Preliminary Development of a Test Method for Obstacle Detection and Avoidance in Industrial Environments

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Abstract

There is currently no standard method for comparing autonomous capabilities between systems. We propose a test method for evaluating an automated mobile system's ability to detect and avoid obstacles, specifically those in an industrial environment. To this end, a taxonomy is being generated to determine the relevant physical characteristics of obstacles so that they can be accurately represented in the test method. Our preliminary development includes the design of an apparatus, props, procedures, and metrics. We have fabricated a series of obstacle test props that reflect a variety of physical characteristics and performed a series of tests with a small mobile robot towards validation of the test method. Future work includes expanding the taxonomy, designing more obstacle test props, collecting test data with more AGVs and robots, and formalizing our work as a potential standard test method through the ASTM F45 Committee on Driverless Automatic Guided Industrial Vehicles, specifically F45.03 Object Detection and Protection.

I. Introduction

Automatically guided vehicles (AGVs) have become very common in industrial manufacturing environments. The use of autonomous mobile robots in this domain is also on the rise. A necessary capability of both systems is obstacle detection and avoidance. Obstacles in this domain range between static objects (e.g., tables, pallets, barrels) and moving agents (e.g., forklifts, people). The location of static objects in some environments is fixed while in others it changes very frequently when a job requires a different workflow and layout. If a system is capable of detecting and avoiding obstacles, it creates a safer work environment and allows for faster integration into a facility as less a priori knowledge of the environment is needed (as is discussed in [1]).

Currently, there is no standard for comparing this capability between systems. The Committee on Driverless Automatic Guided Industrial Vehicles (ASTM F45 [2]) has been formed to achieve this goal; specifically F45.03, which is focused on Object Detection and Protection. We propose a test method design that can aid in this effort by accurately simulating the relevant physical characteristics of an industrial manufacturing environment. In particular, the test method will replicate the physical qualities of common obstacles and objects that can affect a system's ability to detect them with its sensors and avoid collisions.

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II. Related Work

There are a variety of efforts working towards standardized performance metrics and test methods for robotic systems. The National Institute of Standards and Technology (NIST) has been leading an effort for the development of standard test methods for response robots [3] for well over a decade through the Committee on Homeland Security Applications; Operational Equipment; Robots (ASTM E45.08.01 [4]). Those test methods focus on different capabilities of mobility, manipulation, sensors, and human-system interaction, most prominently for teleoperated robots.

For AGVs, there is a safety standard test method specified in ANSI/ITSDF B56.5 [5] that verifies whether or not a system's safety sensor(s) are able to detect a potential obstacle in its path. Within that test method, two test pieces are placed at varying orientations and distances from the system that must be detected and avoided. The surface of the test pieces are either black, as it can cause issues for optical sensors, or highly reflective, as it can cause issues for ultrasonic sensors. That test is primarily focused on dynamic agents (e.g., a person) that temporarily enter a vehicle's path. A similar standard for autonomous robots is ISO 13482 [6], which includes appropriate distances between the system and an agent/object that enters its space and emergency stop functions. It is aimed at personal care robots (not those in industrial environments) and is largely focused on the system's safety when co-located with people. While it specifies standard performance, it does not specify a standard test method for determining performance.

The CLEO and PRIDE efforts outlined in [7] are aimed at measuring the performance of autonomous systems. It notes that the capability of a system to work in unstructured, dynamic environments as a "critical enabler for next-generation industrial mobile robots." The CLEO (Complexity Levels of Environment and Obstacles) framework provides a method for characterizing an autonomous system's ability to navigate through increasingly complex environments and obstacles, as both aspects become more dynamic. The metrics used include geometric correctness, dynamic map update methods, and amount of time to update for environment changes.

The development of standard test methods for AGVs is also prevalent at NIST [8], focusing on collaborative workspaces between humans, unmanned vehicles, and manned vehicles. That work focuses on the detection of objects and agents that either enter the path or stop zone of a vehicle or are beyond it. The test pieces from ANSI/ITSDF B56.5 are used for obstacles, as well as an alternative to ground truth measurement called the Grid-Video method. This method involves placing a grid on the ground and computing ground truth locations from recorded video of a test.

III. Scope

Obstacle detection and avoidance is a common capability of any mobile, autonomous system. Given the existing audience and effort for ASTM F45, the development of this effort is initially focused on automated mobile systems used in indoor industrial environments, particularly for manufacturing applications. Mobile systems in this domain include AGVs, which can take the form of traditionally human-operated vehicles that are instead automated (e.g., Seegrid Vision Guided Vehicles [9]) and autonomous robots (e.g., Adept MobileRobots [10]).

All of these systems are required to detect and avoid objects and agents that either enter their path or form the edges of their path. This includes any entity in an industrial environment that, if a mobile system were to collide with it, could cause damage to the system, its payload, or the entity itself. For developmental purposes, these are what we refer to as obstacles. Obstacles can sit on the ground or protrude from a wall or ceiling in the environment.

Depending on a variety of factors, including the system's capabilities and the layout of the environment, the manner in which an obstacle is avoided varies. Avoidance can mean stopping in place until the obstacle is no longer in the way or driving around the obstacle to continue on a path. The metric of performance in this test method will have to take into account what the system is able to do, given the environment constraints and its own mobility capabilities. Also, depending on the sensors used by the system to sense the obstacle, avoidance does not necessarily mean non-contact. The amount of allowable contact in the test method should not cause any damage to the system or the obstacle that is being hit.

Every industrial environment serves a different purpose and uses different brands of furniture, machinery, etc., resulting in a vast number of possible characteristics. However, all of these obstacles can be grouped into types. The physical characteristics of an obstacle are what determine if an automated system is able to detect it properly. To distill the physical characteristics of each type into those that are relevant to obstacle avoidance, the creation of a taxonomy to guide development is proposed. A simple internet image search of manufacturing environments was performed to determine the common types of obstacles (e.g., tables, shelving units, carts, pallets, barrels, ladders, etc.) to be included in the taxonomy.

When testing an autonomous or automated capability, a dynamic test is more appropriate than a static one to ensure that the system being tested is sensing and reacting to obstacles in-situ, eliminating any possibility of an operator gaming the test to exhibit better performance. To achieve this, external characteristics (e.g., location, orientation) and internal characteristics (e.g., overall and individual feature dimensions) of the obstacles in the environment should vary during a test session. Given the many possible real world objects, variability of internal characteristics will allow for a wide array of these objects to be properly simulated. A downselection process can also be performed to determine the appropriate obstacle types to test depending on the system's dimensions, sensor types, sensor placement, etc.

For some mobile systems, its implementation in an industrial environment requires the areas where the system can drive and landmark locations to be defined. We refer to the edges that define such spaces as boundaries. They can be defined in a variety of ways. Some systems require physical augmentation of a space (e.g., the laying of magnetic tape) in order to be implemented. Others make their own map of the space and the boundaries are virtually augmented in software. The identification of locations also varies between systems; some read markers in the environment to know when a location is reached and others have locations defined in software. All of these features (if applicable to a system) must be possible within the test method, allowing for holistic testing of a system.

An important aspect of the response robot test methods specified through E54.08.01 is the availability of the materials used to fabricate the test apparatuses and props. All of those test methods are made with lumber, wood panels, PVC pipes, and other common building materials. This has allowed them to be easily implemented, disseminated, and used by the first responder and robotics community. This test method should follow the same convention.

A. Requirements

All of these factors form a set of requirements that define the scope of the test method, so that it meets the needs of the manufacturing robotics domain, allows both traditional AGVs and mobile robots to be tested, and can be fabricated by anyone:

R1: The relevant characteristics of common obstacles in an industrial environment must be physically represented.

R2: Obstacle test props must have variable settings to allow for a variety of real world objects to be represented.

R3: Obstacle test prop settings, both internal and external qualities, must be varied during a test session to prevent gaming and test the flexibility of the autonomy.

R4: The semi-permanent boundaries of the environment and locations within it must be represented in the test apparatus such that they are appropriately detectable by the system being tested.

R5: The test apparatus and props must be fabricated using readily available building materials that are inexpensive.

B. Taxonomy of Relevant Characteristics

In order to accurately simulate an appropriate level of detail in manufacturing environments, a taxonomy of relevant characteristics is being developed. The taxonomy will guide the design of the obstacle test props and provide a unified language to describe their purpose. The characteristics that are to be included are distilled through the following process:

T1: Identify types of real world obstacles and features found in an industrial environment.

T2: Break down each obstacle into their physical components.

T3: Outline the constant and variable physical relationships between each obstacle component.

T4: Identify overlaps in the physical characteristics between real world obstacles (this is performed to limit the number of unique obstacle test props that will need to be developed).

T5: Design obstacle test props that capture the physical characteristics while reducing overlap between other obstacle test props.

The use of the taxonomy development process ensures that the requirements that pertain to the obstacle test props are met. Specifically, R1 is satisfied by T1 and T2, R2 is satisfied by T3, and R3 and R5 will help guide T5. This process has been used to develop an initial set of example test prop designs, which are detailed in Section IV.

A snapshot of T1-T3 can be seen in Table I, using a table and shelving unit as examples. Other obstacles included in the taxonomy conveyor belts, chairs, pallets, ladders, railings, bollards, columns, and barrels. Surface quality is not listed as a variable characteristic, as the flat black and reflective surface qualities used on the test pieces described in ANSI/ITSDF B56.5 can be used for all obstacle test props to represent edge cases for sensors. While performing T4 across the obstacles, a set of higher level qualities emerged as relevant characteristics:

T1: Real world obstacles T2: Physical components of each	T3: Constant and variable physical relationships between each obstacle component
Table Leg (vertical column extending from ground) Table top (horizontal plane above ground) Feet (horizontal or vertical features extending from leg on ground) Bracer (horizontal plane extending between legs above or on ground)	Constants At least one vertical leg that extends between the ground and the table top A table top that sits above the leg(s) with empty space between it and the ground Variables Number of legs Horizontal distance between legs Horizontal distance between legs and table top edge Vertical distance between ground and table top Table top dimensions Feet type (e.g., perpendicular extensions, wheels) Vertical distance between horizontal bracers and ground (if any) Type of horizontal bracers (e.g., solid plane between ground and table top, bar)
Shelving unit Shelf (horizontal plane above or on the ground) Side support or leg (vertical plane or column extending from ground and/or between shelves) Back support (vertical plane extending from ground between shelves) Feet (horizontal or vertical features extending from support on ground)	Constants At least one shelf that sits above the ground with back support Variables Number of shelves Vertical distance between shelves Width and depth of shelves Horizontal distance between back support and shelf edge Side support type (e.g., posts, solid planes that extend from front to back of shelves) Horizontal distance between side supports (if posts) Back support type (e.g., environment wall, solid plane that spans shelf width) Shelf, side, and back support material density (e.g., solid, wire frame) Feet type (e.g., perpendicular extensions, wheels)

Table I. A snapshot of T1-T3 of the obstacle taxonomy development process, using a table and shelving unit as examples.

- **Volume:**
  - Closed: all of the obstacle's components are contained within its volume, and/or the volume cannot be entered by part of the system (e.g., a solid block)
  - Open: the volume of the object can be entered by part of the system (e.g., a desk)
- **Spatial Characteristics:**
  - Ground: a component touches or is attached to the ground and can be sensed when on a side of the system
  - Elevated: a component overhangs the ground without another component directly underneath it and can be sensed when above and/or on a side of the system
  - Inset: a component is set into the volume a distance from another component that sits above it (e.g., a table whose legs do not touch the table top edges) and can be sensed when on a side and/or above the system
- **Surface Density:**
  - Solid: the outer surface of the obstacle is solid

  - Porous: the outer surface has many holes (e.g., a wire mesh shelving unit)
  - Empty: the side-facing outer edges of the obstacle are empty
- **Location:**
  - Static, fixed: the obstacle is fixed in place and cannot be moved
  - Static, could be moved: the obstacle is not explicitly fixed and can be moved if hit with enough force
  - Dynamic, moving: the obstacle moves on its own (e.g., a human, a forklift)
  - Dynamic, component enabled movement: the obstacle is able to move when hit due to a component that enables it to do so (e.g., wheels)

These characteristics can be used to design a set of obstacle test props that capture the relevant physical properties of an industrial environment. An initial set is discussed in the next section.

IV. Test Method Design

NIST [3] states that standard test methods specify apparatuses and props (reproducible representations of tasks), procedures (a script for the test administrator to follow), and metrics (quantitative measures of performance). They do not specify standard performance, only a standard way to measure it. For this test method, the apparatus is a representation of the environment, or the boundaries that determine the area where the robot can plan its path. The test props are the variable obstacles that can block the robot's path.

A. Test Apparatus

The size of the system, the obstacles, and the environment determine if an obstacle can be avoided by the system stopping or by navigating around it. Many AGVs are not currently equipped with the functionality to navigate around an obstacle, but some existing autonomous mobile robots can. The size of the apparatus will also dictate where the obstacles can be placed within it and the direction of approach by the system.

Preliminary development of this test method is not concerned with confined space, but rather if an obstacle can be detected and avoided successfully. Therefore, the dimensions of the apparatus should be sized such that there is sufficient space for the system to pass on at least one side of the obstacle, which will depend on the dimensions, locomotion type, and turning radius of the system. An exact formula for determining this has not yet been developed.

As specified in R4, the boundaries of an environment and the locations within it can be interpreted differently by each system. Regardless of how they are sensed, the apparatus should be built such that any people near it are protected from potentially unsafe system behavior (e.g., exiting the boundaries). Thus, a barrier is implemented outside of all physical or virtual augmentations. To meet R5, the barrier is made using wood posts and sheets of wood, which are most commonly available measuring 2.4 x 1.2 m (96 x 48 in). The wall panels can also be used to define the system's path if no additional augmentation is required.

The apparatus is built to define a space for testing wherein the system is instructed to drive from location A to B and back continuously. A dead end after both locations forces the system to turn around and traverse its path again, approaching the obstacle from the opposite direction. If the system is unable to change travel directions within the dead zone then an additional path can be added to allow for continuous, looped travel. The interior measurements can vary, most easily in multiples of 2.4 m (96 in), or 1.2 m (48 in), for simple fabrication. Any required physical or virtual augmentation for boundaries and location definition can occur within this space. A diagram of the apparatus can be seen in Figure 1. A wall in the middle of the apparatus is designed for mounting obstacles to obstruct the path. To adjust the location of the obstacle test props within the space (as per R3), bars of 80/20 Holey Tubing [11] are attached to the wall to allow for precise attachment. The apparatus can be seen in Figures 1 and 2.

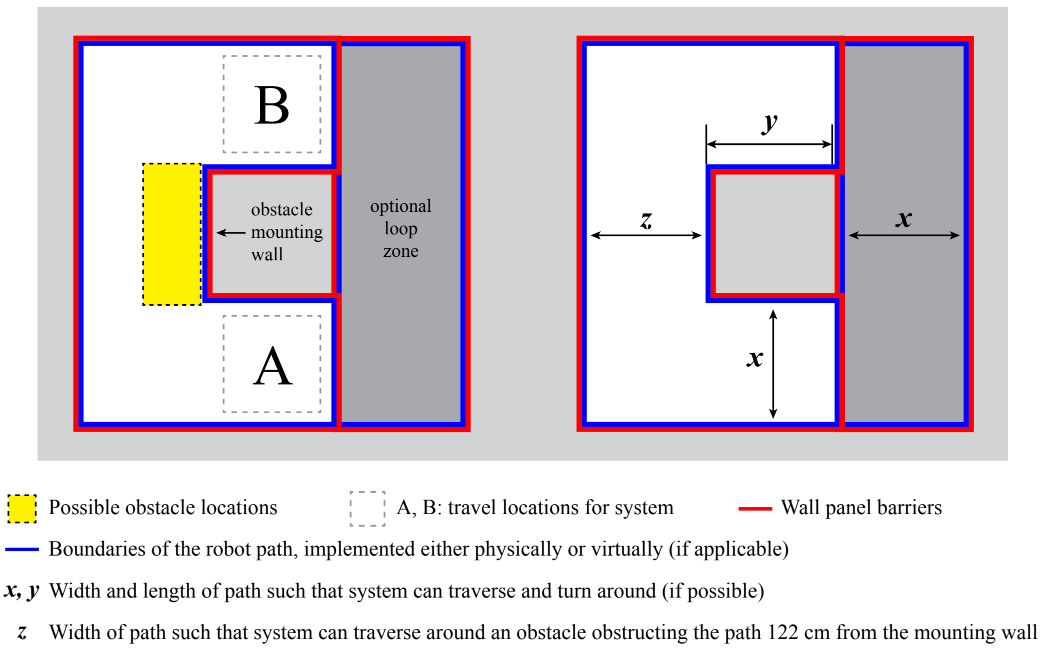


Figure 1. Diagram of the test apparatus environment. The optional loop zone can be added for systems that cannot change travel directions in the allotted space (or at all).

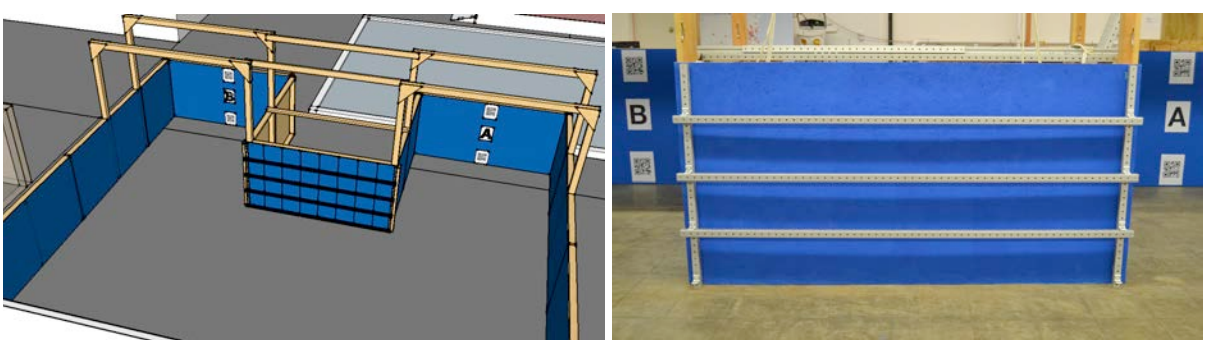


Figure 2. The test apparatus environment set up at the UMass Lowell NERVE Center. Left: 3D rendering. Right: photo of the obstacle mounting wall.

B. Test Props

The test props represent a variety of obstacles whose characteristics are specified through the taxonomy. Their locations and orientations within a space can vary, each which introduces a new challenge of detection for the system being tested. To meet R3, the variable characteristics of each obstacle defined in T3 must be changed during a test session. Rather than designing many obstacle test props that capture all of the possible variations of a single obstacle type, malleable props with adjustable settings can be used. To change the settings of an obstacle test prop, minimal tools should be required as to not add excessive length to a test session.

To meet R5, we have opted to use a common set of building materials to fabricate the obstacle test props. For flat horizontal or vertical solid planes wooden panels are used, 122 cm along at least one dimension. For vertical or horizontal columns, aluminum square tubing (specifically, 80/20 Holey Tubing) is used, which comes pre-drilled with holes that are separated by 3.8 cm, which allows for a very precise granular scale for adjusting attachment dimensions. Each of these items can be painted flat black or metal sheets can be attached to match the surface qualities of ANSI/ITSDF B56.5. Other features like porous surfaces and elevated obstacles are achieved by wire mesh panels and rope with pulleys, respectively. All obstacle test props are fabricated using hand-tightened hardware like bolts and wingnuts for easy assembly and adjustment. Additional pieces of aluminum square tubing can be used as infrastructure on the horizontal plane to attach the obstacle test props to the apparatus along the mounting wall. Holes are cut in the horizontal plane to allow square tubing to pass through perpendicularly and serve as inset features. The common building materials can be seen in Figure 3.

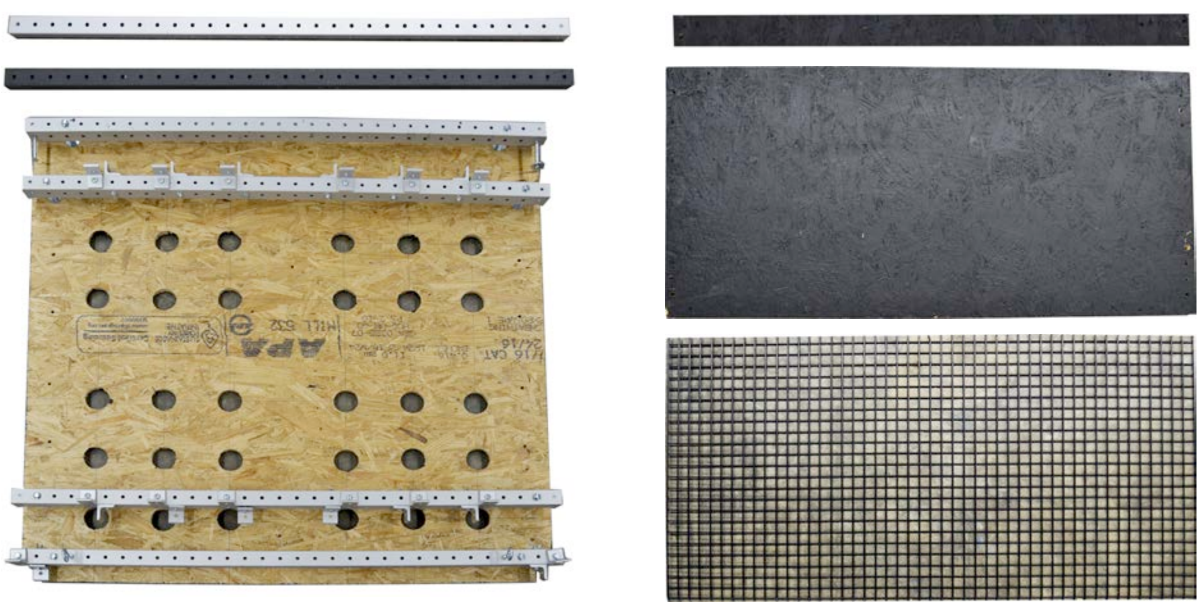


Figure 3. The common building materials used to fabricate the obstacle test props. Left, top to bottom: aluminum square tubing, black square tubing, horizontal plane with holes and hardware for mounting additional components. Right, top to bottom: thin solid panels, tall solid panels, mesh side panels.

A series of obstacle test props have been designed, each satisfying a different combination of the higher level qualities outlined in Section III B. See Table II for images of each obstacle test prop and their corresponding characteristics. Obstacles A and B can used as qualifiers before advancing to obstacles that use multiple surfaces of that type. The “infinite” height characteristic means that the implementation of the obstacle is not considering where the top of the obstacle is; generally, an AGV or mobile robot system does not detect obstacles from the sky down, but rather from the ground up. The default size for wide obstacle features is 122 cm, given the availability of 122 cm x 244 cm wood panels. Elevated obstacles can have their components elevated at a height that allows part of the system (or the entire system) to drive underneath it, potentially causing it to collide with the horizontal plane, unless the obstacle has components on the ground that the system may detect the obstacle before a collision occurs.

C. Procedure

Before conducting a test, the apparatus must be set to the appropriate dimensions. Wall panels and boundaries must be set at dimensions that allow for the system to drive comfortably with enough space for it to detect and navigate around an obstacle (if applicable). The optional loop zone can be added if necessary. Physical and/or virtual augmentation should occur to define the system’s path as needed. The travel locations (A and B) must also be defined to the system, which can occur virtually in software, accompanied by physical augmentations like QR codes or reflectors, etc.

A downselection of obstacle test prop types and a threshold for their variable settings should also be performed to prevent exhaustive testing. Depending on the system’s dimensions and the sensors it has available, some obstacle settings will have larger impacts than others. For instance, if only a forward facing two-dimensional LIDAR is used and is mounted low to the ground, then obstacles that are elevated completely above the system will not be detectable and therefore do not need to be tested. A proper downselection process is still in development.

The system is instructed to traverse from location A to B, then B to A. If a specific path can be commanded then it should fall right through the center of the space defined by the boundaries. One instance of this action performed by the system is referred to as a lap. During each lap, the system will interact with the obstacle twice, or once if the loop zone is used. After each lap, the obstacle’s settings are adjusted as necessary, such as its location and orientation along the mounting wall. This process should be repeated as many times as necessary to achieve a statistically significant measure of successful detection and avoidance of the obstacle type(s).

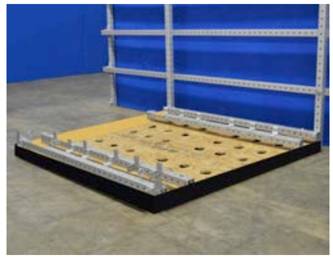
If the system does not properly avoid the obstacle, then that lap will be noted as such. This would require a reset to the last travel location. If too many faults occur, the settings of the test should be adjusted to an easier difficulty, which has not yet been determined.

D. Metrics

The most important metric of performance is whether or not the obstacle was avoided. If non-contact sensors are used by the system being tested, then avoidance means that the system did not collide with any part of the obstacle. If contact sensors are used (e.g., bumper), then avoidance means that upon contact the obstacle did not move enough to cause any damage or create a safety hazard. This can be determined by observing the system as it performs within the test method. The test can also be video recorded for review afterwards.

A.

B.

C.

D.

E.

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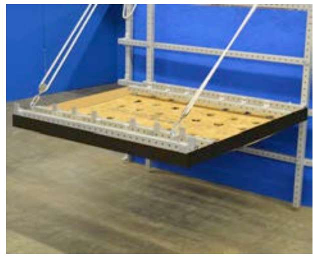
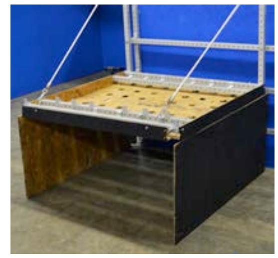
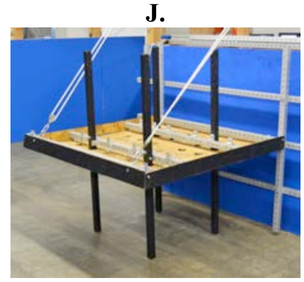

G.

H.

I.

J.


	Volume	Surface Density	Width	Height	Elevation	Spatial Characteristics	Analog Example
A.	Flat	Solid	Thin	Infinite	n/a	Ground	Wall
B.	Flat	Porous	Thin	Infinite	n/a	Ground	Mesh partition
C.	Closed	Solid	Wide	Thin	n/a	Ground	Pallet
D.	Closed	Solid	Wide	Infinite	n/a	Ground	Column
E.	Closed	Solid	Wide	Infinite	Variable	Elevated	Elevated load on forklift
F.	Closed	Solid	Wide	Thin	Variable	Elevated	Shelf
G.	Open	Solid	Wide	Variable	Variable	Ground Elevated	Desk
H.	Open	Porous Solid	Wide	Variable	Variable	Ground Elevated	Mesh shelving unit
I.	Open	Empty Solid	Wide	Thin	Variable	Ground Elevated	Table
J.	Open	Empty Solid	Wide	Thin	Variable	Ground Elevated Inset	Conference table

Table II. A set of example obstacle test props using the common set of building materials. Note: all example images use a flat black surface quality on all outward facing planes (e.g., side panels, underside of horizontal plane, etc.). The same designs are also possible using reflective material. * = All “infinite” heights are depicted at 61 cm, as those are the specific settings used for validation testing in Section V.

A more detailed metric of performance is the distance between the obstacle and the system after it has avoided the obstacle. The distance depends on the speed the system is traveling, at what distance it detects/reacts to the obstacle, and how quickly it stops moving towards the obstacle. For this type of measurement, a motion capture system can be used, although this would not satisfy R5. An inexpensive way to do this is to draw a grid on the ground and calculate the distance by processing images from the recorded video of the test (as is done in [8]).

V. Validation Testing

To aid in validating the design of the test method, a series of tests were conducted at the UMass Lowell NERVE Center. A total of ten tests were conducted using a mobile robot programmed to traverse within the apparatus from A to B and back for five laps. For each test a different obstacle was used; those used can be seen in Table II (their settings are detailed below). In between each lap, the location of the obstacle along the mounting wall was altered, varying between 0 cm from left edge, 61 cm from left edge, center, 61 cm from right edge, and 0 cm from right edge. All tests were recorded using a multi-angle camera system, depicting the obstacle from all observable sides (see Figure 4).

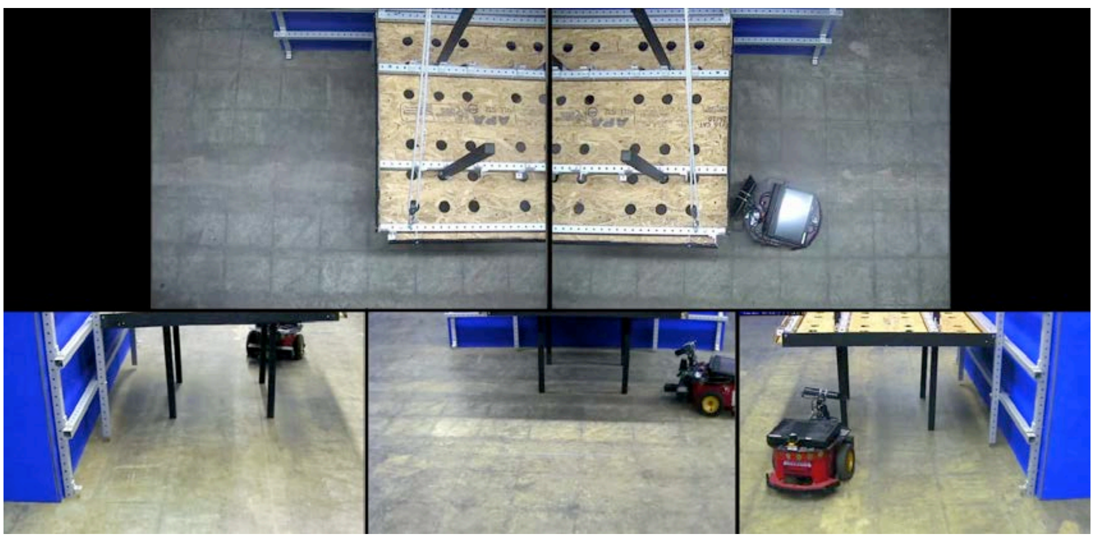


Figure 4. A still frame from the multi-angle camera system used to record the test sessions.

A. Robot Configuration and Obstacle Settings

An Adept MobileRobots Pioneer 3 was used for this testing, which is a small research platform with differential-drive, motor encoders, and was augmented with two Hokuyo URG-04LX-UG01 sensors (one on the front, one on the back) for 360 degree local obstacle detection, as well as a Microsoft Kinect v1 (although it was not active). The Pioneer was programmed using ROS (Robot Operating System) [12], specifically the Navigation Stack, which is a generic suite of tools for differential or holonomic navigation, with parameters specifically configured for the robot. Before conducting the tests, the robot required virtual augmentation of the space, so the robot was manually driven through the apparatus with no obstacles present, building a map of the space using simultaneous localization and mapping (SLAM); see Figure 5. The A and B locations were then programmed within this map. The robot uses the boundaries of the apparatus to determine its path (and will attempt to avoid any obstacles that obstruct its path) and to localize within it. With the additional augmentations, the Pioneer measures 50 cm x 38 cm x 40 cm. The Hokuyo URG is located approximately 30 cm above the ground, offering a two-dimensional LIDAR view around the body of the robot. An image of the robot can be seen in Figure 6.

One instance of each obstacle type listed in Table II was used with specific settings tuned for the Pioneer. The robot's two-dimensional sensors were located 30 cm above the ground, meaning all ground obstacles of "infinite" height did not need to be taller than that, as they would be detected by the robot regardless. For this reason, 61 cm tall side panels were used for obstacles A, B, D, and E. Obstacle C used 8 cm tall side panels such that its thin ground components were below the sensors. No overhead components of obstacles could be detected; if they were elevated less than 40 cm high, the robot would have collided with them (unless there were accompanying ground features that were otherwise detectable). In order to reduce potential damage to the robot, obstacles E-J were elevated 61 cm high. The robot could also possibly enter the volume of obstacles G-J; the default 122 cm size was used for all wide obstacles, as well as insets of 30 cm, to allow for this possibility. Hokuyo URG sensors have been shown to have issues with dark surfaces [13], so all obstacle test props used black surfaces.

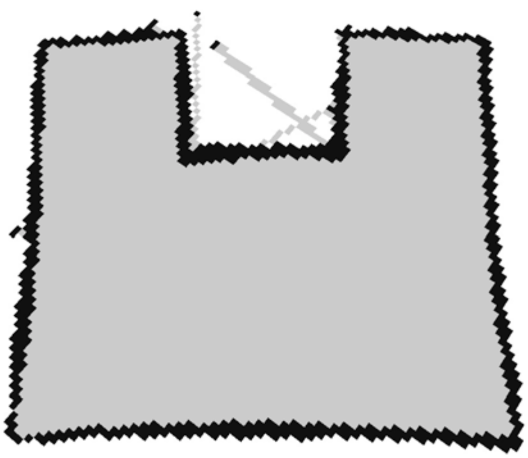


Figure 5. Map of the apparatus generated by the robot using the Rviz package in ROS.

Figure 6. The Adept MobileRobots Pioneer 3 with additional sensors.

B. Results and Discussion

Based on the robot's dimensions and sensing capabilities, we hypothesized it would successfully detect and avoid solid obstacles with ground features that were within its detectable horizontal field of view (30 cm high, parallel to ground; obstacles A, D, and G) and drive under all closed volume elevated and/or open volume obstacles (obstacles E, F, G, I, and J). The prediction of success for detecting and avoiding obstacles with porous surface densities was questionable. In general, our hypotheses were correct; all obstacles with tall solid side panels on the ground were both detected and avoided, and all closed volume elevated obstacles were avoided, but not detected. All open volume obstacles were detected, but not all avoided. See Table III for test results.

Obstacle (see Table II)	Unique Settings	Duration	Successful Reps (out of 5)	Detection	Avoidance
A.	61 cm side panels	13:30	5	Yes	Yes
B.	61 cm side panels	10:00	5	Yes	Yes
C.	8 cm side panels	0:30	0	No	No
D.	61 cm side panels	9:00	5	Yes	Yes
E.	61 cm side panels 61 cm elevation	14:30	5	No	Yes*
F.	61 cm elevation	12:30	5	No	Yes*
G.	61 cm elevation	18:30	5	Yes	Yes
H.	61 cm elevation	2:30	1	Yes	No
H. (trial 2)	Same as above	1:30	0	Yes	No
I.	61 cm elevation 144 cm between columns	1:30	0	Yes	Yes, but did not reach other location
J.	61 cm elevation 114 cm between columns 30 cm between columns and horizontal plane edge	1:30	0	Yes	No
J. (trial 2)	Same as above	8:20	5	Yes	Yes

Table III. Testing results of obstacle detection and avoidance test method with the Pioneer. Note that when performing trial 2 with obstacle J the robot's navigation parameters were changed. * = These obstacles were not detected because their components were elevated above the robot's sensor field of view, but were technically avoided because no part of the robot collided with the obstacles.

Porous surface densities were not reliably avoided (obstacles B and H); the robot needed to be noticeably closer to detect the wire mesh properly. During the second repetition using obstacle H the mesh panel on the right side was detected and avoided, but due to the open volume the robot then traversed underneath the horizontal plane. The mesh panel on the left side was detected while the robot was inside of the obstacle, but its driving settings (e.g., turning radius, acceleration, braking speed) prevented it from detecting the panel in time to avoid collision. A second trial was attempted with obstacle H, but resulted in no successful repetitions.

While the settings for open volume obstacles with empty surface densities (I and J) were adjusted such that would traverse through them, this was not the case. The robot detected the obstacles' ground features, but got stuck during its decision-making process and did not reach the next location. This is due to the parameters in the robot's ROS navigation stack. A second trial for obstacle J was performed after one of these parameters was reprogrammed, which resulted in 5 successful repetitions. Given the change in performance, it follows that a software change like this constitutes a new robot configuration, and any performance exhibited using this configuration is not comparable to those with different configurations.

VI. Conclusion and Future Work

We have developed a preliminary design for a test method to evaluate an autonomous vehicle's ability to detect and avoid obstacles. The taxonomy of relevant physical characteristics will continue to develop to ensure that all obstacles in industrial environments can be accurately represented within the test method. Currently, all of the common building materials are comprised of right angles, with no curves. The use of circular vertical columns for legs (possibly PVC pipes) would also better match with the test pieces used in ANSI/ITSDF B56.5. The common building materials can also be used to fabricate standard test pieces for other test methods for vehicles in industrial environments within ASTM F45. The test method will later be expanded to capture environmental settings such as lighting, ground types, and temperature.

A further specified process for downselecting appropriate obstacle types and settings to be used during a test session is needed. For our testing with the Pioneer, settings were chosen based on the robot's physical configuration with respect to its dimensions and sensors. To formalize this, a proper definition of a system's configuration (both hardware and software) is also needed. The configuration of the system will then inform this process. Some elements of a configuration may be variable, such as whether or not the system is carrying a load behind it, on top of it, or in front of it. For instance, if the Pioneer was carrying a box on top of it and traversed through the open volume obstacles, then the payload may have collided with the horizontal plane, unperceived by the robot.

This work will be leveraged while developing standards and test methods through the ASTM F45.03 Object Detection and Protection subcommittee. In order to do so, more validation testing needs to be performed using real world AGVs and mobile robots to ensure that the test method accurately captures their capabilities at detecting and avoiding obstacles. The manner in which test results are presented must also be refined such that they are usable by industry.

VII. Acknowledgements

This research has been supported in part by the National Institute of Standards and Technology (NIST) under 70NANB14H235. The authors would like to thank Jordan Allspaw, Brian Carlson, James Dalphond, and Alexandra Derderian of the UMass Lowell NERVE Center for their assistance in fabrication of the test method and validation testing.

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