Designation: E3380/E3380M − 23

Standard Test Method for Evaluating Ground Response Robot Endurance Using Reproducible Terrains[1]

This standard is issued under the fixed designation E3380/E3380M; 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, endurance, communications, durability, proficiency, autonomy, and logistics.

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 mission endurance of a robot while traversing complex terrains in the form of continuous pitch/roll ramps or other standard terrains in the terrain suite. This test method is one of several ground robot 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 (SI Units) and U.S. Customary Units (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. The differences between the stated dimensions in each system of units are insignificant for the purposes 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.*

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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.

Current edition approved April 1, 2023. Published April 2023. DOI: 10.1520/E3380_E3380M-23.

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

E2592 Practice for Evaluating Response Robot Capabilities: Logistics: Packaging for Urban Search and Rescue Task Force Equipment Caches

E2826/E2826M Test Method for Evaluating Response Robot Mobility Using Continuous Pitch/Roll Ramp Terrains

E2827/E2827M Test Method for Evaluating Response Robot Mobility Using Crossing Pitch/Roll Ramp Terrains

E2828/E2828M Test Method for Evaluating Response Robot Mobility Using Symmetric Stepfields Terrains

E2991/E2991M Test Method for Evaluating Response Robot Mobility: Traverse Gravel Terrain

E2992/E2992M Test Method for Evaluating Response Robot Mobility: Traverse Sand Terrain

E3349/E3349M Test Method for Evaluating Ground Robot Capabilities and Remote Operator Proficiency: Terrains: K-Rails

2.2 *Other Document:*

NIST Special Publication 1011-I-3.0 Autonomy levels for unmanned systems (ALFUS) Framework Volume I: Terminology[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; or

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 *quarter-ramp terrain element, n*—inclined surface of 15° with square dimensions as projected onto the ground plane equal to ¼ the overall width of the test lane.

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 turning on uneven surfaces 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 continuous ramp 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.

4.5 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 returns to the starting point after crossing the plane at the end of the barrier without a fault after approximately following the white and black paths.

4.6 The terrain may be extended to create a larger turning area for the figure-8 path and more room to fit past the plane at the end of the barrier in the zig-zag path (see Fig. 2 and Fig. 3). The distance per repetition remains the distance between the outer edges of the barriers (see Section 6) regardless of the actual distance traveled.

4.7 *Potential Faults Include:*

4.7.1 Any contact by the robot with the apparatus (that is, walls or barriers) that requires adjustment or repair to return the apparatus to the initial condition;

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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.

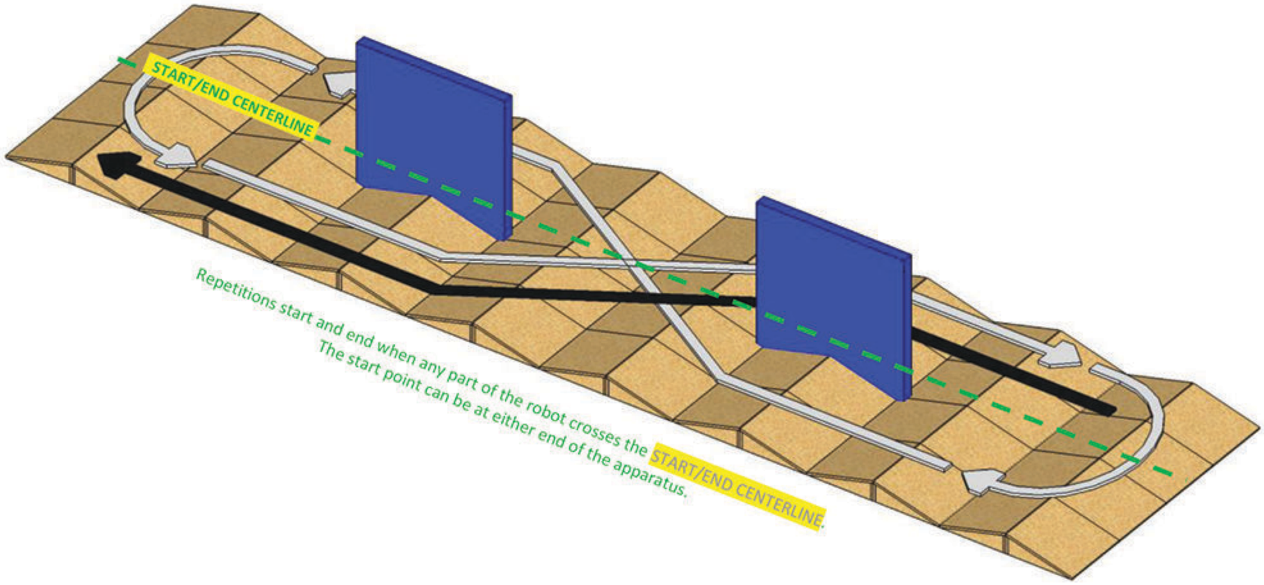


FIG. 1 Overview of the Continuous Pitch/roll Ramp Terrain Apparatus

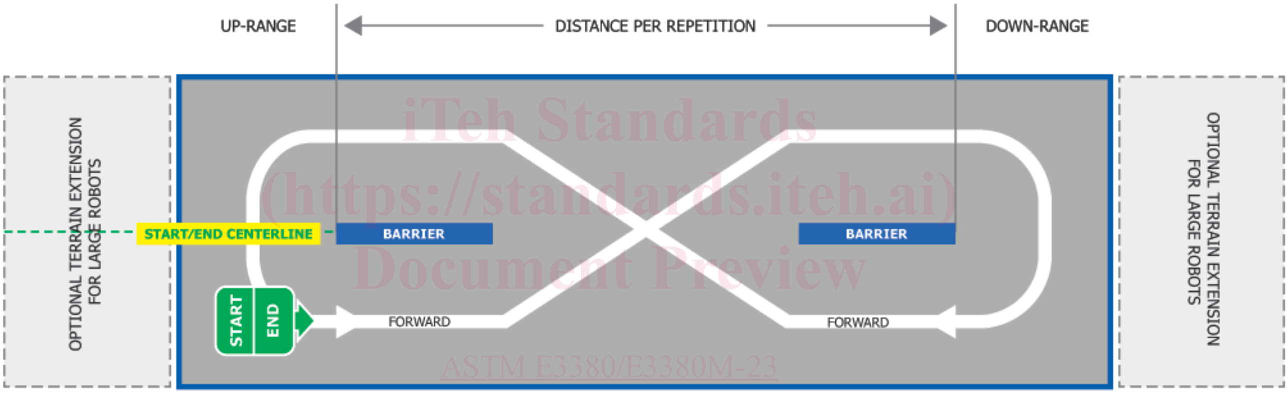


Figure-8 repetitions start and end when any part of the robot crosses the START/END CENTERLINE and approximately follows the white path. Returning to the start position completes one repetition. The distance traversed is measured from the outer edges of both barriers. (Note: The start point can be at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

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

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

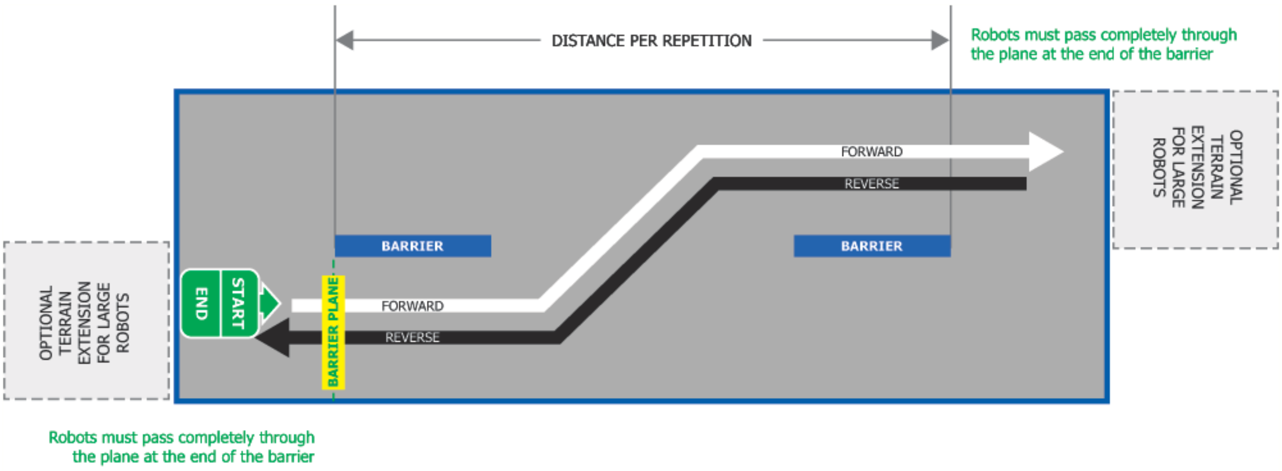
4.7.3 Leaving the apparatus during the trial.

4.8 The endurance test is unique in that a complete test running until exhaustion of the energy source on the robot is required to calculate the performance metrics of distance traveled and runtime. During the test, the higher the ratio of successful repetitions to faults, the more reliable the system or operator, or both. At least 90 % of the attempted repetitions in an endurance test should be successful to consider the performance metrics as valid measurements of endurance. The time required to complete each series of ten laps is an indicator of operator performance. If the operator is consistently driving the robot around the track, the time for each ten-lap segment should be very similar. This is also an indication that the energy required for each ten lap segment is similar. Inexperienced operators often have erratic ten-lap segment times which could affect the validity of the performance metrics.

4.9 There are three metrics to consider when calculating the results of a test trial. They should be considered in the following order of importance: distance traveled, runtime, 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. The results from different scales of test apparatus are also not comparable because they represent different clearances and distances.

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. The operational



Zig-Zag repetitions start and end when any part of the robot crosses the BARRIER PLANE and approximately follows the white and black paths. Each repetition completes alternating forward and reverse turns past the ends of the barriers. The distance traversed is measured from the outer edges of both barriers. The traversal length of the robot beyond the barriers is disregarded because of various size robots. (Note: The start point can be at either end of the apparatus.)

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

endurance of a ground robot significantly impacts the performance of the robot during a variety of tasks. Robot endurance is a complex function of robot design, control scheme design, and energy storage selection. This test method evaluates the endurance of a robot through continuous operation on a complex surface. The continuous pitch/roll ramp terrain chosen for endurance testing 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 outdoor terrain complexity or indoor debris within confined areas. The endurance test standard provides a method in which the operational endurance of a large variety of robot sizes and locomotion system designs may be compared. The test provides both a measure of the endurance of the robot and a measure of the reliability of the robot when operating continuously for extended periods of time on complex terrains.

5.2 The scale 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. The endurance test apparatus 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 required to perform this test method consists of an operational terrain type, barriers to define the robot path, an optional containment structure, and a timer. The main apparatus dimension to consider is the apparatus clearance width (W) for the robot, which can be set to 240 cm ± 2.5 cm tolerance [96 in. ± 1 in. tolerance], 120 cm ± 2.5 cm tolerance [8 in. ± 1 in. tolerance], 60 cm ± 1.3 cm tolerance [24 in. ± 0.5 in. tolerance], or 30 cm ± 1.3 cm tolerance [12 in. ± 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, the length of the barriers is 1W, and the distance is 2W between the barriers. It can be longer for larger robots needing more space to maneuver around the barriers while staying on the terrain. When choosing a specific minimum clearance width for the apparatus, note the resulting data is not comparable to other apparatuses with different minimum clearance widths.

6.2 *Pitch/Roll Ramp Terrain*—The primary terrain type for endurance testing is the 15° continuous pitch/roll ramp terrain. The continuous pitch/roll ramp terrain is an array of individual ramps that form peaks and valleys with no discontinuities greater than 0.05W. Each ramp is fabricated to fit a square dimension on the ground so it can be rotated in place to form more difficult terrains. The square ground dimension is set to half the minimum clearance width (½ W) so apparatuses at every scale have a maximum gap (no greater than 0.05W) between ramps along the centerline of the lane to accommodate the width of the barriers (see Fig. 6). The ramp surface can be made of oriented strand board (OSB), plywood, or similar material to provide a relatively consistent low-friction surface. The supporting structure can be fabricated from lumber posts and OSB panels. Each ramp is fabricated to fit a square dimension on the ground for interchangeability, so the 15° ramp surface is slightly longer than ½ W in the uphill dimension. The width remains ½ W. Four lumber posts cut with 15° tops provide support for the ramp surface and connect the three side panels that provide additional support and enclose the bottom. More information on the continuous pitch/roll ramp terrain can be found in Test Method E2826/E2826M.

6.2.1 *Additional Terrain Types*—While the continuous pitch/roll ramp terrain is the primary terrain type for endurance testing, other terrain types may be chosen to evaluate endurance under different operating conditions. Endurance test results from different terrain types cannot be compared. Additional terrains that may be chosen for endurance testing are:

6.2.1.1 *Crossing Pitch/Roll Ramps*—Test Method E2827/E2827M;

6.2.1.2 *Symmetric Stepfields*—Test Method E2828/E2828M;

6.2.1.3 *Gravel Terrain*—Test Method E2991/E2991M;

6.2.1.4 *Sand Terrain*—Test Method E2992/E2992M; and

6.2.1.5 *K-Rails*—Test Method E3349/E3349M.

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 in case of contact with the robot. The barrier's overall thickness shall be less than 0.05W and the length shall equal 1W.

6.4 *Containment Structure*—While a containment structure is not necessary, it may be used as an additional safety measure. 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, if necessary. The array of individual pitch/roll ramps need to be contained so they do not move relative to one another (see Fig. 8). The minimum containment is an underlayment with an affixed lumber border. Ramps should not be attached to each other for reconfigurability. *Regardless of which containment structure method is used, the robot shall not exit the volume of the apparatus without inducing a fault.*

6.5 *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. A stopwatch can also be used. A light meter is necessary if testing in lighted and

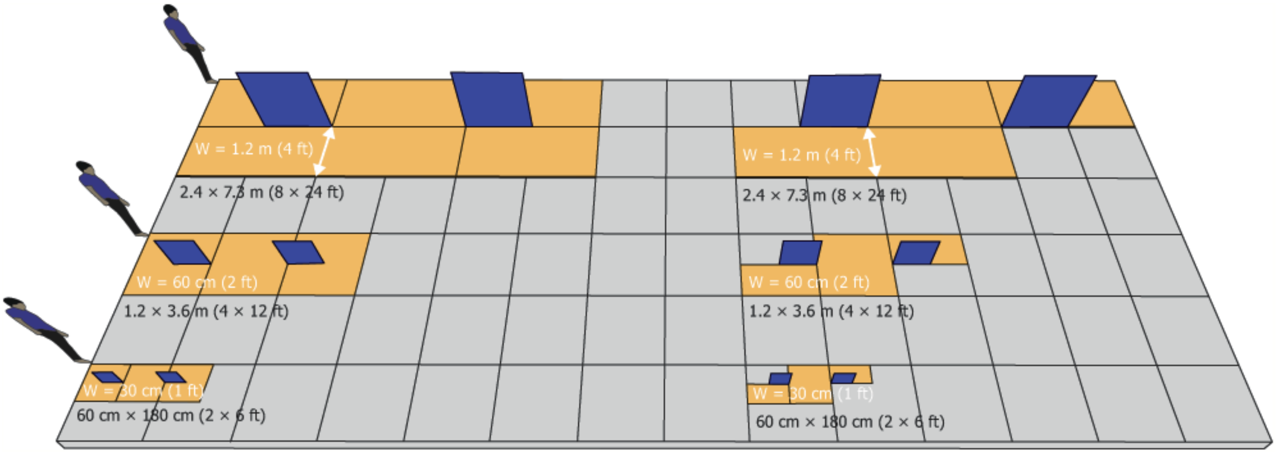


FIG. 4 Both Paths are Scalable to Represent Different Environments

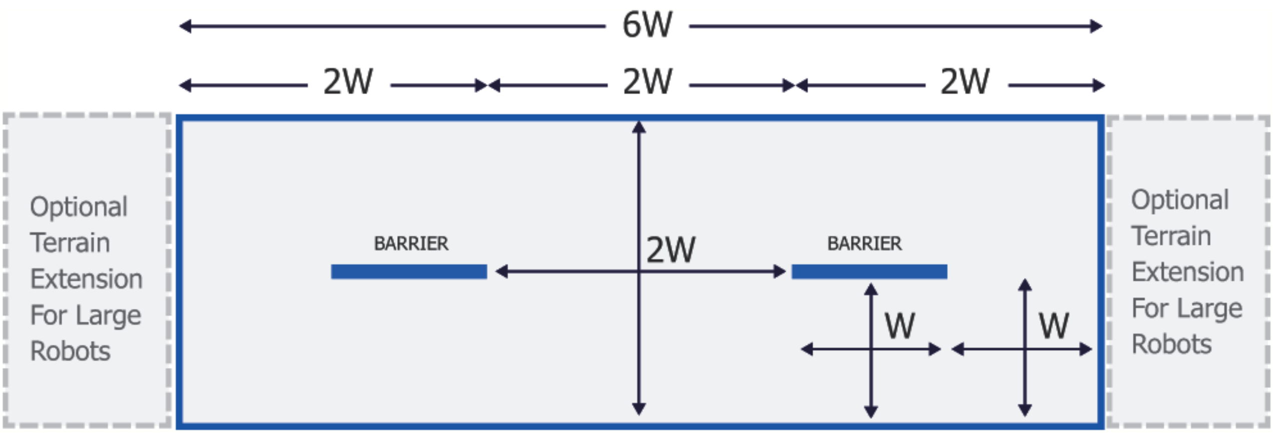


FIG. 5 Top View of a Test Apparatus showing Dimensions Scale Proportionally to the Minimum Clearance Width (W)

dark environments. A lighted environment is considered >150 lx and dark environment is considered <0.1 lx.

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 tending to a robot or carrying equipment within the apparatus.

7.5 Tests that are intended to challenge the endurance of the robot's battery may increase the probability of malfunction, including unpredictable movements of the robot and its manipulator.

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 be representative of a configuration that will be used in its intended application. A given robotic system may have several different configurations. Any number of configurations can be subjected to testing. The system configuration shall remain the same for all relevant tests to enable direct comparison of performance and to identify trade-offs between different configurations. In general, robotic system configurations shall maintain their overall cubic volume, weight, and center of gravity, as well as major sub-systems such as tracks, wheels, legs, manipulator, radio communications, tether, operator control unit, etc. Software settings and versions on the robot may affect the results of the endurance test, therefore they should be noted. If the robot configuration is changed during a trial, the trial is considered invalid and the new configuration shall be re-tested. Documentation should include detailed photographs of all of the above as well as videos of routine maintenance tasks such as a track change, battery change, etc. Additional components can be described as necessary, including:

8.1.1 Weights and measurements of all containers as-shipped or ready for deployment;

8.1.2 List of sustainment items such as batteries, chargers, and consumables;

8.1.3 List of maintenance items such as tools and spare parts;

8.1.4 Optional payloads;

8.1.5 *Energy Source*—Information about the energy source on the robot should be documented when available. For example, if a robot is powered by batteries, this documentation would include if the batteries are new or used, battery serial numbers, date of manufacture, make and model, and time in service; or

8.1.6 *Software Settings*—Software settings on the robot may affect the results of the endurance test. For example, changing the maximum speed of the robot may increase the number of repetitions completed and decrease the runtime. Software settings that may affect endurance should be documented and not changed during the endurance test.

8.1.7 More information on robot configuration can be found in Practice E2592.

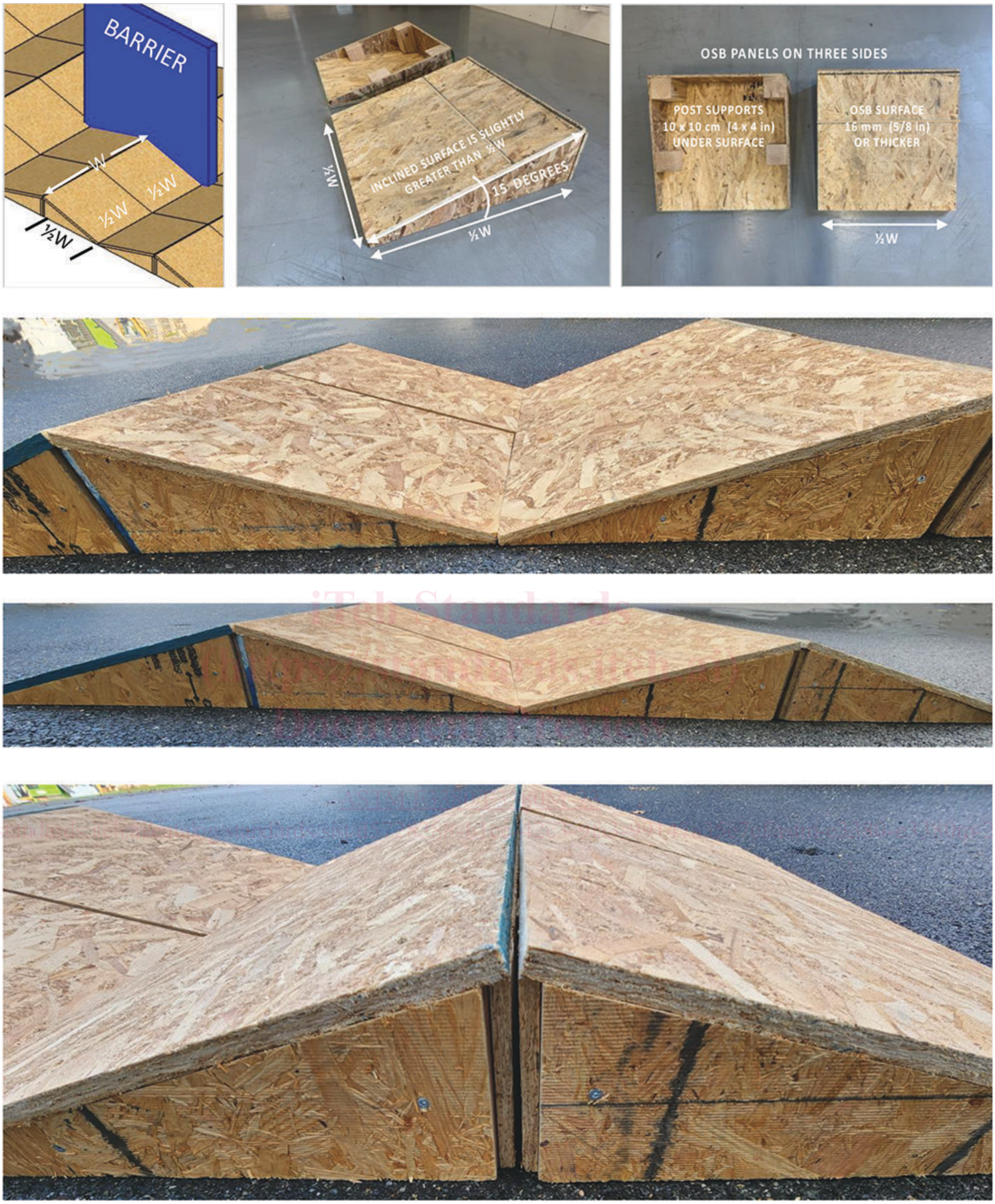


FIG. 6 Details of a Pitch/roll Ramp

8.2 *Prepare the Apparatus*—Ensure that the apparatus and environmental conditions are prepared properly.

8.2.1 The scale of the apparatus with clearance width reflects the intended deployment environment.

8.2.2 The level of difficulty (that is, chosen terrain) of the apparatus is appropriate for the capability of the robot or the operational requirements.