Stepfield Pallets: Repeatable Terrain for Evaluating Robot Mobility

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ABSTRACT

Stepfield pallets are a fabricated and repeatable terrain for evaluating robot mobility. They were developed to provide emergency responders and robot developers a common mobility challenge that could be easily replicated to capture statistically significant robot performance data. Stepfield pallets have provided robot mobility challenges for the international RoboCupRescue Robot League competitions since 2005 and have proliferated widely for qualification and practice. They are currently being proposed as a standard test apparatus to evaluate robot mobility. This paper describes the origin and design of stepfield pallets, and discusses their use in several proposed standard test methods for response robots.

Keywords

Stepfield, step field, robot mobility, robot test method, broken terrain, rough terrain, artificial rubble, urban search and rescue, RoboCupRescue.

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) is developing standard test methods for emergency response robots as part of an ongoing effort sponsored by the Department of Homeland Security and the National Institute of Justice. A series of workshops with subject matter experts from urban search and rescue (US&R) task forces and other emergency response organizations defined thirteen robot categories and over a hundred specific robot performance requirements [1, 2]. Many of these requirements address robot mobility in complex terrains, which necessitated repeatable test methods to capture statistically significant robot performance data. Our approach toward developing mobility test methods has relied upon well-defined apparatuses to differentiate robot capabilities, and typically use the time to negotiate a specified obstacle or path, or the total distance traversed, to measure performance. These mobility tests are always conducted with a remote operator station, out of sight and sound of the robot but within communications range, to emphasize the overall system performance.

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Stepfield pallets were developed to represent complex terrain or rubble that is describable, reproducible, and repeatable for robot testing. Each pallet consists of a grid of square wood posts cut to assorted cubic unit lengths (a unit is the actual post width when using metric dimensional lumber) and assembled into either symmetric or random topographies tending toward flat, perpendicular hill, or diagonal hill patterns. Multiple stepfield pallets have been assembled into configurations such as the stepfield “dash,” a sequential series of five specific pallets in a straight line that has proliferated widely for qualification in the international RoboCupRescue Robot League competitions [3]. A stepfield “figure-8” has also been fabricated using thirteen stepfield pallets and surrounding walls to provide a well-defined continuous path with turns for robot endurance tests. Dozens of stepfield pallets have been configured into a “field” apparatus that allows unconstrained negotiation of stepfield terrain features. Robot developers and purchasers can replicate these common configurations to compare robot performance, improve designs, and support operator training.

2. BIOLOGICALLY INSPIRED TESTS

The concept of using stepfield pallets to evaluate robot mobility in rough terrain derived from researchers investigating biologically inspired mechanisms and control systems. Researchers at the PolyPEDAL Laboratory at the University of California at Berkeley who evaluated cockroaches as effective legged mobility systems noted that they appeared to negotiate relatively rough terrain for their size with almost no loss in speed when compared to negotiation of flat surfaces [4]. They constructed terrain approximating a fractal surface consisting of 1 cm (0.4 in) posts of random height with a variance of 0.5 cm (0.2 in), the height of the insect’s center of mass. Extremes of height and depth of the terrain surface reached three times the height of the insect’s center of mass (see Figure 1A). Researchers in the Biomimetics Robotics Laboratory at Stanford University built a 16 cm (6 in) hexapod robot that emulated the movement of cockroaches. They used strips of wood equal to the robot’s “hip” height as obstacles along the robot’s path (see Figure 1B) [5].

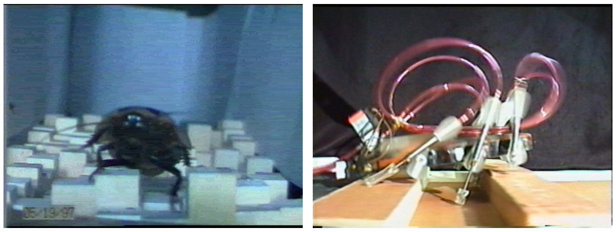

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Figure 1: A) A cockroach running over a fabricated fractal surface at the University of California – Berkeley. (Photo courtesy of Full et al.) B) A 16 cm (≈ 6 in) long hexapedal robot named Sprawlita modeled after cockroach mobility being tested on hip-height obstacles at Stanford University. (Photo courtesy of Clark et al.) C & D) A 53 cm (≈ 21 in) long hexapedal robot named RHex, with 17.5 cm (≈ 7 in) legs, being tested on a scaled up experimental "broken terrain" made of wood posts at the University of Michigan and McGill University. (Photos courtesy of Saranli et al.)

Researchers at the University of Michigan and McGill University scaled up these experimental terrains using an array of wood posts cut to various lengths to test their RHex hexapedal robot, which itself was inspired from the research noted above [6]. They performed extensive mobility experiments in this "broken terrain" and others in an effort to quantify their robot's mobility. Their experimental terrain used clusters of four posts of similar heights ranging from 10 cm (≈ 4 in) to 30 cm (≈ 12 in) with random height variations up to approximately 20 cm (8 in).

Stepfield pallets essentially combine the ideas noted above to form uneven terrains with elevated ridges as obstacles rising to heights roughly relative to the robot dimensions. Several inexpensive materials were considered before choosing the same simple wood posts used by Saranli et al. to form the square flat surfaces. Wood posts provide ruggedness and reasonable cost, thought they limit the scale of the discretized surfaces to typically available post sizes. However, they are easily fabricated and inexpensive enough to allow researchers and emergency responders to assemble many stepfield pallets into large test apparatuses for practice, evaluation, and training.

Three different scales of pallets provide proportional testing for a variety of robot sizes (see Figure 2). Given that emergency response robots can be wheeled, tracked, or legged, stepfield pallet sizes and the associated ridge heights are more generally correlated to overall robot dimensions rather than to "hip" height, axle height, or other single dimension. To be appropriately proportional to the stepfield terrain, a given robot's footprint should be no larger than 1/4 to 1/3 the area of a single stepfield pallet.

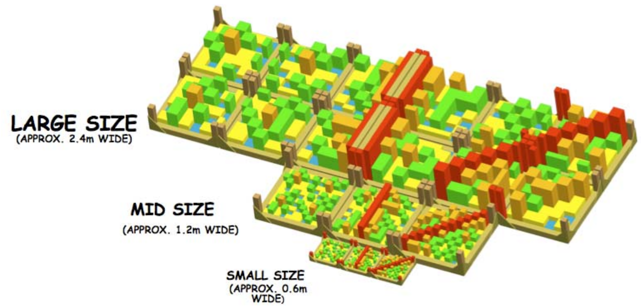

Figure 2: Three different scales of random stepfields for testing different size robots. In each scale, similar pallet topographies are shown using flat, perpendicular hill, and diagonal hill pallets. The hill pallets have posts that randomly tend toward the elevated ridges (shown in red) while following a few rules for continuity.

3. STEPFIELD PALLET FABRICATION

Stepfield pallets are fabricated with a 10x10 grid of square wood posts standing on end to form the terrain with a containment perimeter on all sides made of similar wood post material. The pallet base is made from oriented strand board (OSB) plywood with a thickness of at least 16 mm (≈ 0.675 in) to support the weight of the stepfield when lifted. The containment perimeter is fastened to the plywood base using screws, but the interior grid of cut posts are free to jostle against one another and can be removed and reconfigured as necessary. Blocks can be fastened underneath the plywood base to allow forklift access for easier reconfiguration of test apparatuses made from many stepfield pallets.

The interior posts that form the terrain for each stepfield pallet are cut into four different cubic unit lengths based on defined step heights for each scale of stepfield. Each successive scale increases the step size by a factor of two in length, width, and height. The three different scales of stepfield pallets are described below. Note that each pallet's containment perimeter adds two unit lengths in each direction to the overall assembly:

- Small size stepfield pallets have overall dimensions of 60 cm (≈ 24 in) on a side and are made of a 10x10 grid of 5 cm (≈ 2 in) cubic steps plus a containment perimeter. Each step is made of a single square wood post cut into unit lengths of 5 cm (≈ 2 in), 10 cm (≈ 4 in), 15 cm (≈ 6 in), and 20 cm (≈ 8 in) according to the layouts in Figure 3.

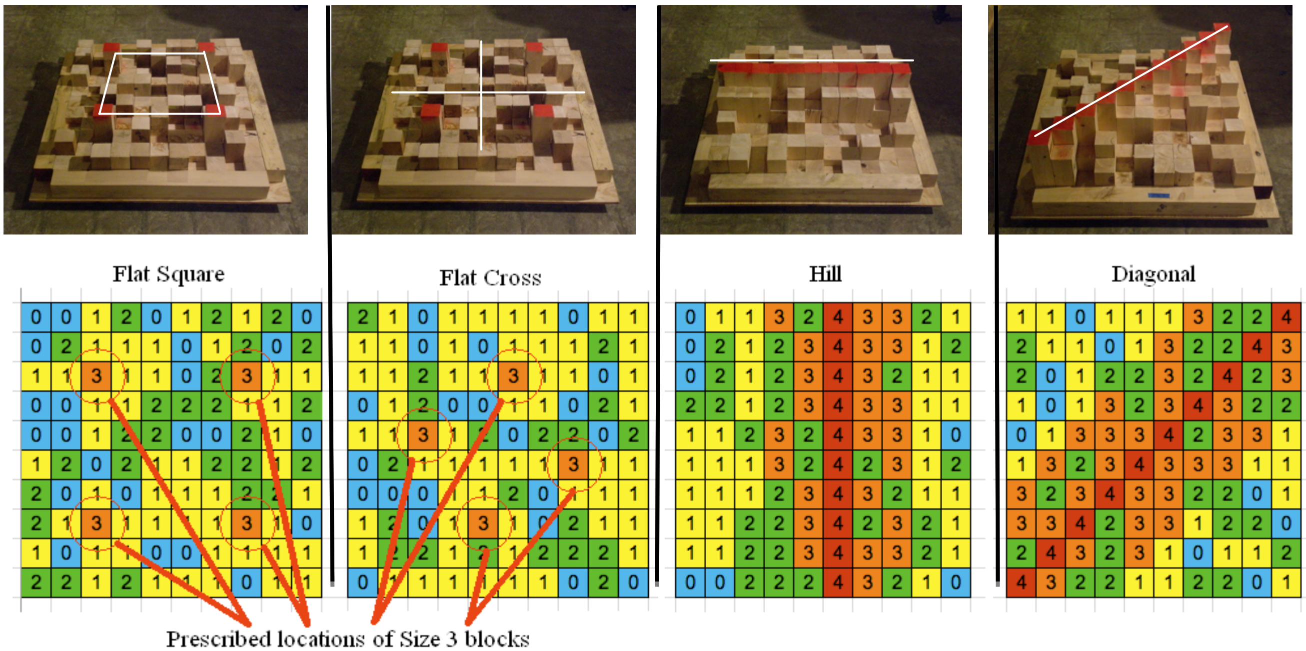

Figure 3: Images and sample designs of random stepfield pallets showing cubic unit post heights. Post heights specified as 0 units are filled with 5 cm (~2 in) posts to maintain grid spacing. (Left-Right) A) Flat square stepfield pallet. B) Flat cross stepfield pallet. C) Perpendicular hill stepfield. D) Diagonal hill stepfield pallet.

- Medium size stepfield pallets have overall dimensions of 120 cm (≈ 48 in) on a side and are made of a 10x10 grid of 10 cm (≈ 4 in) cubic steps. Each step is made of a single square wood post cut into unit lengths of 10 cm (≈ 4 in), 20 cm (≈ 8 in), 30 cm (≈ 12 in), and 40 cm (≈ 16 in) according to the layouts in Figure 3.

- Large size stepfields have overall dimensions of 240 cm (≈ 96 in) on a side and are made of four individual 120 cm (≈ 48 in) pallets with a terrain pattern that spans all four pallets. The terrain is made of a 10x10 grid of 20 cm (≈ 8 in) cubic steps. Each step is made with a cluster of four 10 cm (≈ 4 in) posts cut into unit lengths of 20 cm (≈ 8 in), 40 cm (≈ 16 in), 60 cm (≈ 24 in), and 80 cm (≈ 32 in) according to the layouts in Figure 3.

These dimensions work well with metric wood found in Europe, Asia, and elsewhere. But typical wood posts sizes in the United States are actually ≈ 4 cm (1.5 in) and ≈ 9 cm (3.5 in) square. This reduces the overall dimensions of the stepfield terrains though the ridge elevations can still be cut to the metric dimensions. Non-metric stepfield pallets are good for practice, but the standard apparatus will likely be the metric version.

3.1 Random Pallet Designs

To make random stepfield pallets easy to proliferate, only four different general topographies have been generated: flat square, flat cross, perpendicular hill, and diagonal hill (see Figure 3). Within a given stepfield pallet, the individual post heights are randomly generated using a few rules applied and are shown graphically in the cubic unit lengths mentioned previously. The following rules are used to maintain some continuity in slopes tending toward the elevated ridges:

1. There cannot be a step height difference of more than 2 cubic units between any two adjacent steps.
2. For the two generally flat pallet configurations, there are 4 locations that are 3 cubic units tall. These are the tallest steps on the pallet. The rest of the steps are generated randomly while following rule 1.
3. For the perpendicular hill configurations, the ridge is made of 4 cubic unit step heights and extends across the entire pallet. Two rows on either side of the ridge can range between 2 to 3 cubic units. The remaining rows range between 0 to 2 while following rule 1.
4. For the diagonal hill configurations, the ridge is made of 4 cubic unit step heights and extends across the entire pallet. Three diagonal rows on either side of the ridge can range between 2 to 3 cubic units. The remaining rows range between 0 to 2 while following rule 1.

3.2 Half-Cubic Stepfield Pallets

All of the stepfield pallets discussed so far have been full-cubic stepfields. These are often called red stepfields due to their placement in the RoboCupRescue competition's red arena for advanced mobility. Half-cubic stepfields have also been fabricated which conform to the same general overall dimensions but have half step heights.

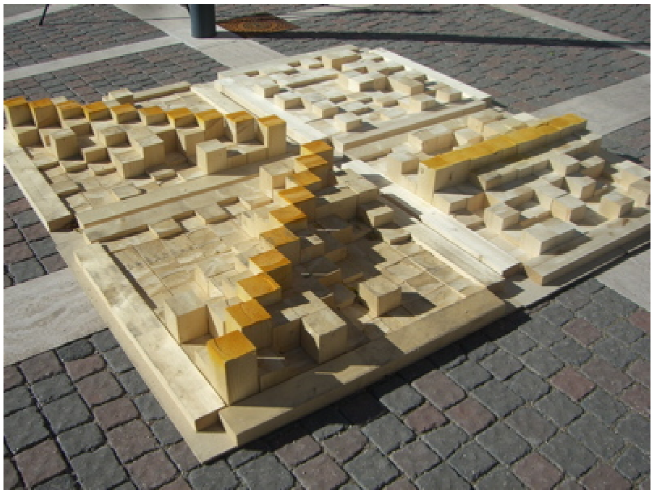

Figure 4: An arrangement of half-cubic (orange) stepfield pallets.

These so-called orange stepfields provide for complexity in robot orientation without challenging mobility for properly scaled robots. They are used to make robotic tasks such as mapping, directed perception, and mobile manipulation more challenging than on simple flat flooring.

4. ROBOT TEST METHODS

A suite of mobility and other test methods for emergency response robots are emerging through the ASTM International standards committee on Homeland Security Applications; Operational Equipment; Robots (E54.08.01) [7]. Stepfields play a prominent role in several of the test methods both to provide challenging and repeatable terrain to evaluate robot mobility and to provide complex flooring for robotic tasks other than mobility. These test methods are always conducted with a remote operator station, out of sight and sound of the robot but within communications range, to emphasize the overall system performance. Several of the test methods that use stepfield pallets are discussed below.

4.1 Stepfield Dash

The Stepfield Dash is a sequential series of five specific pallet types in a straight line: flat square, perpendicular hill, flat cross, diagonal hill, flat square (see Figure 5). It has proliferated widely for qualification in the international RoboCupRescue Robot League competitions, which requires new teams to show a video of the robot traversing this test method along with submission of a team description paper.

The Stepfield Dash was first introduced into the competition arenas at the 2005 German Open. Robots initially had difficulty traversing them but the researchers recognized the challenge. Later that year, at the 2005 RoboCupRescue Championship in Osaka, Japan, several Stepfield Dashes were sequenced together to additionally require turning on pallets. Only a few robots could finish the course. The robot with the fastest time won the best-in-class mobility award. Since then, stepfield pallets have been one of the main mobility challenges in the competition.

Figure 5: A, B) The Stepfield Dash is used for robot qualification for the RoboCupRescue Robot League competitions. C) The 2005 Championship arenas in Osaka, Japan.

4.2 Endurance

The Endurance test method was designed to measure the performance of robots traversing various terrain types within a constrained figure-8 course [8]. The advanced mobility configuration includes a sequential series of stepfield pallets bounded by walls to provide a continuous path with turns (see Figure 6). Robots are timed for average lap speeds and the total numbers of pallets traversed during a single battery cycle.

Figure 6: A) The Endurance test method has one lobe of the figure-8 with perpendicular hill pallets separated by generally flat pallets. B) The other lobe has diagonal hill pallets separated by generally flat pallets. The center path of the figure-8 uses flat pallets (not shown).

4.3 Confined Space
The Confined Space test method is essentially a covered Stepfield Dash (see Figure 7). The tops of the confined spaces are made of inverted stepfield pallets with slight modifications; only the tallest step height posts are used to minimize weight. They are screwed into the OSB plywood base to hold them in place. The minimum gap between the upper and lower stepfield posts can be adjusted in 10 cm (≈ 4 in) increments. Robots are timed to completely traverse the test and the minimum vertical gap is recorded.

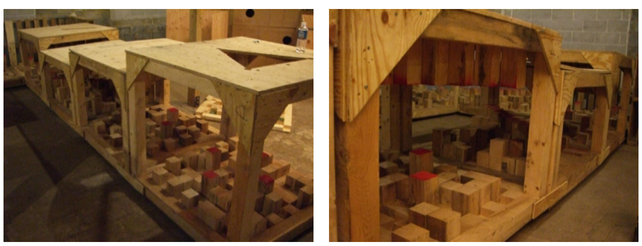

Figure 7: The Confined Space test method uses random stepfield pallets as stalagmites and stalactites.

4.4 Manipulator Test Methods
Half-cubic (orange) stepfield pallets are used as one of three flooring options in the Manipulator Dexerity test methods (see Figure 8).

Figure 8: The Manipulator Dexterity: Perception test method is shown with half-cubic stepfield terrain for added complexity.

The other two flooring options are flat flooring, typically used to capture baseline performance data, and 15 degree pitch/roll ramps to tilt the robot while interacting with the environment. The half-cubic stepfields provide complexity in robot orientation without aggressively challenging mobility.

5. SYMMETRIC STEPFIELDS
All proposed test methods go through a rigorous process to become a standard. One major hurdle is capturing the necessary repeatability data for the test method itself. This requires testing several representative robots for 10 trials each. If the performance range of the proposed test method, or repeatability, produces the same result for a given robot the test method can be considered valid, though it may require a more granular scale. In the case of the random stepfield pallets, the opposite is true. For example, robot performance across multiple stepfield pallets in the Endurance figure-8 with random stepfields can vary widely for each lap. Randomly placed posts on any given stepfield pallet can cause problems for a particular robot's mobility, or for the remote operator's obstacle avoidance capability, even if it can traverse all the other stepfield pallets with relative ease.

A standard test method must also reproduce the same measurable robot performance at different test facilities, which is called reproducibility. A given robot must perform similarly on a particular test method at Facility A, demonstrated by a statistically significant data collection, as it does on the same test method fabricated and tested at Facility B. Although the random stepfield pallets can be replicated with enough precision, particular variants of individual random stepfield pallets have proven inconsistent for some robots. This may ultimately make the standardization of random versions of stepfield pallets difficult to achieve. Nonetheless, they can still provide a good evaluation and training tool for robots prior to deployment.

Symmetric stepfield pallets provide similar mobility obstacles for robots of an appropriate size, but they present the same challenges no matter which direction the robot approaches (see Figure 9). When assembled into a larger test method apparatus, a robot that can traverse a diagonal hill, for example, should always be able to traverse any other diagonal hill pallet, even if it approaches from the opposite direction. Symmetric stepfield pallets were included as mobility obstacles in the 2008 RoboCupRescue Robot League Championship held in Suzhou, China [9]. Over 100 competition missions were conducted, though they do not count toward results regarding test method repeatability since RoboCupRescue teams have other goals and distractions. It appears anecdotally that the symmetric stepfields produce more repeatable robot performance than random stepfield pallets. More testing is required and the designs may evolve, but symmetric stepfields may provide the right balance of rigorous mobility challenges in a repeatable test method apparatus.

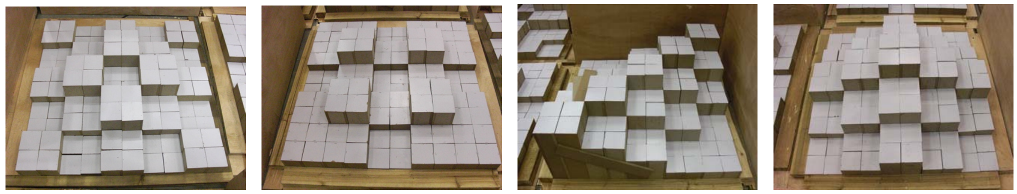

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Figure 9: Symmetric stepfield pallets fabricated in Suzhou, China.
(Left-Right) A) Flat cross pallet. B) Flat square pallet. C) Diagonal hill pallet. D) New center peak pallet.

6. CONCLUSIONS

Stepfield pallets, in both their full-cubic and half-cubic variants, have become a central part of several proposed NIST/ASTM test methods for response robots. They have also proliferated around the world as mobility challenges for international competitions. While they provide repeatable terrain to challenge and evaluate robot mobility and a remote operator's situational awareness, they have proven to be difficult to standardize as a mobility test method. Random stepfields can continue to play a key role in helping robots move from the laboratory toward practice deployments and even to support operator training. But as a standard test method apparatus, a more repeatable version of the stepfields is necessary. More experimentation is required, but initial tests using symmetric stepfield pallets suggest that repeatability in robot performance and reproducibility of the test apparatus can be achieved.

7. ACKNOWLEDGMENTS

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