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Standard Test Method for Evaluating Ground Robot Capabilities and Remote Operator Proficiency: Terrains: K-Rails[1]

This standard is issued under the fixed designation E3349/E3349M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

The robotics community needs ways to measure whether a particular robot is capable of performing specific missions in complex, unstructured, and often hazardous environments. These missions require various combinations of elemental robot capabilities. Each capability can be represented as a test method with an associated apparatus to provide tangible challenges for various mission requirements and performance metrics to communicate results. These test methods can then be combined and sequenced to evaluate essential robot capabilities and remote operator proficiencies necessary to successfully perform intended missions.

The ASTM International Standards Committee on Homeland Security Applications (E54) specifies these standard test methods to facilitate comparisons across different testing locations and dates for diverse robot sizes and configurations. These standards support robot researchers, manufacturers, and user organizations in different ways. Researchers use the standards to understand mission requirements, encourage innovation, and demonstrate break-through capabilities. Manufacturers use the standards to evaluate design decisions, integrate emerging technologies, and harden systems. Emergency responders and soldiers use them to guide purchasing decisions, align deployment expectations, and focus training with standard measures of operator proficiency. Associated usage guides describe how these standards can be applied to support various objectives.

Several suites of standards address these elemental capabilities including maneuvering, mobility, dexterity, sensing, energy, communications, durability, proficiency, autonomy, and logistics. This standard is part of the Terrain suite of test methods.

1. Scope

1.1 This test method is intended for remotely operated ground robots operating in complex, unstructured, and often hazardous environments. It specifies the apparatuses, procedures, and performance metrics necessary to measure the capability of a robot to traverse complex terrains in the form of k-rails. This test method is one of several related Terrain tests that can be used to evaluate overall system capabilities.

1.2 The robotic system includes a remote operator in control of all functionality, so an onboard camera and remote operator display are typically required. Assistive features or autonomous behaviors that improve the effectiveness or efficiency of the overall system are encouraged.

1.3 Different user communities can set their own thresholds of acceptable performance within this test method for various mission requirements.

1.4 *Performing Location*—This test method may be performed anywhere the specified apparatuses and environmental conditions can be implemented.

1.5 *Units*—The International System of Units (a.k.a. SI Units) and U.S. Customary Units (a.k.a. Imperial Units) are used throughout this document. They are not mathematical conversions. Rather, they are approximate equivalents in each system of units to enable use of readily available materials in different countries. This avoids excessive purchasing and fabrication costs. The differences between the stated dimensions in each system of units are insignificant for the purposes

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[1] This test method is under the jurisdiction of ASTM Committee E54 on Homeland Security Applications and is the direct responsibility of Subcommittee E54.09 on Response Robots.

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of comparing test method results, so each system of units is separately considered standard within this test method.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2521 Terminology for Evaluating Response Robot Capabilities

2.2 *Other Standards:*

NIST Special Publication 1011–I–2.0 Autonomy Levels for Unmanned Systems (ALFUS) Framework, Volume 1: Terminology, Version 2.04[3]

3. Terminology

3.1 *Definitions*—The following terms are used in this test method and are defined in Terminology E2521: *abstain, administrator or test administrator, emergency response robot or response robot, fault condition, operator, operator station, remote control, repetition, robot, teleoperation, test event or event, test form, test sponsor, test suite, testing target or target, testing task or task,* and *trial or test trial.*

3.2 The following terms are used in this test method and are defined in ALFUS Framework Volume I:3: *autonomous, autonomy, level of autonomy, operator control unit (OCU),* and *semi-autonomous.*

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *apparatus clearance width (W), n*—a specification for the apparatus dimensions chosen from one of four possible measurements, based on the intended robot deployment environment:

240 cm ± 2.5 cm tolerance [96 in. ± 1 in. tolerance], such as open and outdoor public spaces;

120 cm ± 2.5 cm tolerance [48 in. ± 1 in. tolerance], such as indoor spaces in accessibility-compliant buildings;

60 cm ± 1.3 cm tolerance [24 in. ± 0.5 in. tolerance], residences and aisles of public transportation;

30 cm ± 1.3 cm tolerance [12 in. ± 0.5 in. tolerance], cluttered indoor spaces, ductwork, and voids in collapsed structures.

3.3.1.1 *Discussion*—The measures for these scales are nominal and do not represent the measurement of the narrowest point in the apparatus through which the robot should pass. Consult Section 6 for the overall measurements and dimensions of the apparatus at each scale.

3.3.2 *cross-over slope, n*—an optional test configuration that augments the center of the terrain apparatus which positions two portions of terrain on adjacent slopes of 15° in opposite directions.

3.3.3 *diagonal rail, n*—a solid piece of dimensional lumber that is sized to fit horizontally inside a subfloor at a 45° angle to the direction of travel.

3.3.4 *subfloor, n*—an underlayment of Oriented Strand Board (OSB) or similar material with dimensional lumber borders used to affix multiple subfloors to one another and can contain apparatus elements such as terrains or obstacles.

4. Summary of Test Method

4.1 This test method is performed by a remote operator, out of sight and sound of the robot, while controlling the robot within the test apparatus. The robot follows one of two defined paths in the specified terrain requiring the robot to overcome challenges including pitch, roll, traction, and control of variable chassis shape and articulators within open or confined spaces.

4.2 The figure-8 path (forward) is a continuous forward path through the terrain with alternating left and right turns to avoid barriers. It can be used to demonstrate terrain traversal over long distances within a relatively small apparatus. The continuous traverse is shown as the white path (see Figs. 1 and 2).

4.3 The zig-zag path (forward/reverse) is an end-to-end path that requires forward and reverse traversal through the terrain with alternating left and right turns to avoid barriers. This can be used to demonstrate traversal of the terrain within confined spaces. The down-range traverse, shown as the white path, is performed in a forward orientation and the up-range traverse, shown as the black path, is performed in reverse (see Fig. 1 and Fig. 3).

4.4 The robot starts on one side or the other of a lane full of fabricated k-rail terrain at a chosen scale. The robot follows either the figure-8 path (forward) or the zig-zag path (forward/reverse) between the two barriers. The figure-8 path (forward) repetition is completed when the robot crosses the start/end centerline of the lane without a fault after approximately following the white path. The zig-zag path (forward/reverse) repetition is completed when the robot crosses the start/end centerline without a fault after approximately following the white and black paths.

4.5 *Potential Faults Include:*

4.5.1 Any contact by the robot with the apparatus that requires adjustment or repair to return the apparatus to the initial condition;

4.5.2 Any visual, audible, or physical interaction that assists either the robot or the remote operator; and

4.5.3 Leaving the apparatus during the trial.

4.6 By default, the terrain apparatus is fabricated such that it is not inclined and sits flat on the ground. An optional configuration of this test method is available wherein a

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.nist.gov.

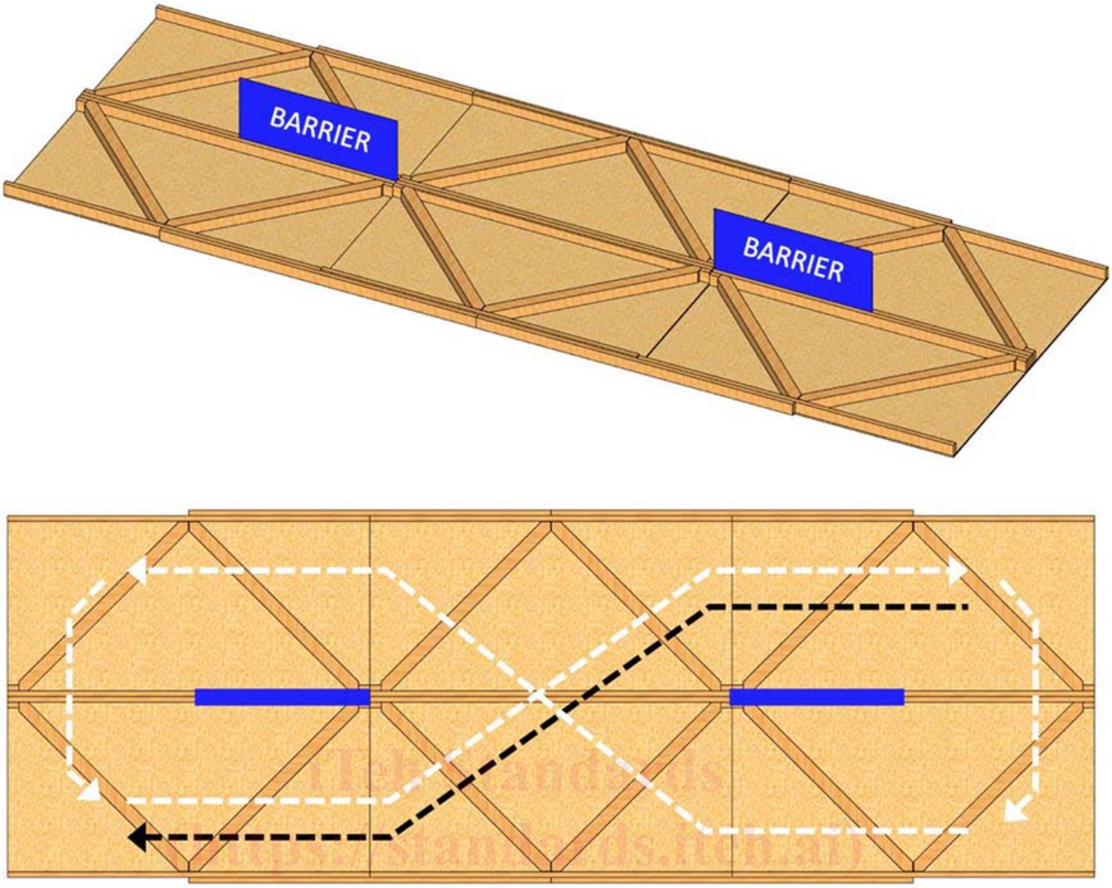


FIG. 1 Overview of the K-rail Terrain Apparatus

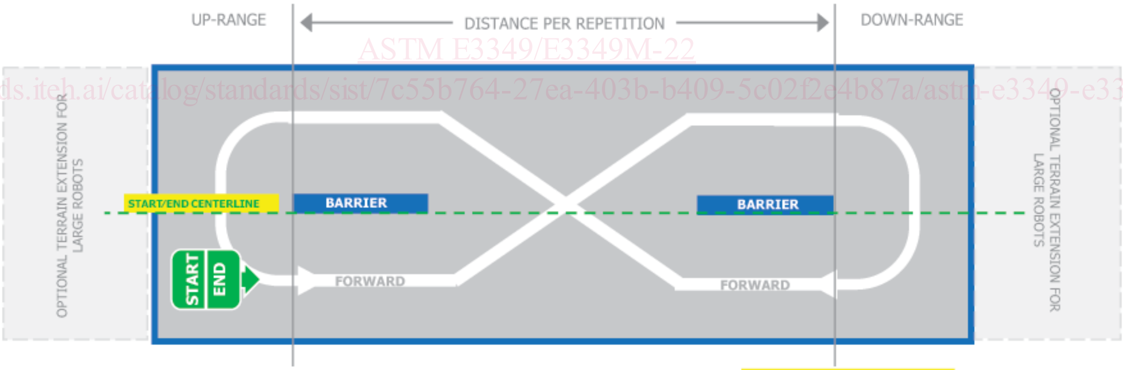


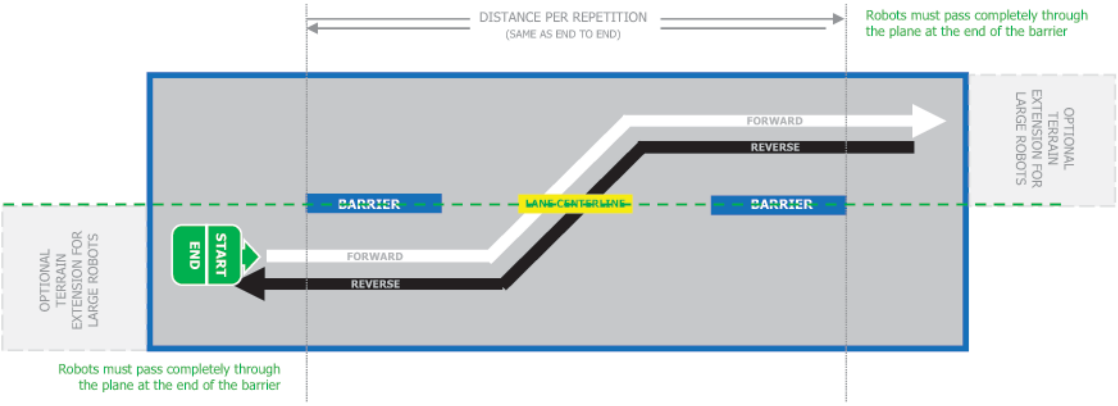
Figure-8 repetitions start and end when any part of the robot crosses the START/END CENTERLINE and approximately follows the white path. Returning to the start position completes one repetition. The distance traversed is measured from the outer edges of both barriers. (Note: The start point can be at either end of the apparatus.)

FIG. 2 Top View showing the Figure-8 Path (forward) Defined by the Barriers

cross-over slope element is added to the center area of the terrain which positions two portions of terrain on adjacent slopes of 15° in opposite directions (see Fig. 4). When this configuration is used, only the zig-zag path can be used.

4.7 Test trials shall produce enough successful repetitions to demonstrate the reliability of the system capability or the remote operator proficiency to the desired level of statistical significance (see Section 9). A complete trial of 10 to 30 repetitions in either one of the defined paths should take 10 to 30 min to complete. When measuring system capabilities, it is important to allow enough time to capture a complete trial with an expert operator. When measuring operator proficiency, it is important to limit the time of the trial so that novice and expert operators are similarly fatigued.

4.8 There are three metrics to consider when calculating the results of a test trial. They should be considered in the



Zig-Zag repetitions start and end when any part of the robot crosses the LANE CENTERLINE between the barriers. Each repetition completes alternating forward and reverse turns past the ends of the barriers. The distance traversed is measured from the center of the apparatus to the end of the barriers and back to the center. The traversal length of the robot beyond the barriers is disregarded because of various size robots.

FIG. 3 Top View showing the Zig-Zag Path (forward/reverse) Defined by the Barriers

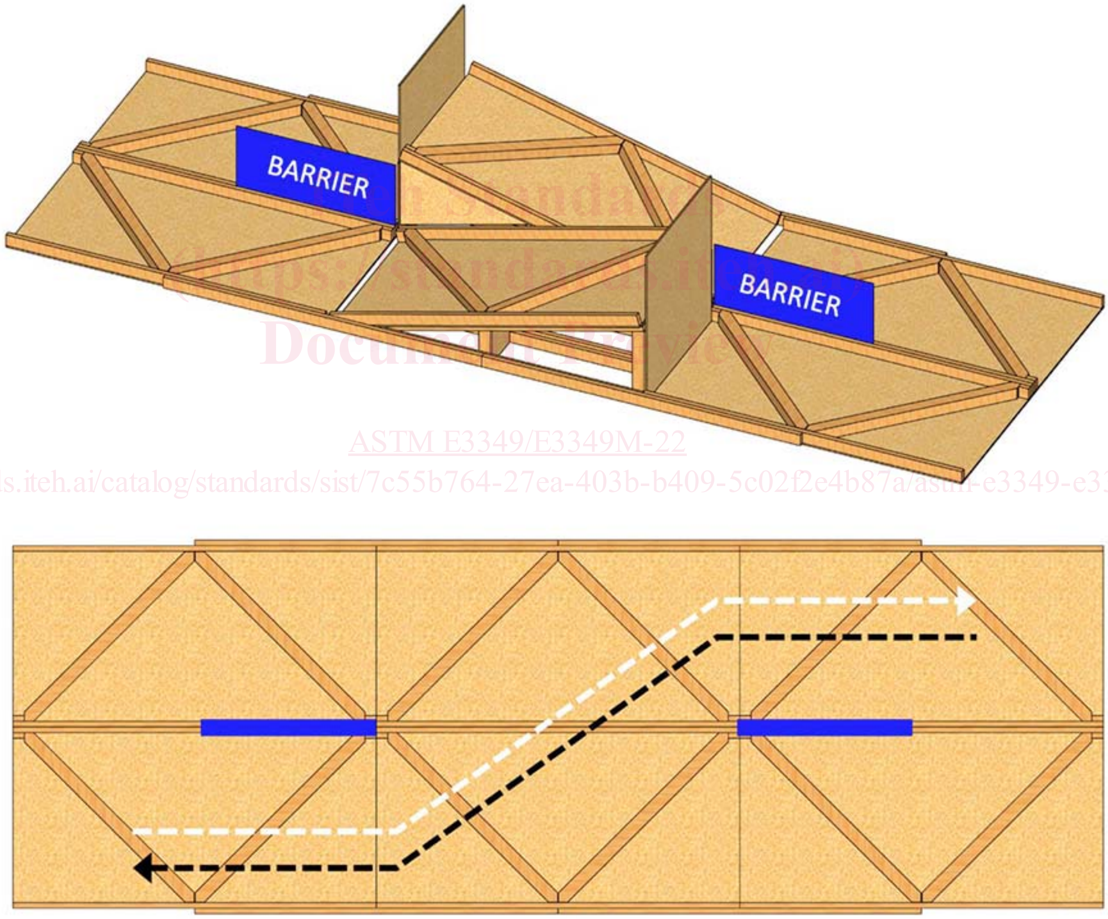


FIG. 4 The K-rail Terrain Apparatus in the Cross-over Slope Configuration

following order of importance: completeness score, reliability, and efficiency. The results from the figure-8 path (forward) and the zig-zag path (forward/reverse) are not comparable because they measure different capabilities. Similarly, the results from the cross-over slope apparatus configuration are not comparable to results from the apparatus in its default flat configuration with the zig-zag path. The results from different scales of test apparatus are also not comparable because they represent different clearances and distances (Fig. 5).

5. Significance and Use

5.1 This test method is part of an overall suite of related test methods that provide repeatable measures of robotic system mobility and remote operator proficiency. This k-rail terrain

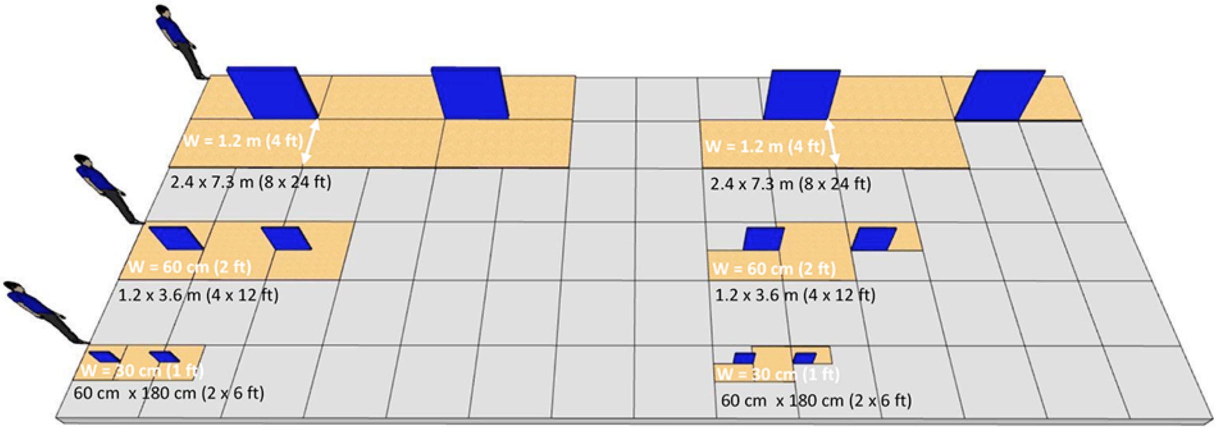


FIG. 5 Both Paths are Scalable to Represent Different Environments

specifically challenges robotic system locomotion, suspension systems to maintain traction, rollover tendencies, self-righting in complex terrain (if necessary), chassis shape variability (if available), and remote situational awareness by the operator. As such, it can be used to represent modest to challenging (when the cross-over slope configuration is used) outdoor terrain complexity or indoor debris within confined areas.

5.2 The overall size of the terrain apparatus can vary to provide different constraints depending on the typical obstacle spacing of the intended deployment environment. For example, the terrain with containment walls can be sized to represent repeatable complexity within bus, train, or plane aisles; dwellings with hallways and doorways; relatively open parking lots with spaces between cars; or unobstructed terrains.

5.3 The test apparatuses are low cost and easy to fabricate so they can be widely replicated. The procedure is also simple to conduct. This eases comparisons across various testing locations and dates to determine best-in-class systems and operators.

5.4 *Evaluation*—This test method can be used in a controlled environment to measure baseline capabilities. It can also be embedded into operational training scenarios to measure degradation due to uncontrolled variables in lighting, weather, radio communications, GPS accuracy, etc.

5.5 *Procurement*—This test method can be used to identify inherent capability trade-offs in systems, make informed purchasing decisions, and verify performance during acceptance testing. This aligns requirement specifications and user expectations with existing capability limits.

5.6 *Training*—This test method can be used to focus operator training as a repeatable practice task or as an embedded task within training scenarios. The resulting measures of remote operator proficiency enable tracking of perishable skills over time, along with comparisons of performance across squads, regions, or national averages.

5.7 *Innovation*—This test method can be used to inspire technical innovation, demonstrate break-through capabilities, and measure the reliability of systems performing specific tasks within an overall mission sequence. Combining or sequencing multiple test methods can guide manufacturers toward implementing the combinations of capabilities necessary to perform essential mission tasks.

6. Apparatus

6.1 The apparatus consists of diagonal rails set into subfloors to form the terrain, barriers to define the robot path, an optional containment structure, and an optional set of cross-over slope stands. The main apparatus dimension to consider is the apparatus clearance width (W) for the robot, which can be set to 240 cm [96 in.] with ±2.5 cm [1 in.] tolerance, 120 cm [48 in.] with ±2.5 cm [1 in.] tolerance, 60 cm [24 in.] with ±1.3 cm [0.5 in.] tolerance, or 30 cm [12 in.] with ±1.3 cm [0.5 in.] tolerance. The dimension chosen for W should represent the intended deployment environment or be based on the size of the robot (that is, the robot shall be able to maneuver within the selected dimensions of the apparatus), or both. All apparatus dimensions scale proportionally with W; the overall width of the terrain lane is 2W, the overall length of the terrain lane is at least 6W, and the length of the barriers is 1W. The diagonal rail height (H) also scales with W; see Table 1 and Fig. 6. The overall length of the terrain lane can be made longer to accommodate larger robots that need more space to maneuver around the barriers while staying on the terrain. When choosing a specific apparatus clearance width, note that the resulting data is not comparable to other apparatuses with different clearance widths.

6.2 *K-rail Terrain Panel*—The k-rail terrain panel consists of a subfloor and two diagonal rails. Each subfloor is 2W by 1W. The subfloor's surface is constructed of OSB or similar material with dimensional lumber along the edges measuring

TABLE 1 Corresponding Height of the Diagonal Rail when Used in Different Apparatus Clearance Widths

Apparatus Clearance Width (W)	Nominal Height (H) of the Diagonal Rail using Dimensional Lumber
240 cm [96 in.]	20 cm [8 in.]
120 cm [48 in.]	10 cm [4 in.]
60 cm [24 in.]	5 cm [2 in.]
30 cm [12 in.]	2.5 cm [1 in.]

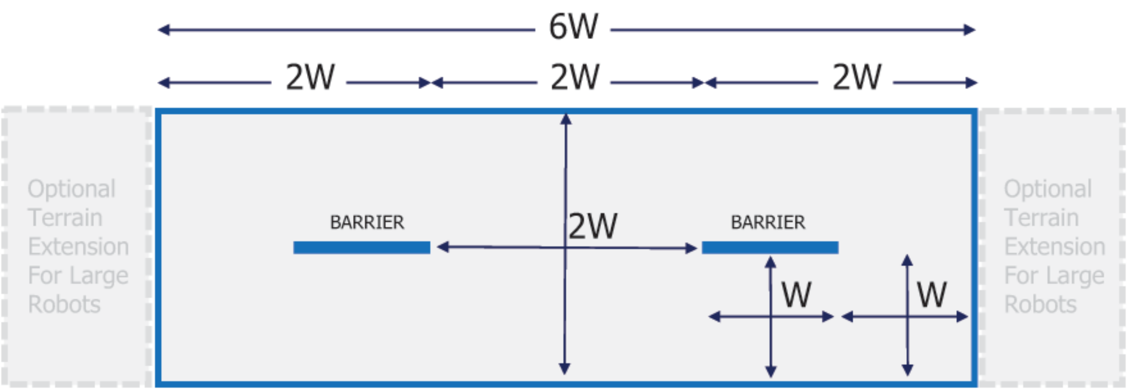


FIG. 6 Top View of a Test Apparatus showing Dimensions Scale Proportionally to the Apparatus Clearance Width (W)

2W. On top of each subfloor are two diagonal rails made of dimensional lumber which fit into the subfloor at 45°. The height of the diagonal rail (H) scales with the apparatus clearance width (W); see Table 1. Two additional blocks of dimensional lumber are attached to the inside of the subfloor and hold the diagonal rails in place. When two k-rail terrain panels are adjacent to one another along the longest edge, they must be oriented opposite of each other such that the diagonal rails form a diamond shape. Additional dimensional lumber can be used on the outside of the apparatus to connect two k-rail terrain panels together, to secure them in place. See Fig. 7.

6.3 *Barriers to Define the Robot Path*—The barriers placed within the terrain must provide visual guidance for the remote robot operator to correctly traverse the defined figure-8 path (forward) or zig-zag path (forward/reverse). The barrier can be made from any solid or porous material that provides visual guidance. They should be sturdy and easily repaired or replaced after contact with the robot. The barrier's overall thickness shall be less than 0.05W and the length shall equal 1W. See Fig. 8.

6.4 *Cross-Over Slope*—The cross-over slope apparatus configuration (see Fig. 9) is implemented by disconnecting the two center k-rail terrain panels from the rest of the apparatus, lifting up one side of each panel, and positioning three cross-over slope stands underneath each panel (see Fig. 10 and Fig. 11). There will be a slight gap between the flat terrain panel and the incline terrain panel when raised. This may be filled with a filler strip of OSB if the test sponsor deems it necessary. The terrain panels are secured to the stands underneath them and the stands are secured to the border of the apparatus.

6.5 *Containment Structure*—While a containment structure is not necessary, one can be used to provide further operational relevance for confined environments. Walls can be fabricated to contain the robot as well as the terrain. It can also provide a safety barrier for nearby personnel within a test facility. The fabricated wood walls are typically supported with arches over the top. Shipping containers can also enclose test methods and turn a parking lot into a test facility. Apparatuses with clearance width W = 120 cm [4 ft] can be slightly undersized to fit into a standard shipping container, which has an interior width that is less than 240 cm [8 ft]. The container walls should be lined with wood panels to cover the corrugated steel and have enough thickness to fill any gaps between the wall and the terrain. See Fig. 12.

6.6 *Other Devices*—A timer is used to measure the elapsed time of the trial. It provides a deterministic indication of trial start and end times to minimize uncertainty. It can count-up or count-down but should have a settable duration in minutes. A stopwatch can also be used. A light meter is necessary to ensure the environment is considered lighted (>150 lx) or dark (<0.1 lx). A thermometer is necessary to measure the temperature of the environment.

7. Hazards

7.1 Functional emergency stop systems are essential for safe remote or autonomous robot operation. The emergency stop on the operator control unit shall be clearly marked and accessible. The emergency stop on the robot chassis, if available, should also be marked. All personnel involved in testing shall familiarize themselves with the locations of all emergency stops prior to conducting trials.

7.2 Emergency stop systems shall be engaged prior to approaching a remotely operated robot. Constant communication is essential between the robot and the operator until the robot is safely within the test apparatus and people are either outside the apparatus or at a safe distance. The remote operator may not be aware that someone is interacting with the robot when they start to drive, actuate a manipulator, or move the robot in some other way. Avoid standing directly in front of the robot, behind the robot, or within reach of the manipulator arm unless the robot is completely deactivated.

7.3 Safety equipment, such as a belay, shall be used from a safe distance to prevent robot damage if necessary. Intervention by hand to try to stop a robot from falling or flipping over is to be prohibited. The belay shall be required for this. Any interaction with the robot, including tightening the belay to save the robot, is considered a fault for scoring purposes.

7.4 Test apparatuses that are intended to challenge robot mobility can be complex and unstable for humans. Proper footwear and other personal protective equipment shall be worn to mitigate risk. Caution is required when attending to a robot or carrying equipment within the apparatus.

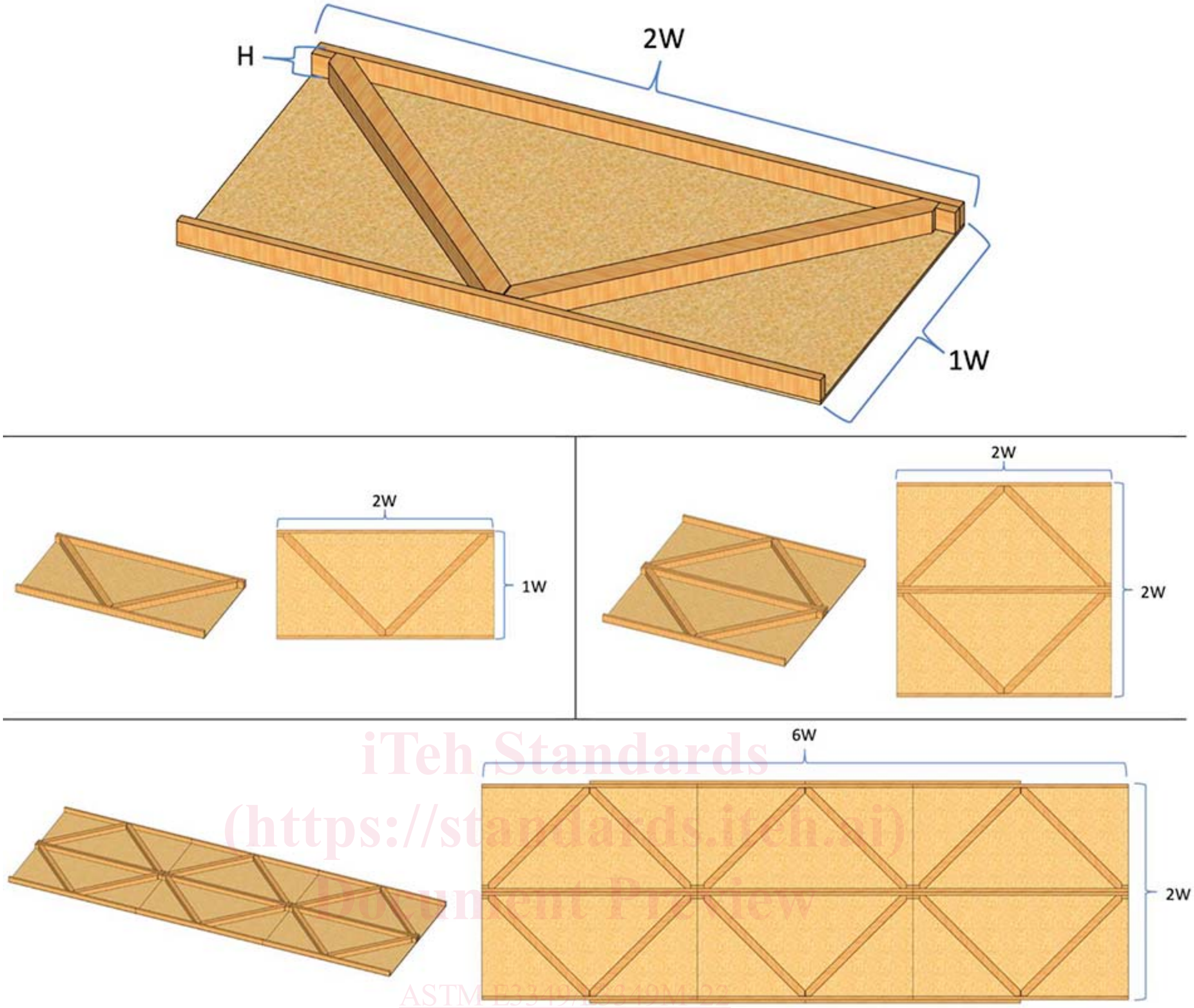


FIG. 7 Top: Dimensions of the K-rail Terrain Panel
Middle: Dimensions of One and Two Adjacent K-rail Terrain Panels
Bottom: Dimensions of Six Adjacent K-rail Terrain Panels

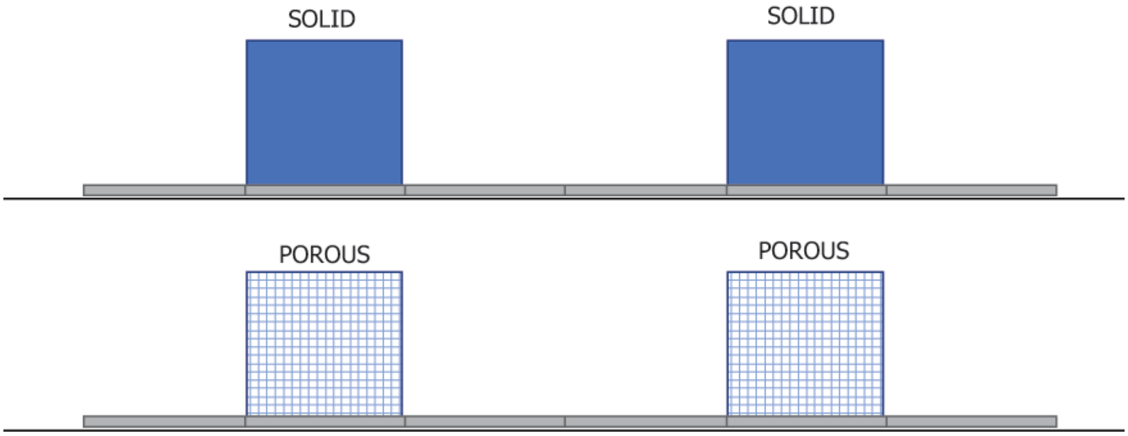


FIG. 8 Side View showing Various Barriers

8. Procedure

8.1 *Identify the Robot Configuration*—The robotic system configuration being tested shall be identified and uniquely named (for example, make, model, configuration), including all subsystems and components with their respective features and functionalities. The configuration of the robotic system should