) when a pedestrian enters the neighborhood of the forklift. The PDS consists of an instigator, carried on the vehicle, and a responder (tag), which is carried by the pedestrian. The features of the vehicle, the instigator, and the responder determine the parameters of PDS measurement.

A. Establish Nuisance Range

A PDS that alarms for pedestrians beyond a reasonable range will be ignored or disabled by the operators. The Nuisance Range should be established by standard based on the vehicle size, speed, and activity.

B. Establish Stop Range

The Stop Range is a function of the vehicle on which the PDS is to be used. The Stop Range is currently defined as the distance required for the vehicle to come to a complete stop once motive power is removed.

C. Assemble Test Mechanism

The measurement of a PDS requires multiple samples. To facilitate the sample collection, we construct a test mechanism that can automatically collect multiple samples.

C. 1. Identify Disabling Mechanism

A PDS may have the means to disable the detection elements. The mechanism is generally used to prevent the manual vehicle operator's tag from triggering alarms.

C.2. Identify Signal Mechanism

A PDS generates an alert in response to the presence of a pedestrian.

D. Determine Initialization Time and Sample Period

The PDS requires a period of time to initialize once enabled.

E. Set System Level

A PDS may have power adjustments to limit the number of nuisance alarms. The power level on those systems should be set such that there are no alarms at the nuisance range as determined in step A, above. The power level should remain constant for all tests. If the power adjustment is automatic (no operator adjustment) the power levels should be set in accordance with the manufacturer's specifications and be allowed to change during testing providing there is no operator input.

4.3 Occluded Obstacles

Unintended collisions with obstacles occur frequently [20]. However, there are few devices available to mitigate obstacle collisions. An occluded obstacle is any non-person item that 1) is not generally visible from the line-of-sight safety sensors onboard the forklift or AGV and 2) is in the vehicle's path. The obstacle may be occluded by a turn in the vehicle's path or by the size and position of the vehicle's load. The obstacle may also have generally low visibility or detectability by onboard safety sensors. Broad object categories that are not standard test pieces in ANSI/ITSDF B56.5 include walls, equipment, materials, edges, and debris. Walls can include posts, columns, shelving, and items protruding from shelving. Equipment can be ground-based or hanging overhead and can include ropes, chains, and hanging payloads. Edges can include the ends of floors, loading docks, trailers, and floor trenches. Negative obstacle (trenches and edges) research has focused on off-road applications [21, 22]. Debris is any object within the forklift's path that is too short to be impacted, but large enough to tilt the forklift by raising a wheel. Vehicle configuration can also create an occluded obstacle. For example, manual or automated forklift configurations include the mass, distribution, and positioning of the load. Active stability [23] is being used to control key manual forklift functions based on the forklift's payload and may reduce configuration-based accidents. Significant research and development are necessary to create the means to reduce or eliminate obstacle-related accidents.

5. OTHER PLANNED RESEARCH FOR STANDARDS DEVELOPMENT

5.1 Safety of robot arms on AGVs

Large-scale manufacturing automation processes cause severe limitations on the flexibility of industrial robot integration. When working with parts or processes that require large area coverage by a robot manipulator, integrators have two choices. First, they can add more robots, which can be costly to purchase, program, and coordinate. Second, they can mount a single robot on a massive linear rail superstructure that spans the length of the process, which is expensive, inflexible to increases in process distances, and wasteful in terms of workspace footprints. To compensate, integrators look to mounting robots on AGV-like bases to effectively extend the reach of a robot without incurring additional cost or complexity. However, these "mobile manipulators" do not fit squarely within the classification of "industrial robots," nor do they fully qualify as being classified as AGVs. The extended functionality of the amalgamation of a robot arm and a mobile base creates impressive capabilities that neither was capable of achieving alone. Unfortunately, they also present significant risks to worker safety.

Table 2: 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
Competing/incompatible safety protocols	A/R	--	A/R	--	A/R	--
Human carrying large load into AGV/robot path	--	--	--	--	--	--
Velocity of any point greater than that of AGV/robot individually	Not Applicable				R	--
Unplanned restart from pause/stop	A/R	--	A/R	--	A/R	--
Error recovery startup	R	--	R	--	R	--
AGV/robot software safety interlock	R	--	R	--	R	--
AGV/robot position/configuration update and verification	A/R	--	A/R	--	A/R	--
AGV/robot assumes master control during a pause or emergency stop event	A*	--	A*	--	A*	--

*ANSI/ITSDF B56.5 is not specific to onboard equipment causing a fault.

While there exists some overlap and complementing protective clauses, neither the industrial robot safety standards nor the AGV safety standards fully address all of the potential hazards of mobile manipulators when applied either separately or collectively. These protections break down even further when mobile manipulators are introduced into a manufacturing environment free of physical barriers between robots and humans. A sample subset of operational and environmental conditions that have limited or no coverage in existing AGV or robot safety standards is provided in Table 2. Concerns such as competing safety protocols, error recovery procedures, interlock prioritization, unexpected startup of the AGV or the arm, and state verification can be alleviated to an extent by controlling both the arm and the AGV by a single controller, but break down completely when the two are controlled separately. Safety issues are compounded further when both the arm and the AGV are moving simultaneously.

NIST is currently coordinating with the industrial robot and AGV communities to develop a new, joint, standards working group to address the safety concerns of mobile manipulators. Both communities have expressed interest in the effort, and the output is expected to be a new standards document addressing robot arms mounted on AGVs rather than extending the AGV and industrial robot safety standards.

5.2 AGV Performance Standard

Although modifications to the ANSI/ITSDF B56.5:2012 safety standard are suggested as described in previous sections of this paper, potential users of AGV technology can be confident that AGVs are safe when AGV manufacturers conform to the standard. However, there are no current standards to allow direct computation of an AGV's intelligent performance and users cannot fully appreciate their potential AGV investment without conducting their own tests and evaluations.

Some measurements of the intelligence levels of AGVs have been included in the ANSI/ITSDF B56.5 safety standard. For example, vehicle speed must be reduced when navigating through confined areas and control performance tests must prove that the vehicle stops prior to contact with human-representative obstacles when they are sensed using non-contact safety sensors. Specific tests, described in section 3.1, are expressed in the ANSI/ITSDF B56.5 standard to measure performance of the navigation and safety sensors when integrated into the vehicle control. This estimates the vehicle safety performance for the user. However, vehicle capabilities that may or may not involve safety functions would benefit from the availability of performance measurements to allow potential users to compare AGV products from one manufacturer to another. Since there is no current performance standard, users must rely on specifications provided by manufacturers with no standards basis. As a result, users may purchase AGVs based only on specifications that may or may not be correct or appropriate for the automated task. Additionally, unnecessary additional capital investment may be required to change the AGV application or even replace the AGV as the user's manufacturing methods or facilities change. Non-industrial vehicle applications (such as driverless cars, search and rescue vehicles, and military vehicles) are rapidly improving their capabilities and intelligence. As a result, they are providing a clear sense of the capabilities and intelligence that can be installed in industrial AGVs. An intelligence-level performance standard would measure current capability levels and provide standardized test methods to enable higher AGV performance. This could open niche areas such as adapting to unstructured environments with workers present.

Recently, NIST formally proposed that an AGV Performance Standards committee be established by a standards body and held related discussions with AGV manufacturers. Positive feedback for the new standard has been received. Planned next steps include formal discussions between the standards body and the AGV industry and formulation of the specific clauses to be included in the standard. For example, the standard, upon working group acceptance, is expected to divide into two main parts 1) AGV classes describing specific vehicle types and capabilities that will result in dramatically different performance and test method development; and, 2) application-specific performance criteria. For each criterion, task complexity, adaptability to the environment, and verification of performance will be addressed. These include: docking, palletizing, obstacle detection/avoidance, human detection, interaction with manual operations, environments and surfaces, synchronization among vehicles, X/Y movement, open source, and intelligence. Other possible areas to consider for an AGV performance standard include: interfaces with humans and AGV assistance from sensors, or factory clothes worn by workers.

6. CONCLUSIONS

NIST has been researching human-robot collaborative environments for AGVs and manned forklifts. Safety of AGVs and manned vehicles with automated functions, such as the ability to slow/stop automatically in hazardous situations, are the focus of the ANSI/ITSDF B56.5 safety standard. NIST has been developing test methods for AGV responses when humans or other obstacles enter or may enter the manned or unmanned vehicle path. Standard test methods described in this paper address both line-of-sight and non-line-of-sight conditions. These methods will provide ANSI/ITSDF B56.5 with the measurement science basis for both non-contact and contact sensing systems – some in use now and some planned for the future. Previously developed test methods to advance ANSI/ITSDF B56.5 when using non-contact sensing devices on AGVs or on manned vehicles with automated functions have been accepted into the standard. Accepted test methods include situations where standard test pieces are statically positioned beyond the vehicle stop zone. However, additional test methods being developed and described in this paper include cases when humans or other obstacles appear within the vehicle stop zone, humans or obstacles are struck by vehicle contact bumpers, and humans or obstacles are occluded by line-of-sight onboard vehicle safety sensors. Line-of-sight, 2D safety sensors currently being used do not fully detect obstacles in 3D environments even when using multiple 2D sensors. Based on 2D line-of-sight sensor research, it is highly recommended that 3D imaging sensor manufacturers develop safety rated 3D imaging sensors for the AGV industry. NIST has also been measuring capabilities of advanced non-safety-rated 3D imaging sensors for detection of overhanging obstacles and humans. This work will provide the measurement science basis to expedite safety rated 3D imagers. Also, there is limited research ongoing for detection of occluded obstacles that do not have detection devices. Test methods for detection of humans and other obstacles, non-occluded or occluded, should also be included in ANSI/ITSDF B56.5.

Other standards efforts have also begun at NIST in addition to test method development for ANSI/ITSDF B56.5. These include development of a standard for a robot arm on an AGV and also an AGV performance standard. Next steps will include completing ANSI/ITSDF B56.5 test method development, proposing the test methods to B56.5, developing and demonstrating initial test methods for robots mounted on AGVs, and collaborating with AGV manufacturers and users to develop an AGV performance standard.

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