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A review on snake robot testbeds in granular and restricted maneuverability spaces

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ABSTRACT

This article reviews the state of the art in evaluating snake robots for small spaces such as a collapsed building where the snake is either locomoting in restricted maneuverability spaces, such as narrow pipes or tunnels, or pushing through granular regions, such as dirt and rubble. It makes recommendations on designing a testbed that can enable a comprehensive evaluation of a snake robot's overall capability and an objective comparison of different snakes. A survey of 31 papers reveals that 20 testbeds were used to test snake robots in restricted maneuverability environments. All of those were built specifically to test a particular snake robot rather than for comparison with other snake robots, but each offers insights into designing comprehensive, comparative testbeds. The article analyzed these 20 testbeds in terms of how well they addressed the previously established disaster robotics metrics of scale (a dimensionless number) and four traversability elements, i.e. verticality, tortuosity, accessibility elements, and surface properties. This review suggests that two kinds of general testbeds are in need for the snake robot community: (1) a testbed with high physical fidelity for measuring suitability for a target application, and (2) a testbed which provides a dimensionless comparison of different snake robots. The review is expected to benefit the community in several ways. It can help form a consensus on a suite of metrics and test methods to incorporate into a testbed for evaluating and comparing different types of snake robots and capturing the performance of snake robots in more realistic work envelopes. The metrics and test methods can also pro-actively inform snake robot design as they offer more formally quantified work envelopes, thus accelerating technology transfer. The use of scale and traversability is expected to be applicable to robots in general.

1. Introduction

Snake-like robots offer the advantage of being able to enter small, irregular voids such as in the rubble of a collapsed building. Snake robots have been reported at three disasters: the 2004 Niigata Chuetsu Earthquake (Japan) [1], the 2007 Jacksonville Florida parking garage collapse (USA) [1], and the 2017 Mexico City earthquake [2] and it is to be hoped that more will be used in the future. Future use poses the questions of how to test how well a snake robot is likely to perform in a particular disaster environment and how well one snake robot works compared to another in that situation, e.g., is a particular gait or locomotion strategy superior to another for a specific type of void? While previous surveys have defined performance metrics for snake-like robots, notably Hirose and Yamada [3] and more recently Paez and Melo [4], there appears to be no formal categorization of work envelopes and test methods used by snake robots. This creates a gap in designing useful test methods for disasters.

This article addresses the gap in incorporating the work envelope into snake robot testing. It summarizes what has been reported on physical testbeds for testing snake-like robots in small, confined environments. As there is no apparent consensus in the snake robot community on what is small, locomotion-challenging space, this article will use the definitions of small, confined environments in *Disaster Robotics* [5]. That work describes general ground robot work envelopes in rubble as a dimensionless number that normalizes the characteristic dimension in entering a void, usually the cross sectional diameter, of the robot agent A_{cd} to the cross section, or characteristic dimension, of work envelope E_{cd}. A *restricted maneuverability* space is defined as $E_{cd}/A_{cd} < 2$, in effect the narrowest cross section of the work envelope is less than twice the cross section diameter of the snake-like robot. A tracked ground vehicle would be unlikely to easily turn around in such a relatively narrow space. A *granular space* is $E_{cd}/A_{cd} < 1$, where the robot must burrow into the work envelope. There are two advantages to using this characterization of the snake's work envelope. One is that is it independent of the morphology or gait

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of a robot and thus allows test methods developed for robot $R1$ to be compared with test methods for robot $R2$, and even the performance of $R1$ and $R2$ to be compared. A second advantage is that provides an explicit mechanism for including or excluding papers. A disadvantage is that using the cross sectional diameter of a snake robot may not normalize snakes with different ranges of oscillation, but the E_{cd}/A_{cd} ratio is being used only to help select the relevant subset of published work.

This article identifies thirty-one papers describing 20 different testbeds where a snake robot was tested in a restricted maneuverability or granular work envelope. The review incorporated any work on snake robots that described a testbed that fit a restricted maneuverability or granular work envelope; this was determined from the reported dimensions of the testbed or inferred from figures showing the testbed and the snake. The review was not limited to robots originally intended for disasters, but many papers about medical or surgery snake robots, pressurized soft snake robot for clinical settings, or industrial snake-arm manipulators were not within scope of this review, even though they were tested in real medical or industrial applications, because the definition of granular and restricted maneuverability spaces does not fit their workspace. Articles using regular testbeds, such as a "flat ground", to test snake robot are excluded as well, since those testbeds do not qualify as granular and restricted maneuverability spaces [5]. Articles that only discussed the snake robot itself without any testbed information were also excluded from this survey.

The survey found two interesting trends and yielded two surprises. One is that all of the testbeds were built to test a specific robot. This suggests that testbeds which are built to permit comparisons will be of value. It may be of further value to have robot testbeds that adjust the dimensions of a region to give the same E_{cd}/A_{cd} ratio so that different robot morphologies can be more fairly compared. A second trend is that the testbeds were constructed to capture performance under work envelope dimensional constraints (e.g., size, turn radius, etc.), but did not capture realistic traversability elements of tortuosity, verticality, surface properties, and number of accessibility elements. These four elements are cited in [5] as key to describing constraints on mobility in rubble or subterranean environments. Tortuosity, a metric from animal behaviors that captures the number of turns in the environment, quantifies the irregularity of the robot's work envelope. The verticality or slope is important as building collapses are generally conducted from the top of the rubble, with the robot expected to penetrate several stories down. The surface properties are important, for example, the combination of dirt and water prevented a robot from climbing stairs at the 9/11 World Trade Center and at the Fukushima Daiichi nuclear accident and shag carpeting detracked a robot at the La Conchita Mudslides [5]. The number of accessibility elements is important because robots have to move between regions within a void that have different sizes, shapes, and surface properties. A robot that can only perform in one region may fail in the others and thus lead to an overall failure. One surprise was that a new metric is needed to measure the irregularity of the void beyond tortuosity, because some snakes move against environment and thus locomoting through a smooth tube may produce different results than locomoting through an irregular surface. A second surprise was that all robots were teleoperated in full view of the operator, and so future advanced testbeds which investigate snake robot autonomy will need to consider how to capture data.

The remainder of the paper is organized as follows. Section 2 presents 12 snake robots in order to introduce the 20 testbeds used to test them. Section 3 compares the testbeds in terms of scale, tortuosity, verticality, surface properties, and accessibility elements. Section 4 discusses the results and recommends a generic testbed that can be adapted to the size of the robot and traversability characteristics of a building collapse. Section 5 concludes with the survey results.

2. Twelve representative snake robots

Thirty-one papers on snake robots with explicit descriptions of the testbeds used to measure performance were identified in the academic literature [6–36]. Since several papers discussed different aspects of the same robot or testbed in ongoing research projects, this section will forgo summarizing each paper individually and instead ground the survey by describing the 12 snake robots with the purpose of presenting the testbeds that were used to test them, then analyzing the testing in the next section.

The specifications for the snake robots and the testbeds used for their evaluation are summarized in Table 1. The robot specifications are divided into five attributes: the robot's degrees of freedom (DoF), the characteristic cross-section diameter A_{cd}, the length of the snake, the sensor payload, and the body-shape dimension. These attributes are worth noting because they give information on the variety of snake robots, which calls for testbeds to normalize their performances. The testbed specifications are divided into four categories: the smallest cross section of the work envelope (E_{cd}), the estimated ratio of envelope to robot size (E_{cd}/A_{cd}), the run length of a path through the testbed, and the slope. Columns for the tortuosity, surface properties, and accessibility elements attributes of traversability are not shown because none of the testbeds showed any variation in those attributes, as will be discussed later.

2.1. CMU modular snake

CMU Modular Snake has been tested in six different testbeds. The snake consists of 16 fully enclosed actuators and incorporates a modular architecture. Each module from the snake is rigid and contains two 1-DoF half-joints, each connecting to the next and previous modules. The typical snake robot has 16 degrees of freedom (although more modules can be added if needed), alternating vertically and horizontally along its body. Even-indexed joints control lateral rotation, while odd-indexed joints control dorsal rotation, or vice versa [23]. The narrow minimum cross section (5.1 cm) and extreme range of joint motion (180°) make this snake robot useful in diverse environments, such as uneven ground, slopes, channels, pipes, poles, etc. The usage of the snake robot in these environment was successfully demonstrated in custom-built testbeds, in the form of ad hoc mockups of these environment. With the camera and laser (Snaser) on the head module, the robot was expected to be applicable to diverse tasks in confined and granular environment such as urban search and rescue, mine rescue, industrial inspection, reconnaissance, and even in archeology.

One testbed, CMU-MS-Pipes, tested the CMU Modular Snake's pipe-climbing ability (Fig. 1). The pipe diameter was not specified in related papers, but from observation it was less than twice the snake's 5.1 cm-diameter. The snake robot would form a helix with changing pitch and radius and as long as the pipe parameters were in scale with the helix, it could climb into it. The metric was either success or failure when negotiating with the pipe. In addition to mapping and localization capability as criterions in test design, the ability of autonomously navigating the robot in restricted maneuverability areas horizontally was also tested. In [9], only one trial was performed while the heading error of the navigator was plotted and analyzed. Eight consecutive gait phases were executed and the ability to navigate through restricted maneuverability environment to the target pipe was demonstrated. Other than that, three dimensional reachability, especially in the vertical z axis, was tested in [8], when suspending pipe without direct ground contact was present in the restricted environment. Two different trials, one with and one without specified pipe location, were executed. Pipe-climbing test should not only focus on pipes, but treat all necessary accessory abilities as a whole.

Table 1
Reviewed snake robots and their testbeds.

	Robot Specifications					Testbed Specifications				
Snake	DoF	A_cd (cm)	Length (cm)	Payload	Body-shape Dimension	Testbed	E_cd (cm)	E_cd/A_cd	Length (m)	Slope (°)
CMU Modular Snake	16	5.1	94	Camera, laser	3D	CMU-MS-Pipes	<10	<2	Unk.	90
						CMU-MS-Slopes	120 (sidewinding)	<1.5	4.8	−18.84–24.62
						CMU-GT-Fluidized	$\ll 1$	$\ll 1$	2 × 1	0–20
						CMU-MS-Mockup1	Unk.	<2	Unk.	None
						CMU-MS-Mockup2	Unk.	<2	Unk.	None
						CMU-MS-Mockup3	Unk.	<2	Unk.	None
CMU SEA Snake	16	5.1	117.4	Camera	3D	CMU-SEA-Pegboard	5	1	Unk.	None
						CMU-SEA-BB	$\ll 1$	$\ll 1$	Unk.	None
MSR	16	34	107	None	3D	MSR-Pipes	17, 34, 68	0.5, 1, 2	Unk.	None
Lola-OP	8	86	86	None	3D	Lola-Pipes	13, 27, 54	<1	4.1	None
Kulko	18	14	10 modules (14 each)	FSR IR, camera	3D	Kulko-Pegboard	20	1.4	Unk.	None
PIKo	8	14	5 modules (15 each)	FSR, camera	3D	PIKo-Pipes	24	1.7	Unk.	90
AIKO	18	11.5	10 segments (12.2 each)	FSR, 3D camera, IR	3D	AIKO-Pegboard	15	1.3	3.5	None
OmniTread	8	18.6	127	None	3D	OmniTread-Pipes	30	1.6	Unk.	22
						OmniTread-Underbrush	$\ll 1$	$\ll 1$	Unk.	None
AIRo-2	3	10	55	Camera	2D	AIRo-2-Pipes	10	1	8	90
Pipe Inspection Snake Prototype 1	6	4	105	Camera	2D	PISP1-Pipes (2 walls)	5.5	1.4	Unk.	None
Pipe Inspection Snake Prototype 2	6	1.4	49	Camera	2D	PISP2-Pipes (2 walls)	1.8	1.3	Unk.	None
						PISP2-Pipes	1.8	1.3	Unk.	None
Pipe Inspection Snake Prototype 3	12	2	118.7	Camera	2D	PISP3-Pipes (Inclined)	3.6	1.8	Unk.	10, 30–90 (15 step)

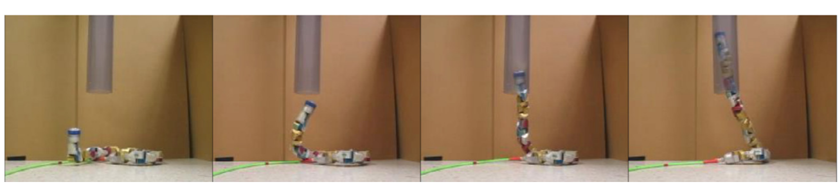

Fig. 1. CMU Modular Snake negotiating CMU-MS-Pipes testbed, which is representative of pipe testbeds in [7–9,16,18–20].

Another testbed, CMU-MS-Slopes, captured slopes for sidewinding gait [26–29]. Instead of the confinement caused by the interior of pipes, the gravitational force pulling the snake down slope was the major concern of the locomotion research. A chain of four angled slopes, -18.84°, -17.58°, 12.02°, 24.62° (Fig. 2), was built to test how the CMU Modular Snake can adapt to different slopes using sidewinding gait [21]. In addition to success or failure analysis, the time to traverse each slope using different strategies was evaluated. An overly aggressive sidewinding strategy failed to complete the task, while conservative strategy led to poor performance (70 s finish time) and trained strategy took only 35 s. In feasible ascending slopes (successful trials), test could be designed to determine the maximum climbing speed using sidewinding facing a certain slope, or the maximum slope angle the snake can climb given a certain speed. This resembled the test method used by biologist to test how snakes can negotiate slopes with granular materials [30], which was also applicable to robot experiments.

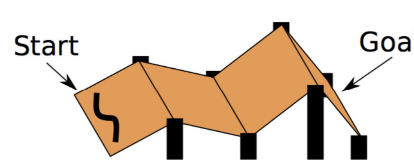

Fig. 2. A diagram of CMU-MS-Slopes testbed to capture verticality, the only slope testbed found in this survey [21].

CMU Modular Snake was also tested in an air-fluidized testbed filled with 200 kg sand, labeled as CMU-GT-Fluidized, which was

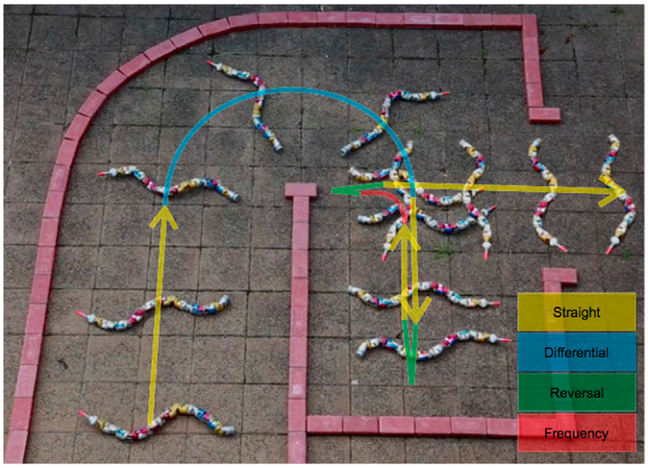

Fig. 3. CMU Modular Snake traversing CMU-MS-Mockup2, which is representative of all testbeds constructed to delimit different types of restricted maneuverability spaces [9–11].

Fig. 4. CMU SEA Snake slithering through CMU-SEA-Pegboard with reconfigurable peg pattern through mounting holes, which is a typical representation of all pegboard-type testbeds used in [6,15,17,25].

also shared with biological snakes from Georgia Institute of Technology in Zoo Atlanta [30]. In the $2 \times 1m^2$ bed, in order to conduct systematic, repeatable testing of the devices to discover important principles [31], air flow was used to restore sand to a loosely packed state with a flat surface so that disturbances to the medium from previous experiments were no longer present. The inclination angles were also controlled. The testbed was aiming at investigating how biological and robotic snakes can operate on inclined granular media that induce failure in field-tested limbless robots through slipping and pitching. For the robotic experiments, it was found that by increasing the length of its body in contact with the sand (just like biological rattlesnakes do), the snake robot was capable of ascending sandy slopes close to the angle of maximum slope stability. Important snake locomotion principles were discovered, which effectively helps to evaluate and develop robot capabilities in granular environments.

Mockups of restricted maneuverability regions were used to test CMU Modular Snake robot's agility and maneuverability (Fig. 3). The evaluation was based on success or failure in negotiating the environment. In CMU-MS-Mockup1 [9] and CMU-MS-Mockup2 [10] the robot's ability to turn in or traverse through very tight spaces using a certain gait and in CMU-MS-Mockup3 [11] ability to get over a certain obstacle on its path in restricted mobility region were tested. In [9] and [10] only one single demonstration trial was used to prove the maneuverability in restricted spaces. The space was confined by either bricks or artificial cones. Over 100 trials in CMU-MS-Mockup3 [11] showed that obstacles higher than 4.25 inches (the snake diameter was 2 inches) were beyond the capability of rolling hump gait while obstacles lower than one inch were easy to climb over. For obstacles of heights between 1 to 4.25 inches, a decision boundary was fit to the experimental results using linear support vector machine (SVM). These mockups were ad hoc, and were only designed to demonstrate improved performance of a certain research work, such as a hardware refinement, a new motion planning algorithm, a better control strategy, etc.

2.2. CMU SEA snake

CMU SEA Snake was a newer version of CMU Modular Snake that has been applied to two testbeds. Each module of the SEA snake was equipped with a series elastic actuator. In addition to joint position control, it allows force control [24].

One testbed, CMU-SEA-pegboard, evaluated the snake's locomotion capability to navigate through restricted maneuverability spaces (Fig. 4). The pegs were in regular or irregular patterns and the distance between two adjacent pegs E_{cd} (characteristic dimensions of the environment, the minimum distance between two pegs was 2 inches) was less than twice the characteristic dimension of the agent A_{cd} (the snake module diameter was 2 inches) ($E_{cd} < 2A_{cd}$). The purpose of the testbed was to compare the performance of different control strategies, position-based and force-based control, joint-level and shape-level compliance, etc. and their related parameters. For the sake of comparison and evaluation, the performance metric used was distance traveled by the robot per gait cycle. Particularly in [6], experiments were conducted on an approximately random peg pattern. The robot was covered with a braided polyester expanding sleeve to reduce friction. Five trials for each of the five different control strategies were executed and the data was normalized by a metric that divided the number of gait cycles by the total distance traveled, measured in terms of the integral of arc length in meters. This metric provided a measure of how many cycles it took for the robot to travel one meter. Travel distance of the robot, either in the form of COM displacement in desired direction or integral of arc length along the snake body was the key to evaluate snake robot locomotion performance in restricted maneuverability regions. Robot which moves smoothly through the environment should be assigned a better performance score than those which get lagged, trapped or even stuck in pegs.

The CMU SEA Snake was also tested in a BB pool [22] (Fig. 5), CMU-SEA-BB, which provided experimentation in locomotion in granular region surface, The 6 mm BBs in a 2.6m×1.2m×0.23m pool provided a simulated granular medium and the snake traversed on the surface of it. Motion capture system (4 OptiTrack Flex 13 cameras) was equipped to precisely capture the movement of each individual joints. The linear displacement of forward locomotion and lateral translation (in the unit of body lengths), and turning rate (rad per gait cycle) were used as metrics to evaluate snake performance. Same trials have been performed after placing the aforementioned pegboard into the BB pool and same longitudinal displacement was measured and compared with the pure pegboard experiments.

Fig. 5. CMU SEA Snake swimming through CMU-SEA-BB (pool) testbed filled with simulated granular material. This is the only testbed found to emulate environments with $E_{cd}/A_{cd} \leq 1$ [22].

2.3. Modular snake robot (MSR)

The Modular Snake Robot (MSR) [12] developed by SIRP Research Group contains 16 modules, each twisted by 90°. Each module is actuated by servomotors. High strength plastic frame brackets provide links between modules. The link size is variable by changing the plastic bracket. This feature of the Modular Snake Robot can provide different characteristic dimension A_{cd}, which is defined as the diameter of the circle formed by snake length (length/π). It was extensively tested on horizontal pipes, including a series of bushes [12,13] (labeled MSR-Pipes). Different gaits, i.e. side winding, lateral rolling, and helix rolling, were executed to negotiate with pipes of different diameters. The pipe dimension A_{cd}, outer diameter in this case, was chosen to be 0.5, 1, and 2 times of the snake's characteristic dimension. MSR's speed and energy consumption were measured during the test.

2.4. Lola-OP

Lola-OP [14] is a modular snake robot composed of 8 1-DoF modules with in-series compliance. Similar as above-mentioned snake robots, each Lola-OP module is connected to each other with a twist shift of 90°. Four different Lola-OPs were built, with different compliance. The compliance was added in the form of cylindrical beams in each joint, being able to bend in any tangential direction and twist on their longitudinal axis. The snake is used to negotiate pipes with varying diameters.

Lola-OP was tested on a horizontal pipe testbed specifically designed to test its compliance (Fig. 6). The diameter of each pipe was chosen with respect to the snake robot's characteristic dimension (length in term of lateral motion). The testbed also included diametrical bumps on the medium pipe to represent rough terrain. To connect pipes with different diameters, gradually changing regions provides "slope" features to the testbed. The testbed is manufactured using a combination of plastic pipes, cardboard, and plastic fencing meshes. A thin layer of plastic netting (with a square mesh size of 12 mm) wrapped around the pipes to provide more friction. The effect of amplitude value on locomotion speed is tested on the testbed. In another set of experiments, locomotion speed and power consumptions for the locomotion were tested over bumps on the middle pipe. The whole testbed is setup within the capture volume of a motion capture system composed of 14 OptiTrack s250e cameras. Only 3 DoF translation of the robot center of mass is recorded by a 25 mm wide reflective tape.

2.5. Kulko

Kulko was mainly used for obstacle-aided locomotion research in restricted maneuverability regions and was tested only in one custom-built testbed. The contact force sensor enables it to sense the contact with the environment and helps to maintain forward propulsion.

The robot was tested in a particle board [15,25], labeled Kulko-Pegboard (Fig. 7), which was a black horizontal surface measuring about 100 cm in width and 200 cm in length. Circular obstacles were placed on the surface and the location of each obstacle could be easily changed by means of a grid of mounting holes in the floor. The placement of the particles guaranteed $E_{cd} < 2A_{cd}$ and restricted the maneuverability of the snake. The testbed was to demonstrate the efficacy of obstacle-aided locomotion control strategy. The researchers used the changes in snake position and orientation, and contact force profile to evaluate each trial. Three obstacle environments were created and tested using this testbed. There were five obstacles placed on the test course, whose x coordinates, y coordinates, and diameters were specified.

2.6. PIKo

This snake-like robot with a set of active wheels and a series of two degrees of freedom actuated joints was only tested in one testbed (labeled PIKo-Pipes) since it was designed to navigate in complex pipe structures for inspection, maintenance and repair (IMR) of pipelines, both horizontally and vertically [16]. In those pipelines, horizontal motion was achieved through a train-like scheme, while vertical motion was achieved through spanning the pipe alternating with snake modules.

PIKo-Pipes tested horizontal snake motion through bend and the results indicated that the follow-the-leader control scheme was capable of making the robot act as a train in conjunction with measurements from wheel odometry (Fig. 8 left). No details about the virtual bend other than that it was created by installing wall markers on a flat surface were mentioned. Although the clearance of the bend was not specified by the researcher, it was clear that it was smaller than twice the snake width ($E_{cd} < 2A_{cd}$). It was also tested in vertical pipes (0.24m in diameter, compared with module dimension 0.15m×0.13m×0.14m, Fig. 8 right). Results indicated that the robot was capable of propelling itself vertically.

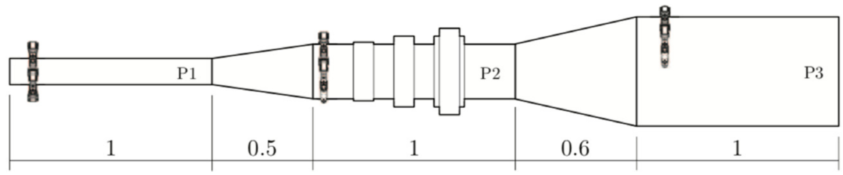

Fig. 6. Lola-OP's testbed is a series of connected pipes with different diameters [14].

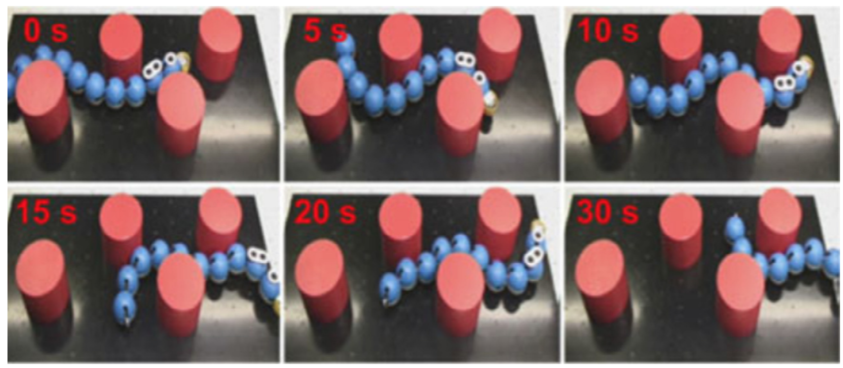

Fig. 7. Kulko traversing through Kulko-Pegboard [15].

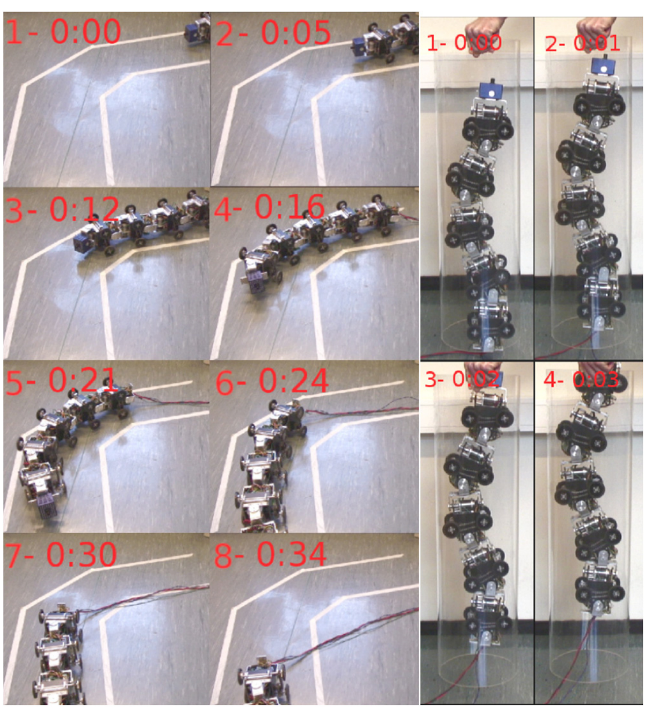

Fig. 8. PIKo's horizontal bend and vertical pipe [16].

2.7. AIKO

Similar to Kulko, AIKO was also built for an environment with obstacles restricting the robot's mobility and was only tested in a pegboard-type testbed. AIKO consists of 10 identical segments, a spherical head segment, and 10 joints connecting the segments.

The AIKO testbed, AIKO-Pegboard (Fig. 9), was a modular obstacle course developed as an artificial benchmarking environment [17]. The testbed was aimed at evaluation of motion patterns and path planning strategies. So this required the testbed to be able to reproduce reproducible experiments and reconfigurable. The obstacle course consisted of a floor with holes as equilateral triangles with side length 15 cm. This pattern was used both as placing points for obstacles, and position references for the camera system. Obstacles of different shapes (squares and circles) and sizes (side lengths 20 cm and 30 cm for squares, and radius 10 cm and 15 cm for the circles) were placed on these holes. The motion of the robot was tracked by a ceiling mounted camera system. Tracking of arbitrary points on the snake was possible, allowing for a detailed analysis of the snake's movement through the course. Although this testbed was supposed to serve as a general benchmarking facility for all kinds of snake robots, only tests on AIKO were found in the literature. Only one single configuration of the testbed was included and no quantitative details about the obstacle course were provided other than an overhead snapshot of the environment. Position and orientation data of the snake were interpreted. The evaluation was based on resulting path of the snake head from Dijkstra's algorithm and the distance to target. Force readings from obstacle interference were also collected and evaluated.

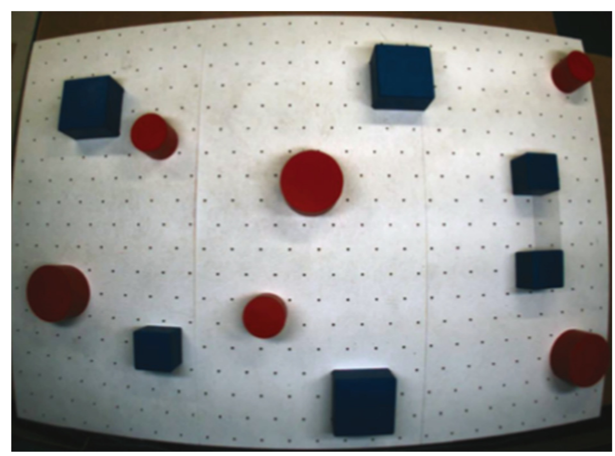

Fig. 9. AIKO-Pegboard consists of a reconfigurable modular obstacle course [17].

Fig. 10. OmniTread traversing dense underbrush. Rather than being stuck by the branches touching the robot from all directions, powered tracks around the snake robot provide extra propulsion against the environment.

2.8. OmniTread

The OmniTread [33,34] design offers two unique and fundamentally important advantages: (1) maximal coverage of the robot's surface with propulsion elements and (2) joint actuation with pneumatic bellows. The largest possible surface area of the robot with propulsion elements can effectively prevent the robot from getting stuck in confined spaces. The pneumatic bellow design guarantees sufficient torque and compliance for serpentine motion.

The OmniTread was tested at the Southwest Research Institute (SwRI). The testbeds that satisfy our survey criterion as granular and restricted maneuverability spaces are pipes [34] (labeled OmniTread-Pipes) and dense unberbrush [33] (labeled OmniTread-Underbrush). OmniTread was tested in a PVC pipe with an inside diameter of 30 cm and an inclination of 22°. The compliance and power of the actuators allow the robot to wedge itself within the restricted maneuverability space while producing enough normal force against the inside walls to climb up. OmniTread was also tested in SwRI's dense underbrush environment, where branches touch the robot from all sides and could easily stall the locomotor. The branches in the underbrush works as granular materials. For OmniTread, branches touching the large propulsion surfaces help the robot, rather than impeding it (Fig. 10).

2.9. AIRo-2

AIRo-2 is a multilink-articulated wheeled inspection robot designed for winding pipelines [35,36]. It consists of four links connected by three spring joints. Each of the joints is also attached with an omni wheel, two of which are active along the pipe (longitudinal) direction. On both ends of the snake robot are two active spherical wheels in the rotational direction around the pipe axis. The snake robot maintains zigzag shape using torsion springs mounted at the joints.

AIRo-2 was tested in a collection of pipes, labeled AIRo-2-Pipes, including vertical and horizontal straight pipes including the transition in between, T-branch, and winding pipes (Fig. 11). The speed of the snake robot is reported to be less than 0.1 m/s.

2.10. Pipe inspection snake prototype 1, 2, and 3

These robots were designed and built specifically for pipeline inspection, so they were only tested in pipes, either cylindrical of 2-wall pipes. In contrast to other studied snake robots, these three robots were only planar and their bodies cannot form three dimensional shapes. So only planar motion was used to propel the snake within pipelines. The dimensions for each prototype are shown in Table 1.

For the testbed used by Prototype 1, labeled PISP1-Pipes (2 walls), it has only been reported that T-branch negotiating experiments in plastic pipes (120 mm in diameter) suggested the robot's good mobility. It can also negotiate short elbow pipes [18]. Since the robot was developed for pipe inspection, the camera image stabilization algorithm was also tested. The paper claimed that the camera stabilization works well, but without quantitative analysis.

For Prototype 2, testbed labeled PISP2-Pipes (2 walls) for simulated pipe interior spaces, and PISP2-Pipes for vinyl chloride pipes, were used to test the robot [19]. Using two parallel walls, the clearance of the simulated interior space in pipe could be adjusted by changing the distance between the two walls. The test results showed that the snake robot can negotiate between two walls whose distance varies from 18 mm to 100 mm with the frequency of 0.2cycle/sec. And the maximum velocity was 36 mm/s, which was caused by the frequency of 1.0cycle/sec. Two real pipes were used in the test as well, one was 50 mm in inner diameter, and the other was 75 mm. The traveling velocity of the robot was 4.35 mm/s (13.1 mm/cycle) in the former, 8.55 mm/s (25.7 mm/cycle) in the latter, with the frequency of 0.33cycle/sec. For this prototype, test result for camera image stabilization was based on the measured angle between the front link to pipe wall in pipe axial direction. In case of applying the camera image stabilization, the value of integration of the angle during one cycle decreased by 45%. T-branch pipe was also used to test the snake robot's steering ability. The additional offset parameter to realize steering activity was controlled manually and the robot can negotiate in any desired direction with manual control.

For the testbed used by Prototype 3 [20], labeled PISP3-Pipes, the same two-wall tests (6 different wall distances between 36 to 180 mm plus 55 mm and 80 mm real pipes) and T-shape pipes (80 mm) were used, plus vertical pipes. The robot was experimentally examined in inclined pipes by gradually increasing pipe inclination from a horizontal position. The traveling velocity was measured from 30° to 90° with 15°-step. Two different pipe diameters were tested, 55 mm and 80 mm. For both cases, velocity decreased with increasing inclination and the snake robot was able to negotiate with vertical (90°) pipe. Other than that, tests of traveling in pipes with changing diameter was performed. The snake robot is manually controlled and can traverse from 55 mm to 80 mm pipe, and vice versa.

3. Analysis of existing snake robot testbeds

The snakes and testbeds reported in the previous section can now be analyzed in order to answer the three specific questions:

(1) *Do the testbeds adjust their scale to fit different robots?*,
(2) *Do the testbeds capture relevant traversability factors of tortuosity, verticality, surface properties, and number of accessibility elements?*, and
(3) *Were there any surprises in testing snake robots versus more traditional tracked or wheeled robots?*

3.1. Cross-sectional scale

The testbeds used by the snakes in the previous section either tailored the scale to the snake, which posed a $A_{cd} \propto E_{cd}$ scale, or were built with a fixed E_{cd} that represented the expected region sizes.

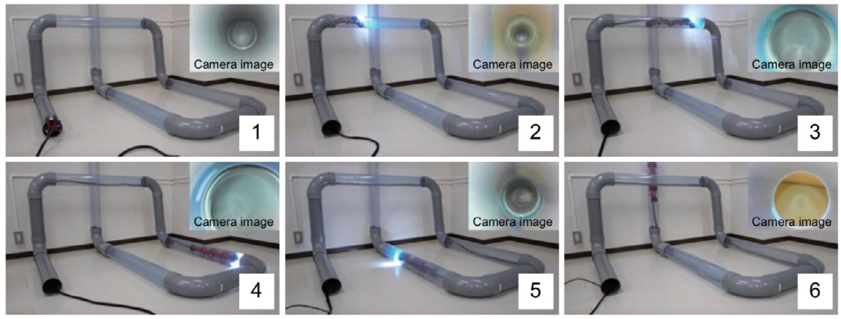

Fig. 11. AIRo-2 navigating through 8m's winding pipe.

3.1.1. Cross-sectional scale tailored for snake testbeds: Nine out of the 12 snakes

Nine of the 12 snakes were tested in testbeds that were tailored to provide a $E_{cd} \propto A_{cd}$ scale for that robot. The attributes being measured for performance evaluation and how does the related testbed or method of data capture enabled by the testbed support the measurements are summarized in Table 2.

The tailored testbeds fell into three design styles: *pegboard*, *horizontal pipe*, and *BB pool*. The pegboard style testbeds all had mounting holes on the bed with a dense grid pattern. These mounting holes provided proper intervals for E_{cd} adjustments. Peg or obstacle arrays were placed on the bed in either regular or irregular patterns and were easily reconfigurable. The CMU SEA Snake, Kulko, and AIKO were tested with pegboards. The simulated inner horizontal pipe style testbed were used by PIKo, Pipe Inspection Snake Prototype 1, 2 and 3. MSR and Lola-OP were tested in outer horizontal pipes. The BB pool testbed provided a typical granular environment for snake robots. The relative size of the BBs to the snake robot was similar to the relative size of real sand to biological snakes. By choosing materials of different granularities, the A_{cd} and E_{cd} ratio could be adjusted. The CMU SEA Snake was also tested in this style of testbed.

The two intents behind the adjustability for current testbeds are: 1. tailor to create different configurations with similar characteristics (E_{cd}) and thus same equivalent difficulty to conduct multiple experiments. This can add diversity to the test and provide statistical significance (such as different peg patterns). 2. adjust to quantify one snake robot's ability in different E_{cd} to see its versatility or adaptability (such as two wall experiments). Another application of adjustable $A_{cd} \propto E_{cd}$ testbed is adjust to fit different robot sizes, so that a fair comparison could be made for different size snakes by allowing the same A_{cd}/E_{cd} ratio and therefore difficulty. However, this area of application has not been exploited yet.

3.1.2. Fixed cross-sectional scale testbeds: Five out of the 12 snakes

Real pipes with a fixed diameter belongs to fixed scale testbeds, which were used for the CMU Modular Snake, PIKo, Pipe Inspection Snake Prototype 1, 2, 3. It should be noted that the NIST ASTM Vertical Insertion/Retrieval Stack with Drops [37] test method for rescue robots exists, but no tests have been reported to be actually conducted on that testbed.

3.2. Length scale

In contrast to the cross-sectional scale, the length scale is also a dimensionless number that captures the relative size between the environment and agent (E_L/A_L). Long snakes are used to traverse longer courses, while small snakes are targeted at shorter environments. In the literature, snake robot traveling speed is always measured in the unit of distance per body length. This measure is based on the idea of a fair comparison of snakes of different sizes. True performance should also factor in the dimensions of the robots, since large snakes definitely travel faster than small snakes do in an absolute sense. However, this is not sufficient to capture the snake performance with respect to the environment. Testbed length is of importance if researchers need to know how fast the snake robots can traverse the environment. A 1.5m snake may take 20 s to go through a 5m corridor, while a 0.4m miniature snake may take minutes. It is only fair when a snake robot is tested in a testbed with proper length. Therefore, choosing suitable testbed length can give a meaningful length scale so that robot performance could be objectively compared. Testbed length, however, is only mentioned for CMU-MS-Slopes [21], CMU-GT-Fluidized [30], and AIKO-Pegboard [17].

3.3. Traversability

Table 3 summarizes the 12 reviewed snake robots and their tested scale and traversability elements. "x" means that the snake robot is tested with respect to this feature.

3.3.1. Verticality

Verticality was addressed in four snake robot testbeds, in forms of either slopes or pipes.

Two of the four testbeds considered slopes. CMU-MS-Slopes consisting of four different degree slopes (plywood clamped to vertical wood bars at two ends) was used to test CMU Modular Snake [21]. The testbed verticality could be changed by adjusting two ends of the board (-18.84°, -17.58°, 12.02°, 24.62°). Other than manually observed success/failure test in different slopes to determine how steep the slope could be for the snake to climb, maximum climbing speed facing a certain slope and maximum slope angle the snake can climb given a certain speed were also tested. No measuring methods were mentioned, but it is most likely to be manual timing, measurement and calculation. One of the granular testbeds surveyed in this paper, CMU-GT-Fluidized, also addressed verticality by looking at how snake robot can negotiate with inclined slope with granular material. Although this research was more focused on investigating biological snakes, it also touched another test dimension of snake robot. Optimizing contact planning policies can improve the snake's capability to operator on granular slopes.

Vertical pipes were used to test mobility of three out of 12 snakes (CMU Modular snake, PIKo, and Pipe Inspection Snake Prototype 3). The testbeds for CMU Modular Snake also tested its accessory ability in addition to mobility: the ability of localizing [7], approaching [9] and mounting [8] into vertical pipes will be further discussed in Accessibility Elements. All vertical pipe testbeds included failure/success test in climbing 90° pipes, while Prototype 3 was also measured for velocity in different inclinations (30° to 90° with 15° steps) and different pipe diameters (55 mm and 80 mm) [20].

Table 2
Attributes and measurements.

Attribute	Measurement	Method	Reason
Displacement and rotation [6,13–15,17]	Body position and orientation	Motion Capture/Camera system Averaging and Singular Value Decomposition on multiple markers/tracking head module and use kinematics calculation/Manual measurement	Used to evaluate the effectiveness of motion strategies/mobility
Physical interaction with surface [15,17]	Contact force on body segments	Force Sensing Resistor (FSR) sensor on the robot	To capture physical interaction with the environment and validate theoretical results
Manual steering ability [16,35,36]	Success/failure	Manual observation, no time limit	Manually controlled by direct visual to validate steerability, may not be suitable for real application
Viable E_{cd} range [19,20]	E_{cd} dimension	Measuring E_{cd} when robot motion is possible. Varying E_{cd} by physically move testbed components (changing distance between two walls)	Determine how adaptable is the robot to different E_{cd}
Maximum velocity [19,20]	Displacement and time	Manually measuring test course length and traverse time	Quantify the robot's mobility
Energy efficiency [13,14]	Translational work and internal rotational work	Torque measurement from servomotor or current probe on power supply	Quantify the robot's energy efficiency

Table 3
Snake with scale and traversability elements in their testbed.

Snakes	Scale	Verticality	Tortuosity	Accessibility Elements	Surface Properties
CMU Modular Snake	x	x	x	x	
CMU SEA Snake	x			x	
Modular Snake Robot	x				
Lola-OP	x			x	
Kulko	x				
PIKo	x	x	x		
AIKO	x				
OmniTread	x	x			
AIRo-2	x	x	x	x	
Pipe Inspection Snake Prototype 1	x		x		
Pipe Inspection Snake Prototype 2	x		x		
Pipe Inspection Snake Prototype 3	x	x	x	x	

3.3.2. Tortuosity

Tortuosity is calculated as the number of turns taken by the robot per unit distance [38]. The test for tortuosity on snake robots needs to be distinguished between two types of motion: lateral or longitudinal, because cross-section of the locomotor is completely different in different motion modes (the whole body length for lateral and the width of one individual module for longitudinal motion). This will affect the necessary turns and testbed configuration.

Lateral motion was tested on one out of the 12 snakes. Testbeds on lateral motion for tortuosity were built for CMU Modular Snake's sidewinding gait [26–29]. The testbeds were in the form of mockups of restricted maneuverability environments: narrow passages [9,10] or obstacle in path. Tortuosity value was not specified by any of the papers, but from visual estimation, it was about 1 (turn/meter). Only the number of turns executed and success/failure to get to the final destination were recorded. Success/failure of rolling hump [11] when obstacle is in the middle of the path was manually observed.

Longitudinal motion was tested on four out of the 12 snakes. For longitudinal motion, tortuosity was used to test the robot's steering ability in turning pipes, either using slithering [18–20] or follow-the-leader control by active wheels [16]. In [16], tortuosity was embodied in the design of the horizontal virtual bend. In [18–20], the T-shape branch represented the tortuosity in the test environment. Only failure/success of manual steering was determined by manual observation.

No pegboard testbeds included tortuosity for longitudinal turning: instead of trying to circumvent the obstacle using turns, the snake robot slithered through the obstacles while pushing against them. Researchers only paid attention to the longitudinal linear displacement of the snake head or center of mass through the obstacle array, which was an indication for the effectiveness of the motion strategy. The direction of the displacement was not of interest. This is shown in eight out of 31 papers. Instead of obstacle avoidance, the obstacles were usually located in the bounding box of the snake robot. The head module was always turning left and right due to the nature of sinusoid motion, not to fit into free space in restricted mobility regions. It was ambiguous to represent the snake robot orientation. So tortuosity currently has not been specifically addressed in testbeds for longitudinal movement (other than pipes), especially pegboard.

3.3.3. Accessibility elements

The accessibility elements for the snake testbeds can be subdivided into two different categories: those that contain transitions between regions with different shapes or between regions with the same shape but with different characteristics (such as pipes with different diameter).

Only one type of testbed including transition between different types of regions was created for CMU Modular Snake, in this case, from narrow passage to vertical pipes. The NIST ASTM Vertical Insertion/Retrieval Stack with Drops [37] was supposed to contain multiple transitions between different types of regions, but no snake has been tested in this testbed. Testbed in [8] included a transition from ground to pipe and the support polygon approach was used to negotiate the transition. In [9], testbed was customized so the snake robot was tested navigating to a pole in restricted maneuverability spaces and climb onto it for increased surveillance. Other than locomotion, perception was the test subject of testbed in [7] to guarantee the successful detection of and transition to the second region. However, all three testbeds only tested success/failure of snake mounting into, navigating to, and detecting the next region type. Those testbed did not yield quantitative metrics. The second region of the transitions was always vertical pipes. No other types of regions were involved.

In contrast to the transition between different types of regions, four testbeds included transition between same type of regions but with different E_{cd}. Pipe testbeds with transition between different diameters tested Lola-OP [14] and Pipe Inspection Snake Prototype 3 [20]. Testbed including narrow passages with different tortuosity [32] was used for CMU Modular Snake. Pegboards with dense and sparse peg patterns quantified CMU SEA Snake's adaptability [6]. Testbeds of CMU Modular Snake and Prototype 3 only included manual observation for success/failure, while the former was autonomous selecting gait from a gait library and the latter was based on manual control for pipe transition. Lola-OP utilized its own compliance to negotiate with pipes with different diameters and transitions between them. For CMU SEA Snake's testbed with different peg grids, snake center of mass displacement was measured by motion capture system, the same attributes as in one uniform pegboard, to show the effectiveness of shape compliance control.

3.3.4. Surface properties

Surface properties were only briefly mentioned for CMU SEA Snake (pegboard from plywood and PVC pipe segments) [6], PIKo (plastic pipe) [16], Pipe Inspection Snake Prototype 2 [19] and 3 [20] (vinyl chloride pipe). CMU-GT-Fluidized used a sandy slope. CMU-MS-Pipes, Kulko-Pegboard, and AIKO-Pegboard were estimated to be plastic from observation. No information could be gathered regarding the surface material of the pipe testbed for Prototype 1.

Furthermore, no related work regarding different surface properties in those environments were discussed in the literature. Nor was its effect on performance. This indicated that insufficient attention has been paid to surface properties when testing snake roots.

The 20 testbeds used for testing the 12 different snake robots are summarized in Table 4. The testbeds provide insights into designing more generalizable testbeds.

3.4. Surprises

Regarding the third question: *Were there any surprises in testing snake robots versus more traditional tracked or wheeled robots?*, most testbeds overlooked snake robots' autonomy, or semi-autonomy. Traditional tracked or wheeled robots has a relatively stable first-person-view camera, but it is hard to find a stationary position to mount a camera on a snake robot, all body segments of which are constantly translating and rotating. In most testbeds, tests were in an open-loop fashion or teleoperated within operator's line-of-sight. This is not true with realistic conditions. Furthermore, while tracked or wheeled robots' motion commands (forward, backward, left, and right) are simply mapped to wheel rotations, snake robot's hyper redundant Degrees of Freedom make the control less intuitive and require more human assistance. This includes change of gait or tweaking the body geometry to fit into certain confined spaces. Those kinds of manual assistance require more situational awareness. This is not a problem in line-of-sight testbeds, but in real application the snake would be located at a remote location out of human visual. How snakes can achieve those good performance without human presence is not addressed in most of the testbeds.

4. Recommendations for a snake robot testbed for disaster work envelopes

The literature suggests that a general testbed, which captures at least one of two major test perspectives, is of importance for the current snake robot research community. A testbed should incorporate the collective suite of metrics from the community. It should also provide:

- high physical fidelity to target application so that valid predictions can be made about the performance in the real world
- a dimensionless comparison of different snake robots so that different mechanisms, software control of gaits, etc., can be compared.

The purpose of such kinds of testbeds should not be limited to simply demonstrating a proof-of-concept or working system, but serve as a benchmark facility to produce replicable and comparable performance results.

4.1. Metrics

4.2. Testbeds with high physical fidelity to target application

This kind of testbed duplicates a work envelope in the real world that have *a priori* known features and therefore provides a high physical fidelity to snake robots' target application. The motivation for high physical fidelity is to project the performance of snake robot for realistic conditions. The design of such a testbed should be guided by these principles:

- *Design high work envelope fidelity for typical traversability elements* The testbed should be representative of real-world scenarios. Testbeds for inspecting pipes with representative turns do exist, see [16,18–20] discussed earlier, but these are limited to pipes with short distances. An ideal testbed would design a series of modules representing the different shapes of regions: surface properties including water, sludge, and dirt, angles of verticality, and accessibility elements such as flanges, curbs, and stairs. These individual components culminate into a mockup of the target application with a high physical fidelity.
- *Design modular and reconfigurable components* Testbed components should be modularized so that the whole testbed is reconfigurable. Systematic and repeatable trials can be enabled by eliminating all the effects caused by previous trials to the testbed. Not only exactly identical testbed configurations for repeatable experiments, but also reconfigurable environments to replicate different environments but with same granular and restricted maneuverability features contribute to statistical significance of the snake robot testing. New trials could be created by changing the order of the modules encountered along the path or adding new modules. The ability to add, subtract, rearrange regions and accessibility elements, plus to change the verticality of modules, would allow different trials with the same testbed. However, each trial may not be equally challenging, so the environmental metrics of scale, tortuosity, and verticality could be used to quantify equivalent difficulty of different trials. Snake robot testing could benefit from systematic, repeatable testing of the devices to discover important principles. This approach requires sophisticated testbed functionalities and could directly contribute to the evaluation and development of robot capabilities in granular and restricted maneuverability environments.

Table 4
Traversability attributes of snake robot testbeds.

Testbed	Type	Minimum E_{cd}	E_L/A_L	Number of Regions	Different E_{cd}?	Different tortuosity?	Range of Slopes	Surfaces
CMU-SEA-Pegboard [6]	Pegboard	0.05m	unk.	1	yes	no	0°	Plywood, plastic pegs
Kulko-Pegboard [15,25]	Pegboard	About 0.2m	unk.	1	no	no	0°	Plastic
AIKO-Pegboard [17]	Pegboard	0.15m	2.87	1	yes	no	0°	Plastic
CMU-MS- Pipes [7–9]	Pipe	Not specified	unk.	2	no	no	90°	Plastic
MSR-Pipes [12,13]	Pipe	0.17m, 0.34m, 0.68m	unk.	1	yes	no	0°	Plastic/bushes
Lola-Pipes [14]	Pipe	0.13m, 0.27m, 0.54m	5	3	yes	no	0°	Plastic netting
PIKo-Pipes [16]	Pipe	Not specified for horizontal and 0.24m for vertical	unk.	1	no	Horizontal yes, vertical no	0° and 90°	Plastic
OmniTread-Pipes [33]	Pipe	0.3m	unk.	1	no	no	22°	PVC
AIRo-2-Pipes [36]	Pipe	0.1m	14.5	> 2	no	yes	0° and 90°	Vinyl chloride
PISP1-Pipes (2-walls) [18]	Pipe (2 walls)	0.055m-0.331m	unk.	1	yes	yes (T-shape)	0°	Not specified
PISP2-Pipes (2-walls) [19]	Pipe (2 walls)	0.018m-0.1m	unk.	1	yes	no	0°	Not specified
PISP2-Pipes [19]	Pipe	0.05m and 0.075m	unk.	1	yes	yes (T-shape)	0°	Vinyl chloride
PISP3-Pipes (inclined) [20]	Pipe	0.055m and 0.08m	unk.	2	no	no	30°-90° (15°-step)	Vinyl chloride
CMU-MS-Slopes [21]	Slope	1.2m width (sidewinding)	5.1	4	no	no	−18.84° – 24.62°	Plywood
CMU-GT-Fluidized [30]	Slope (Granular)	Granular	2.1	1	no	no	0°-20°	Sand
CMU-SEA-BB [22]	Granular	Granular	unk.	1	no	no	0°	6mm BBs
OmniTread-Underbrush [34]	Granular	Granular	unk.	1	no	no	0°	Surrounding branches
CMU-MS-Mockup1 [9]	Mockup	Not specified $E_{cd}/A_{cd} \leq 2$	unk.	2	no	no	0°	Hard ground and PVC
CMU-MS-Mockup2 [10]	Mockup	Not specified $E_{cd}/A_{cd} \leq 2$	unk.	1	no	no	0°	Hard ground
CMU-MS-Mockup3 [11]	Mockup	Not specified	unk.	1	no	no	0°	Hard and rough ground

- *Design built-in performance data capture* This high physical fidelity testbed must be designed to support the capture of macroscopic performance data. The motivation is to support a thorough analysis of how well the snake was moving, where it experienced problems, and what were the contributing influences on the performance. In particular, the testbed should support good camera angles to capture performance and possibly even 3D motion capture. Any other sensors for recording the ground truth of movement should be considered. IR sensors could be used for accurately measuring the entry and exit times in each module. The data captured should be able to reveal how well the snake is interacting with the whole test course, as well as each individual subregions, so that the researchers could be aware of the strength and weakness of the snake of interest when dealing with different environments.
- *Design realistic Human–Robot Interaction and teleoperation scenarios* One important aspect which is largely overlooked in current testbeds are human–robot interaction and teleoperation possibility. Testbed should avoid direct line-of-sight visual from the operator to the snake robot, if the real-world scenario precludes this possibility. Human-in-the-loop tests should only give the human operator the same amount of situational awareness as they will get in real operational missions. The high fidelity is not only in terms of physical interaction, but also a complete simulation of the actual application scenario.

4.3. Testbeds for dimensionless comparison of different snakes

Different from the first one, this type of testbed focuses more on performance comparison of individual robotic components, including locomotion, control and sensing. The design of such a testbed should be guided by these principles:

- *Design adjustable testbed components* This kind of testbed provides dimensionless performance comparison of different snake robots, where the dimensions of each snake is a result of prototyping, not a design for a specific work envelope. The dimensionless aspects include scale, verticality, and tortuosity. For instance, given 2 snake robots that use different methods of gait control in transversal movements, one is much larger than the other and thus one robot will be penalized by having too much or too little clearance. In this context, the performance cannot be directly compared. This type of testbed should have adjustable scale and size-specific traversability properties to address this problem. It could have fixed sized modules that would be substituted for a different size snake or perhaps walls, liners, or pegs to change the diameter or boundaries. It can also use adjustable components, such as slopes with changing angles or pegboards with adjustable peg clearance and tortuosity. Reconfigurable modules could as well help to create test environments with similar difficulty levels so that multiple trials can contribute to test statistical significance for thorough comparison.

- *Design built-in performance data capture* Built-in data capture methods are also of importance for this type of testbed. However, the data capture would focus on a more microscopic perspective since a comparison of individual robotic components are of interested to this type of testbed. For example, the movement of each individual snake joints or segments could be recorded to enable precise snake gait analysis. Physical interplay between snake robot and the obstacles, such as Force Sensing Resistors or elastic deformable components for physical interaction as per [15,25], could reveal how well the locomotion principle was interacting with the environments. Those kinds of performance data capture are out of the scope of the macroscopic investigation of the first type of testbed.

4.4. Hybrid testbed for general purposes

Although the two types of testbed have different testing purposes, the design components of the second type is primarily a subset of those of the first one, but with more detailed microscopic perspectives. It is possible to design a hybrid testbed that supports the purposes of both kinds. In other words, a combination of multiple second type testbeds could be integrated as one complete first type testbed. For example, a peg board with adjustable peg distance, pattern, and diameter can serve the purpose of the second type testbed to compare snakes with different scale and creating different tortuosity. A pipe library with a variety of inner diameters and an adjustable slope can compare snakes of different sizes in environments with different verticality. Those testbeds could be designed and built as a second type testbed. However, a combination of them could be used to simulate a post-earthquake collapsed building, where snake robots are used for search and rescue. Each subregion adds up to a high physical fidelity target application. In this sense, a hybrid testbed is possible that can serve both purposes at the same time.

5. Conclusion

Twenty testbeds for 12 different snake robots have been described in 31 papers. The current state of the art in testbeds is that each testbed is designed ad hoc for a specific robot, its intended performance metric, and expected idealized environment. The difficulty of navigating through a path in a testbed is not quantified, the test methodologies are not standardized, and data capture methods are not consistent. The testbeds do not support comparing snakes independently of the scale of the environment and generally do not consider traversability factors beyond verticality. As a result, it is not clear how effective these testbeds are for predicting the actual performance of a snake robot in actual field conditions. While none of the testbeds were intended for comparing different snake robots, this review confirms expectations that no existent testbed could be easily adapted for quantitatively comparing performance of different snakes or algorithms.

The state of the art in snake robot testbeds and the metrics in [5] suggest three recommendations:

(1) If the goal of the testbed is to measure performance for a well-defined target application, researchers should focus on high physical fidelity of the robot work envelope, along with Human–Robot Interaction and teleoperation aspects. The testbed should represent traversability elements in the target application. Modular and reconfigurable components would add to the variety of test trials within the high fidelity testbed. Data capture approaches need to be precise, objective, and automated. Close attention should be paid to the possibility of Human–Robot Interaction and teleoperation.

(2) If the goal of the testbed is to compare different snakes, researchers need to focus on dimensionless measures with cross-sectional scale, length scale, verticality, and tortuosity as a minimum. This means the testbed will likely have to contain adjustable components to provide dimensionless comparison between snakes of different sizes. The testbed should also integrate data capture devices.

(3) If only one testbed is to be built, this hybrid testbed should consist of multiple modular and reconfigurable test courses that can be used to provide dimensionless measures to compare different snake robots. At the same time, the combination of those test courses could add up to a high fidelity work envelope to simulate target applications. Embedding data capture sensors are also recommended for the hybrid testbed.

It is worth to propose and remind that snake robot researchers should pay attention to real world values when designing their robot and a general testbed is an effective approach to help with that. The ultimate goal of developing a snake robot is never to achieve certain ad hoc locomotion capabilities, but to use them in their targeted real world applications where humans and traditional robotic platforms cannot approach, in particular, granular and restricted maneuverability environments. The testbed aims at this ultimate purpose of designing and deploying snake robots, not intermediate results. A general testbed can help them to determine and quantify if their snake can have a real world impact in granular and restricted maneuverability spaces, which are the primary reason to develop this type of versatile hyper redundant locomotor. The metrics and features of a general testbed proposed in this paper are from real world disaster robotics and its applications, from an objective point of view not in favor of any particular contributions. The design of the general testbed should be based on "what we need" (in real world disaster), not "what we can do" (snake robot capabilities). Lessons learned from actual disasters are the only evaluation metric, which is defined in [5] and is not biased toward any snake robot. Contributions to improve snake performance in the proposed general testbed could be defined as important since the testbed's high fidelity to disaster environments will guarantee a real impact when deploying the snake robot.

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