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A Survey of Snake-Inspired Robot Designs

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ABSTRACT

Body undulation used by snakes and the physical architecture of a snake body may offer significant benefits over typical legged or wheeled locomotion designs in certain types of scenarios. A large number of research groups have developed snake-inspired robots to exploit these benefits. The purpose of this paper is to report different types of snake-inspired robot designs and categorize them based on their main characteristics. For each category, we discuss their relative advantages and disadvantages. This paper will assist in familiarizing a newcomer to the field with the existing designs and their distinguishing features. We hope that by studying existing robots, future designers will be able to create new designs by adopting features from successful robots. The paper also summarizes the design challenges associated with the further advancement of the field and deploying snake-inspired robots in practice.

1. INTRODUCTION

Snakes have a wide range of locomotive capabilities, ranging from crawling and burrowing to climbing and even swimming. While all snakes have a similar structure, they do exist in a variety of sizes and aspect ratios. For example, snakes such as the Boidae family (Boas and Pythons) tend to have thicker, heavier bodies, while snakes in families such as the Leptotyphlopidea family (thread snakes and worm snakes) tend to have thinner body types. Snakes also range in length from more than 8000 mm for reticulated pythons and anacondas, to substantially less than 250 mm long for many of the smaller varieties.

The design of a snake is a simple structure that is repeated many times. Snakes bodies are elongated forms that consist of a long backbone made of many vertebrae. In fact, there are only three different kinds of bones in the entire snake skeleton: the skull, the vertebrae, and the ribs. Snake backbones consist of 100-400 vertebrae, and the design of each vertebra allows small motions in both the lateral and vertical directions. They do not allow any twisting, however, and thus act as compliant universal joints. Each vertebra itself only allows a very small amount of angular motion, but the motions of many vertebrae allow snakes to drastically curve their bodies. Each vertebra allows rotation of 10-20 degrees in the horizontal plane, and between 2-3 degrees in the vertical plane.

Snake-inspired locomotion provides the following advantages over traditional forms of locomotion in both animals and machines.

- Due to their elongated form and lack of legs, snakes have compact cross-sections and thus can move through very thin holes and gaps. Likewise, snake-inspired robots have much thinner cross sections than other robots with equivalent sizes and capabilities. In addition to the thinner cross section, snakes also have the ability to climb up and over obstacles that are much taller than their body height. This is done by lifting the front half of their long bodies.

Similarly, a snake-inspired robot can lift its body up and over obstacles much larger than most legged or wheeled devices. These properties are very desirable when moving through complex and cluttered environments.

- Gaits used by snakes for locomotion are very stable. Because their bodies are constantly in contact with the ground at many different points, it is difficult to knock them over, especially since they have a low center of mass and do not lift their bodies off the ground much during locomotion. The form of locomotion that snakes use also relies on a large amount of contact between the ground and the posterior. This large surface area gives the snake good traction characteristics in variable environments. Whereas one wheel or leg in a traditional kind of robot may slip, the large contact surface of a snake-inspired robot would make this occurrence less likely.
- Snakes have redundant designs that rely on the same kind of joint (and structure) that is repeated many times. This means that if one joint fails, the snake can continue to locomote. The simplicity of the design also means that the snake does not have any fragile appendages that can easily break.
- Snakes are very versatile and can act as both locomotors and manipulators, as they can use their bodies to wrap around objects to grasp them. This can be seen in the climbing action across tree branches, or when a constrictor is clenching its prey. Since one structure can do both things, the need for different mechanisms to achieve different tasks is eliminated.
- Despite frictional opposition to their locomotion, snakes actually have been shown to consume a comparable amount of energy to other biological forms with similar sizes, weights, and speeds. This can be explained by the fact that snakes do not perform a significant amount of lifting of their body in their motion, and they also do not consume as much energy by moving different appendages like legged animals.

Snake-inspired robots were introduced in the early 1970's by Shigeo Hirose [1]. Since that time, numerous snake-inspired robot designs have been conceived and prototyped. Although the various robot designs follow the common theme of mimicking snake locomotion, they may differ greatly in physical configuration and purpose. For example, some robots are redundant; while others are hyper-redundant and others still may have no redundancy at all. Some robots use powered wheels or treads, while others may use passive wheels or no wheels at all. Some designs are even amphibious, traveling effortlessly between ground and water environments. Snake-inspired robots have been proposed for missions ranging from exploration to search and rescue to military reconnaissance and surveillance. There are four major snake locomotion gaits: (1) lateral undulatory, (2) concertina, (3) crotaline (or sidewinding), and (4) rectilinear progression. The majority of snake-inspired robot designs use either lateral undulation or rectilinear progression.

The goal of this paper is to develop a general classification of snake-inspired robots based on a survey of published designs to aid a designer in determining which aspects of proven designs may be useful in a given application. This paper will help the designer to understand the strengths and weaknesses for various designs. By studying existing robots, future designers will be able to create new designs by adopting features from successful solutions. The paper also summarizes the design challenges associated with the further advancement of the field and deploying these robots in practice.

Due to the space constraints, it was not possible to discuss every published snake-inspired robot designs in the paper. Instead, we have tried to create a taxonomy to which a significant number of published snake-inspired robot designs can be mapped. Based on the survey conducted, the general categories of snake-inspired robot designs were determined to be: (1) robots with passive wheels, (2) robots with active wheels, (3) robots with active treads, (4) robots based on undulation using vertical waves and (5) robots based on undulation using linear expansion. This work will also provide various examples of snake-inspired robots in detail to support each category. The criteria for selection of the design examples include: availability of detailed mechanical design information, knowledge of intended application, validation of design functionality thorough a physical prototype. Finally, a comparison of some representative designs of this taxonomy will be presented in this work and the results of the comparison discussed in detail.

2. CATEGORY I: ROBOTS WITH PASSIVE WHEELS

The first category of snake-inspired robot designs to be covered is arguably the most well known: snake-inspired robots with passive wheels. Since their introduction by Shigeo Hirose, a number of current robot designs executed lateral undulation using passive wheels to mimic snake motion [1]. Lateral undulatory motion, also known as serpentine motion, is considered one of the fastest, most common modes of the travel for snakes and is employed by both land bound snakes and swimming snakes [3]. Serpentine motion is also one of the most recognizable snake locomotion gaits by the general public. It is described by a series of S-shaped, sinusoidal-like curves that the body forms while in execution. In most robots, this motion is usually mimicked by the utilization of serpenoid curve, introduced by Hirose, and using passive wheels to resist lateral movement of the robot’s segments [1].

In this section, we will discuss in detail Active Cord Mechanism designs and AmphiBot robot designs. Additionally, noteworthy robot designs with passive wheels also include the Michigan Snake 1 (MS-1), the Variable Geometry Truss (VGT), G.S. Miller’s robot family and a robot design introduced by Dalilsafaei 2008. The MS-1 design introduced an interesting variation of previous passive wheel-based snake-inspired robots, which utilized links with linear solenoids with sharp tip pins and ball casters to achieve forward motion [3]. The VGT consisted of a longitudinal repetition of 10 identical truss modules, each one equipped with idler wheels and linear actuators in a 3-DOF planar parallel manipulator configuration [5-7]. G.S. Miller developed a series of snake-inspired robot, S1-S5, which utilized passive wheels on the bottom to assist in movement using a lateral serpentine gait [8-10]. In addition to mimicking the movements of snakes, Miller’s design goals also included realism and aesthetics as part of the robot design, which led to his most sophisticated design, called the S5. The robot design, introduced by Dalilsafaei, used an artificial muscle actuator which consisted of a motor and a set of ropes to control the relative motion between robot modules [11]. The modules were connected to one another through rubber joints.

2.1 Active Cord Mechanism 3 (ACM III)

The ACM III, introduced by S. Hirose, consisted of 20 links and was capable of only 2D motion [1, 12]. At the core of Hirose’s theories about snake locomotion was the fact that the scale pattern produces anisotropy in the friction coefficients between the lateral and tangential frictions on their ventral surface. This concept is the basis for forward propulsion using the serpentine gait. In order to mimic the function the snake’s scale pattern performs in a robot, Hirose placed small wheels on casters on the bottom of each link, facing in the tangential direction of the length of the robot. This resulted in a very low friction coefficient in the tangential or forward direction and a high coefficient in the lateral direction. The links were connected using powered joints that allow rotation relative to one another, and locomotion was accomplished by propagating a wave in the form of the serpenoid curve throughout the robot. This meant that locomotion was only accomplished through shape changing, like a real snake.

The primary applications of the mechanism were to further Hirose's study of snake-like motion and demonstrate the serpenoid curve developed by Hirose. The robot was mostly demonstrated over smooth surfaces and labyrinths with walls equal in height to the robot. The robot, shown in Figure 1, had a length of 2000 mm and weighed 28 kg. Each link was 162 mm in height, 102 mm in length, and 144 mm in width. Each joint was actuated using a servo system that consisted of a 10W DC motor and a potentiometer. The servomotor in each segment could bend each trailing segment to the left and right. In laboratory experiments, the ACM III utilized limit switches as tactile sensors to signal the robot when it was in contact with walls or obstacles. The tactile sensors allowed the robot to react to its environment and conform to irregular channels in labyrinth experiments. The ACM III achieved a forward velocity of 400 mm/s.

2.2 ACM-R3

Hirose later applied his results with the initial ACM robots to an improved robot design called the ACM-R3, illustrated in Figure 2 [12-15]. The most obvious differences in the ACM-R3 compared to previous designs were that it was capable of 3D motion and it had large wheels on all sides of the body. These large passive wheels had diameters of 110 mm, and added additional functionality to the system because they can roll against contacted obstacles. The links were designed to contain all the components within a shell that had orthogonal axes of rotation on each end. In addition to serpentine locomotion, the robot could also lift its body up to move over obstacles. Hirose also experimented with other gaits on using this mechanism, including lateral rolling and sidewinding gaits. This design provided a marked improvement over the first ACM because it was self-contained, meaning that it had on-board power and could be radio-controlled.

The ACM-R3 was designed to be more functional in an actual search and rescue application. The ACM-R3 had a width and height of 110 mm due to its 110 mm diameter passive wheels. It had a total length of 1755 mm and weighted 12.1 kg. The maximum twist angle of any of the joints was 62.5 deg in each direction (without wheels it is 91 deg). A key requirement in the development of this design was that the robot be able to lift its body weight up. Hirose accomplished this by using servomotors that could provide a maximum of 19.1 Nm of torque and a joint speed of 36 deg/s, and the design could lift 8 units up. It was not documented if the robot was equipped with sensors or not, however, the robot was commanded by an operator with an R/C controller. Unlike the initial ACM robots, that used an electrical power supplying tether, the ACM-R3 contained batteries for power. Each unit contained its own battery and controller, making the design fully modular. The design provided an extra DOF such that the robot could lift up to maneuver over obstacles. The design, however, still required a flat enough surface to allow the wheels to roll in order to achieve locomotion.

2.3 ACM-R5

The ACM-R5, shown in Figure 3, was an amphibious design also introduced by Hirose and his design team [12, 15, and 16]. The joint between each segment or module of the robot consisted of a universal joint and bellows. The universal joint acted as the bones and bellows acted as an integument, an enveloping layer (as a skin, membrane, or cuticle) of a snake. The universal joint had one passive twist joint at the intersection point of two bending axes to prevent mechanical interference with bellows. The robot consisted of nine segments with 2-DOF joints between the segments. To generate propulsive force by undulation, the robot needed a resistance property to allow it to glide freely in a tangential direction but not in a normal direction. Due to the inclusion of paddles and passive wheels around the body of each segment, the robot obtained that resistance property on both ground and in water.

The ACM-R5 measured 1750 mm in length and 80 mm in diameter. The robot's total weight was 7.5 kg. Actuation was achieved by a pair of servomotors in each water tight module, which were capable of 9 Nm of torque each. Maximum joint speed was 70 deg/s. The ACM-R5 incorporated an advanced control system. Each modular unit had a CPU, battery and motors so that they could operate independently. Each unit automatically recognized its number from the head and how many units were in the robot through communication between the modules. Using this system, an operator could easily remove, add, and exchange units without major modification to the robot. Although the robot was quite advanced and performed well on flat surfaces and in the water, the robot was still mostly a demonstration platform. Hirose and his design team stated that "a large number of problems still remain for realization of practical snake-like robots, both in software and hardware."

2.4 AmphiBot I

AmphiBot I, shown in Figure 4, was a modular amphibious snake-inspired robot, constructed out of several identical segments, known as elements [17]. As quoted by the authors, "The project does not aim at mimicking a snake or a lamprey per se, but to take inspiration of their body shape and their neuronal control mechanisms to develop novel types of robots that exhibit dexterous locomotion." The robot design included seven actuated elements. Each of the robot's elements had a one DOF and the elements were fixed such that all axes of rotation were aligned. The robot was designed to have distributed actuation, power and control; therefore, each element carried its own DC motor, battery, and microcontroller. For motion on a terrain, the robot could be equipped with removable sets of passive wheels. To support its amphibious role, each individual element was made waterproof, as opposed to having a covering over the entire chain of elements. This approach was deemed preferable since it ensures that a possible leakage would only damage a single element. Also, each element was made to be slightly buoyant, so that the robot would passively float at the surface of the water when inactive. In addition, the center of gravity of each element was purposely placed below the geometrical center, in order to obtain a vertical orientation that self-stabilized in water.

The application of the robot was to serve as a test bed to support two research goals of the authors: (1) to take inspiration from snakes and elongated fish such as lampreys to produce a novel type of robot with dexterous locomotion abilities, and (2) to use the robot to investigate hypotheses of how central nervous systems implement these abilities in animals. Each element of AmphiBot I had a length of 70 mm and a cross-section of 55 mm by 33 mm. The robot had a total length of approximately 490 mm. Each element was actuated using a 0.75W DC motor which drives a set of reduction gears with a reduction factor of 400 and an efficiency of approximately 60%. The DC motors had a maximum torque of 1.2 Nm. The output axis of the gears was connected to a potentiometer and the next element. Each joint could achieve a maximum oscillation frequency of approximately 0.3 Hz if the full amplitude (±45 deg) was used. The speed of the robot had been measured by running the robot on a Styrodur® plain surface, a type of rigid polystyrene foam. This material was chosen by the authors due to its properties of friction with the wheels of the robot. During trials, the robot achieved a maximum surface locomotion speed of 35 mm/s.

2.5 AmphiBot II

AmphiBot II, shown in Figure 5 was the newer version of AmphiBot I equipped with improvements based on trials of the first robot prototype [18]. The construction of AmphiBot II had been simplified, allowing all of the components to be assembled without soldering. The second robot was also equipped with more powerful motors, with maximum torque increased by a factor of 3.5 compared to the first robot design. Like AmphiBot I, the robot design included seven actuated elements, however with the included electronics suite; a robot with up to 127 segments can theoretically be built by simply adding other elements to the chain. The robot had also been designed to be tether-less, using wireless communication through an internal transceiver. Finally, AmphiBot II was equipped with central pattern generators (CPGs). The motor commands were generated directly in the robot, by the central pattern generator running on a microcontroller, therefore removing the need of running the controller on an external computer. The robot was still amphibious and made use of removal wheel sets to achieve locomotion on surface terrains.

Like AmphiBot I, the application of the robot was to serve as a test bed to support two new research goals of the authors: (1) to build an amphibious snake-like robot that can both crawl and swim for outdoor robotics tasks, taking inspiration from snakes and elongate fish such as lampreys, and (2) to demonstrate the use of CPGs as a powerful method for online trajectory generation for crawling and swimming in a real robot. Each element of AmphiBot II had a length of 94 mm and a cross-section of 55 mm by 37 mm. The total length of the robot was 772 mm. Each element was actuated using a 2.83W DC motor which had a maximum torque of 4.2 Nm and drove a gearbox with a reduction factor of 125. The output of the gear set was fixed to a connection piece that inserted into the next element. Internal to each element, a water detector circuit was placed at the bottom of the element and used internally to detect and localize any leakage. When water was detected, the circuit blinked a LED fixed through the top of the element, alerting the user of the leakage. Unlike AmphiBot I, the robot was primarily tested on wooden surfaces, as opposed to the Styrodur® plain surface, during speed trials. During trials, the robot was reported to have achieved a maximum surface locomotion speed of 400 mm/s. The robot was also report to have achieved a maximum swimming speed of 230 mm/s.

3. CATEGORY II: ROBOTS WITH ACTIVE WHEELS

The second snake-inspired robot category encompasses robots that utilized active driven wheels to provide propulsion for the robot. However, the robot designs still exhibit snake-like motion due to the multi-segment configuration. One of the main advantages of using powered wheels is ability to simulate snake-like motion without a large number of segments [12]. Powered wheels also generally are more able to deal with non-smooth terrain types. Although the introduction of powered wheels adds additional flexibility in terms of active DOF, it also adds additional complexity to the robot, which now has to actively control these additional DOF and coordinate them with the rest of the actuated joints during global movement.

In this section, we will discuss the following four robot designs in detail: Koryu-II, GMD-SNAKE2, ACM-R4 and the NUTA Robotic Snake. In addition to these robots, two additional examples of robots with active wheels were the OBLIX and the Genbu robots. OBLIX was an oblique swivel mechanism-based 16 segment robot arm prototype which was equipped with drive wheels and used mimic snake-inspired locomotion [1]. The oblique swivel joint rotated around an axis that formed an angle from the central axis of the arm and a coaxial swivel joint. Genbu1 was characterized by multiple bodies connected by passive joints and multiple active wheels of large diameter [12, 19]. Bodies of Genbu2 were connected by elastic joints so that the robot can change the posture adaptively for terrain. Genbu3 was loaded with a motor driver and battery in each wheel, and micro controller in each body, providing it with adaptive control for the terrain.

3.1 Koryu-II (KR-II)

The KR-II, seen in Figure 6, had a similar configuration to the KR-I [1, 12]. The robot was formed from a lead unit (link 0) and six cylindrically shaped units (link 1-6) which had three DOF: the first in the rotational movement axis which swings to the left and right of each segment (q-axis), the second in the perpendicular movement axis (z-axis) which slides the segments up and down, and the third in the wheel axis (s-axis) for the purpose of forward advancement. Unlike its processor, KR-I, this robot used wheels instead of crawlers on the s-axis for the purpose of lightening the unit. The robot configuration also made use of a unique construction, where each unit was supported by an independently powered single wheel. This configuration allowed the robot to adapt to a variety of ground shapes through use of the powered z-axis. The robot was also equipped with a large manipulator arm mounted on the lead unit.

The robot was designed to further the development of robots which made use of an articulated body to distribute loads and carry them, much like a train. This type of robot was meant to function in environments were large body robots were typically not maneuverable enough to negotiate turns in a cramped spaces and small robots could not transport the operational equipment that will be needed. KR-II had a total length of 3300 mm and a total height of 1080 mm. The link 0 had weight of 25 kg and links 1-6 had a weight of 50 kg. The robot had a width of 460 mm and had a total weight of approximately 370 kg. The driving system for each wheel was a DC motor. The robot was able to propel itself over rough surfaces and elevated surfaces by impedance control through the use of optical force sensors attached to the z-axis and the s-axis. The robot had been demonstrated on steps, outdoors, and city street environments, while running autonomously. The robot was able to travel on a sloping surface of up to maximum incline of 48 deg. The maximum speed of the robot observed on a flat terrain was 500 mm/s.

3.2 GMD-SNAKE2

In 1999, Klaassen and Paap introduced an improvement over their previous GMD-Snake robot, the GMD-Snake2, which imitated the rectilinear motion of a snake [20]. The robot is illustrated in Figure 7. Klaassen and Paap noticed that the main propulsion of a snake during rectilinear motion came from hundreds of tiny scales that are moving ahead and back on the bottom side of the snake. To imitate this motion, they determined that the sections of their mechanism needed to follow two main principles: (1) each section should be actively moveable in direction of its longitudinal axis and (2) each joint should bend according to the movement of its predecessor with a certain delay. The GMD-Snake2 design consisted of six active segments and a head segment.

The robot was designed to be rugged for practical applications, such as, inspection of sewage pipes. The diameter of this robot was 180 mm and the length was 1500 mm. The robot had a mass of 15 kg. The GMD-Snake2 consisted of cylindrical segments that were connected by universal joints and had an array of 12 electrically driven wheels evenly spaced around each segment, driven by small motors. Additionally, the position of each joint was controlled by three motors that used small ropes to move the joint. Links were built around an aluminum cylinder with holes on the surface. The device could be operated on a tether, or the last section could be entirely filled with batteries. Each section contained its own processor and communications were achieved via a bus. Therefore every section could calculate the delay after which its own joint position must be identical to the predecessor's former position and when it had to send this data to its successor. The robot was also equipped with an array of sensors, including six infrared distance sensors, three torque sensors, one tilt sensor, two angle sensors in every segment, and a video camera.

3.3 ACM-R4

Building upon the success of the ACM-R3 design, Hirose's lab developed a version of the ACM which utilized powered wheels known as the ACM-R4, illustrated in Figure 8 [12]. The robot followed the same basic structure of the ACM-R3 by utilizing a series of joint units, each with one DOF. The robot consisted of 18 units. The robot design was reported to have the following advantages: (1) the design of a 3D motion capable ACM became relatively easy, (2) the joints range of motion became relatively large, and (3) the robot could be equipped with large wheels at the same axis as the joints. The ACM-R4 used motors to drive the wheels. In general, snake-inspired robots could generate propulsive force by undulation and omit the use of motors to drive the wheels. However, this movement required a large number of joints, so the developers adopted active wheels from the viewpoint of practical use and reduced complexity of the robot through other elements of the design.

The robot was designed to explore the practical use of snake-inspired robots in a narrow environment such as inside a pipe, or in a disordered environment such as a disaster site. The ACM-R4 robot had a total length of 1100 mm and a cross-section of 135 mm by 135 mm. The robot's total weight was 9.5 kg. The joints were actuated by electric motors capable of a maximum torque of 20 Nm and a maximum joint speed of 30 deg/s. To function within its mission environment, the robot was designed to resist water and dust. Experiments using the robot have confirmed the ability to make right-angle turns in a 240 mm wide passage and climbing of 400 mm high step. In addition, experiments confirmed a continuous 3 hours of operation in muddy water.

3.4 NTUA Robotic Snake

The National Technical University of Athens (NTUA) robotic snake was introduced as a multi-articulated mobile robot design to access complicated and unstructured areas inaccessible to human operators [21]. The robot consisted of seven links which were connected by six revolute joints. The first link had free space to carry a payload or instrumentation. With the exception of the first link, the robot was composed of three modules which were made up of two links and the six revolute joints. Two of the revolute joints provided relative motion between two successive links about a horizontal and vertical axis. Another two revolute joints provided relative motion about the central axis of the robot's cylinder-shaped body. The last two joints provided relative motion on vertical axis for each wheel through small servomotors, which allowed precision turning control for each wheel. Additionally, the forward half of each module was equipped with two independently driven wheels to provide forward propulsion. The total robot had 24 DOF.

The primary purpose of this robot design was to experiment with a robot that was able to perform inspections and minor repairs in industrial environments such as nuclear power plants. One of the main design points was to ensure that the robot would be able to traverse inside medium and large size pipes. Each module of the robot was 541 mm in length and 11.5 mm in height. The modules each weighed 5.5 kg. The total length of the robot was 1650 mm in length and 16.5 kg in weight. The robot's configuration allowed it to traverse a minimum piping internal diameter of 150 mm. The maximum load capacity of the robot was 0.5 kg. Each revolute joint about the vertical and horizontal axes was powered by a brushed 22W DC motor and gear chain. The system provided a maximum torque of 14.4 Nm at the joint at an average speed of 45 deg/s. The revolute joints about the central axis were powered by small brushed 6V DC motor with a gear reduction ratio of 102. The wheels were driven by small DC motors. The robot had the ability to lift the front link to a maximum height of 700 mm enabling it to overpass obstacles with a maximum height of 250 mm.

4. CATEGORY III: ROBOTS WITH ACTIVE TREADS

The need for natural disaster relief efforts, such as search and rescue operations following a major earthquake, had inspired the design of several snake-inspired robots which utilized powered treads or crawlers to traverse extremely rough terrain [12]. Considering that it was very difficult and dangerous to creep into the debris to find victims, robots which could maneuver in this environment in order to find these victims with TV cameras and microphones were highly desired. Such robots which combined the capability of treads with the advantages of snake-inspired robots would be able to navigate small, tight openings within the debris and locate and assess the condition of possible survivors, and allow rescuers to focus their effort more efficiently in extremely time critical scenarios.

In this section, we will discuss in detail four robot designs: Koryu-I, the OmniTread robots and the JL-I. Other noteworthy examples of such robot designs were Souryu I and II and MOIRA snake-inspired robots. In 1997, Hirose-Fukushima Robotics Lab introduced the Souryu I and II robot designs for search and rescue operations following disasters such as earthquakes [12]. The robots were composed of three parts: (1) front body, (2) center body, and (3) rear body, and each body segment was equipped with a crawler on both sides. The front body included a CCD camera and a microphone to find victims, the center body included the driving actuators and batteries, and the rear body included the radio receiver. The crawlers were driven all at once by the motor at the center of the body through the use of universal joints. The MOIRA robot was a serpentine robot that used tracks for propulsion and pneumatics for joint actuation [22, 23]. MOIRA was comprised of four segments, each with two longitudinal tracks on each of its four sides, for a total of eight tracks per segment. The 2-DOF joints between segments were actuated by pneumatic cylinders.

4.1 Koryu-I (KR-I)

The first Koryu robot design illustrated in Figure 9, prototype KR-I, was developed by Hirose to explore the possibility of a functional ACM being used in restricted spaces [1, 12]. The full scale robot design was meant to carry manipulators, visual equipment, communication equipment, and computer hardware. The full scale design would also have to traverse slopes of 40 deg, overcome level differences of 300 mm in height and breadth and operate in passage way with a maximum width of 600 mm and height of 1500 mm. The robot prototype consisted of six cylindrical sections with 16 DOF. The robot was characterized as being able to allow two DOF of movement to operate: the z-axis and the θ-axis. The translation of the sections mutually at their coupling points on a vertical axis was known as the z-axis. The rotational movement around a vertical axis of each section was known as the θ-axis. In addition, there was an s-axis that described the crawlers, mounted at the bottom of each section, used to generate propulsive movement for the robot. There were five z-axis actuated joints, each between two robot sections, and similarly five θ-axis actuated joints. There were six powered s-axis drives, each underneath a section of the robot, which gave the robot the total 16 DOF.

The concept of the robot design was meant to negotiate passages supplied for service workers inside a nuclear reactor and carry outer inspections and other tasking. Each section of the robot had a diameter of 206 mm. The robot had a length of 1391 mm and a total height of 393 mm. The mass of robot was 27.8 kg. The z-axis was actuated with a 30W drive motor with a rated torque output of 180 Nm and a maximum speed of 80 mm/s. The θ-axis was actuated with a 30W drive motor with a rated torque output of 4.7 Nm and a maximum speed of 50 deg/s. The s-axis was powered by a 12W drive motor with a rated torque output of 44 Nm and a rated speed of 532 mm/s. The crawler unit was driven with a reduction ratio of ½. Each section was equipped with a force sensor between the crawler segment and the body of the section. The force sensor was based on an optical detection system and provided information to the impedance based control system of the robot. The robot was demonstrated on flat surfaces, climbing over obstacles and crossing gaps. The robot was capable of a maximum forward velocity of 266 mm/s.

4.2 OmniTread OT-8

The first OmniTread robot was called the OT-8 and is shown in Figure 10 [24]. This robot consisted of five segments that were connected by four, 2-DOF joints. The propulsion of the robot was achieved by an innovative means: using tank treads on the four sides of every link. The tank tread design maximized the “propulsion ratio”, the ratio of surface area that was active in propulsion to the surface area that was not. In order to maximize this ratio, tank treads covered as much of the sides as possible and the gap size between the links were minimized. The idea behind the maximization of this ratio was that any environmental feature that contacts the robot at a location not covered by treads would not impede the motion. Treads on each side also made the design indifferent to falling over. The second innovative feature of the OmniTread design was that it is designed with pneumatic bellows that acted as the actuators between the segments. The bellows allowed compliance between the segments, allowing the robot to passively conform to the terrain to maximize traction. The pneumatic bellows meant that stiffness could be adjusted “on the fly”. An example of when this would be needed was when the robot was climbing over a gap. Thus, the bellows were used to both actuate the joints and adjust the compliance. A total of 16 bellows were used, which gave the robot 16 position parameters and 16 stiffness parameters. Two valves were used to control each bellow.

Like many other snake-inspired robot designs, the robot was designed to support research into a robot which can perform operations in difficult to reach areas or environments which many prove very dangerous to human operators. The dimensions of the OmniTread OT-8 segments were 200 mm by 185 mm by 185 mm and the entire robot was 1270 mm long, including the 68 mm of joint space between each segment. The complete robot weighed 13.6 kg. One motor provided the power to all of the tracks in the robot using a central drive shaft spine running the entire length of the robot, using universal joints. Each universal joint was located in the center of the space between segments (between the bellows) in order to maintain structural rigidity. The motor used was a 70W DC motor using a 448:1 total gear reduction from the motor to each of the tread driving sprockets. Using the unique pneumatic bellows configuration, the robot was able to achieve a minimum turning radius of 530 mm. The robot has demonstrated the ability to climb up a curb more than 36% of its length, and 240% of its height. Additionally, the robot could lift up two of its head or tail segments. The OT-8 operated off of a power and pneumatic tether. The OT-8 demonstrated a maximum forward velocity of 100 mm/s.

4.3 OmniTread OT-4

The OT-4, shown in Figure 11, was the improved version of the OT-8 and was named as such because the OT-4 could pass through an opening as small as a diameter of 4 in (101.6 mm), while the OT-8 could only traverse openings no smaller than a diameter of 8 in (203.2 mm) [25, 26]. The robot consisted of seven segments as opposed to the five of the original OT-8. Besides the smaller size, the OT-4 possessed other improvements in design over the OT-8, such as, a tether-less design. The OT-8 required a tether to provide compressed air and electric power to the pneumatic bellows and electric drive motor. The OT-4 carried onboard compressed gas tanks and electric batteries. The robot also had the ability to selectively disengage individual tracks from the shaft spine through the use of electrically actuated micro-clutches to reduce power consumption when the tracks were not needed. Finally, the OT-4 contained payload compartments in the first and last segments to carry sensor equipment, tooling or any other required payload for an operation.

The OT-4 shared the same intended application as the OT-8: the robot was designed to perform operations in difficult to reach areas or environments which may prove very dangerous to human operators. The motor or drive segment of the robot was 109 mm in length and the actuator segments are 103 mm. The pneumatic joint assemblies had a length of 36 mm. This gave the OT-4 a total length of 940 mm and a cross-section of 82 mm by 82 mm. The robot was a much lighter design at 3.6 kg, compared to the 13.6 kg OT-8. The pneumatic bellows were powered using a miniature air compressor and liquid CO_2 tanks. The pneumatic system allowed the robot to lift a maximum of three of its segments from the terrain. Also, utilizing the pneumatic bellows for steering, the robot was able to achieve a minimum turning radius of 229 mm. The DC drive motor was powered by onboard Lithium-Polymer batteries that could provide power for up to 60 minutes of operation. The micro clutch mechanism consisted of a 6 mm diameter micro-motor, which drove a lead screw to engage and disengage a worm gear with its worm using a 4-bar mechanism. Electric limit switches prevented improper engagement of the gear and worm. Like the OT-8, the OT-4 demonstrated operation over many terrain types such as gravel, dirt, ramp conditions and smooth surfaces. Similar to the OT-8, the OT-4 demonstrated a maximum forward velocity of 150 mm/s through various testing.

4.4 Reconfigurable Robot JL-I

A novel reconfigurable modular robotic system named JL-I was introduced in 2006 by Zhang et al., with the ability to traverse terrain with snake-like motion [27, 28]. JL-I, illustrated in Figure 12, was really a three-part robot system that utilizes a unique docking mechanism, which endowed the robot with the ability of changing shapes in 3D space. The three modules were identical and were capable of individual locomotion through a pair parallel powered treads. The docking mechanism consisted of 3-DOF active spherical joints between modules and enabled the adjacent modules to adopt configurations to negotiate difficult terrain or to split into three small units to perform tasks simultaneously. The robot was capable of climbing stairs, crossing gaps, and recovering from roll-over conditions. The robot was also capable of performing rolling about the x-axis, pitching about the y-axis, and yawing about the z-axis to change its posture. A parallel mechanism was responsible for the yawing and pitching movements of the robot. The rotation about the x-axis was achieved by the use of a serial mechanism.

The design purpose for this robot was to develop an automatic “field” robot for unstructured environments to meet the requirements of high flexibility, robustness, and low cost. A single module dimensions were about 350 mm in length, 250 mm in width and 150 mm in height. A module weighed approximately 7 kg, including the on-board batteries. A single module had two powered tracks, a serial mechanism, a parallel mechanism, and a docking mechanism. The tracks were driven by two DC motors which provided each unit with skid-steering ability in order to realize omni-directional movement. The docking mechanism consisted of two parts: a cone-shaped connector at the front of the module and a matching coupler at the rear of the module. The coupler was composed of two sliders propelled by a motor-driven lead screw. The sliders formed a matching funnel which guided the connector to mate with the cavity and enabled the modules to self-align with certain lateral offsets and directional offsets. Two mating planes between the sliders and the cone-shaped connector constrained the movement, thereby locking the two modules. The robot contained two types of external sensors: a CCD camera and tactile sensors. Its internal sensors included a GPS, a digital compass, a gyro sensor and limit switches which provided joint position information. In trials, the robot demonstrated that it was capable of climbing a maximum step height of 280 mm and a maximum ditch length of 500 mm. The robot demonstrated a maximum forward velocity of 180 mm/s and a maximum slope angle of 40 deg.

5. CATEGORY IV: ROBOTS BASED ON UNDULATION USING VERTICAL WAVES

Although the robots presented thus far mimicked snake-inspired locomotion, none of these robots advance using pure undulation or the changing of the robot’s position due entirely to changes in body shape (e.g., wheels, treads or legs are not used). However, there exist a number of snake-inspired robot designs which do utilize pure undulation, in particular rectilinear motion, to mimic snake-inspired motion. The next two sections will introduce snake-inspired robots which demonstrate rectilinear motion in one of two forms: (1) rectilinear motion using vertical waves and (2) rectilinear motion using expanding/contracting segments. In this section, the former type of rectilinear motion will be covered, which can be described as a creeping motion where a segment of the robot advances an adjacent segment forward while anchoring itself to the terrain. In turn, the “advanced” segment repeats the process for a segment adjacent to it until the entire robot has advanced forward a distance equal to the displacement of the first segment in the sequence.

In this section, we will discuss the following four robot designs in detail: Kotay’s Inchworm robot, Dowling’s Snake robot, the PolyBot and CMU’s Modular Snake robots. Other noteworthy examples of such robot designs were the NEC Quake Snake, GMD-Snake, Ver-Vite, CONRO and M-TRAN. One of the earliest recorded snake-like robot designs was the NEC Quake Snake, a 12-DOF teleoperated robot developed and introduced by Ikeda and Takanishi in 1987 [29]. The NEC Quake Snake consisted of six segments, each connected with a passive universal joint to prevent adjacent segments from twisting, while allowing bending and rotation about a lengthwise axis through the segment. The robot was capable of lifting one or more of its segments and was equipped with a small video camera in the front segment. In 1996, Paap et al. introduced the GMD-Snake, the predecessor to the serpentine robot GMD-Snake2 [30-32]. The GMD-Snake robot was designed to “show useful behavior by reacting flexibly within various environments” as inspired by observing real snakes creep across rough surfaces. Each internal section consists of two joints, composed of octagon-shaped aluminum plates, which used rubber joints to allow flexible bending. The segments were connected by means of cables to produce curvature horizontally or vertically along several segments simultaneously. The inchworm robot Ver-Vite, introduced by Rincon et al. in 2003, simulated inchworm locomotion with friction only and the use of variable masses [33]. The locomotion mechanism in Ver-Vite was inspired by the actually locomotion process observed in inchworms, known as peristaltic contraction. In this process, the widening of several segments serves to anchor that part of the body against tunnel walls, while other sections of the body are narrowed and elongated to extend the leading segment forward. In the Ver-Vite robot, the variable mass, water, was moved back and forth between the aft and forward sections of the robot in order to vary the weight of the segments in contact with the surface and thus increase the frictional force to anchor the segment to the surface. The CONRO and M-TRAN robot systems were examples of self-reconfigurable modular robots [34, 35]. These systems consisted of simple robot “blocks” which were capable of docking with one another to form more complex robot systems, such as snake-inspired robots.

5.1 Inchworm Robot Introduced by Kotay and Rus 1996

An inchworm robot, inspired by inchworm and caterpillar motion, was introduced by Kotay and Rus in 1996 for use in vertical climbing of steel structures [36]. The robot is illustrated in Figure 13. The robot had four sections, linked with three joints providing three degrees of freedom. These joints allowed the inchworm to extend and flex. The first and fourth sections were the “feet” of the robot. These sections contained attachment mechanisms which allowed the robot to adhere to the surface being traversed and provided the anchoring force needed to support the robot when walking. The attachment mechanism of the robot was comprised of electromagnets. These electromagnets provided enough force to securely anchor a foot and support the weight of the robot when the other foot is completely extended. Although the choice of electromagnets provided a large amount of holding force in a small package, it limited the use of the robot to steel surfaces. In 2000, Kotay and Rus introduced a second variation of the inchworm robot, which included an additional degree of freedom [37]. The fourth degree of freedom was provided by a pivot joint mechanism attached to the rear foot, allowing the robot to rotate relative to the rear foot. This pivot joint provided the robot with the ability to turn.

When fully extended, the length of the first inchworm robot was 252 mm and its height was 52 mm. When fully contracted, the length of the robot was 180 mm and its height was 120 mm. The weight of the inchworm robot was 0.455 kg. Joint actuation was achieved through the use of servomotors. The servomotors had a maximum torque of 0.52 Nm and a maximum joint speed of approximately 140 deg/s. The robot also possessed a suite of sensors in the form of four tactile and five infrared proximity sensors. The robot's power supply and control were provided through a tether. There were two 12-volt electromagnets per robot foot, arranged in-line with the body of the robot. The robot was designed to explore the possibility of using inchworm-like robots in general inspection of construction in 3D environments. The forward velocity of the robot was 4.2 mm/s, equivalent to one fully-extended robot length per minute. The second robot had a fully extended length of 330 mm and height of 80 mm. When contracted, it had a length of 175 mm and a height of 160 mm. The robot weight 0.566 kg and a forward velocity of 12.5 mm/s.

5.2 Snake Robot Introduced by Dowling 1997

Another early design of a snake-inspired robot utilizing vertical waves was developed by Dowling at Carnegie Mellon University [38]. The entire robot is shown in Figure 14. The robot was composed of 10 links, each with 2 DOF. Dowling developed the snake-inspired robot while studying gait generation using machine learning. Dowling took a comprehensive look at a wide range of possible actuation technologies that could be utilized in snake-inspired robots. The author is quoted as stating that "some of these [actuation] technologies were initially examined with the intent of using scaled snake vertebrae in a robotic mechanism." The final result of this study was a snake-inspired robot that could move in a 3D environment using only servomotor actuation. Dowling looked at the geometric design of a snake-inspired robot as it related to mission parameters. He determined the dimensions of curved and right-angle pathways that a snake could fit into as a function of link geometry and twist angle. Dowling found that the angle of motion was not as important as the link length. He determined that the link length should be as short as possible. The mechanical design of this robot consisted of an aluminum sheet with servos mounted to it. The servos were mounted orthogonally, so that each end of the link contained an actuated revolute joint. The rotating sections were mounted directly to the servo horn, and adjacent links were attached to each other such that orthogonal servos connect to each other.

The primary purpose for the robot's development was to support gait optimization studies. A gait optimization program would execute a given gait using the robot and observe its performance data to be used in an evaluation of the gait itself. Each link of the robot was 102 mm in length, thus the entire robot had an overall length of 1020 mm. The mass of the robot was 1.48 kg, and each link had a diameter of 65 mm. The joints of the robot were actuated using commercial servos which possessed a maximum torque of 0.84 Nm and a maximum joint speed of approximately 270 deg/s. The robot was controlled using centralized control and powered using a tether. The control circuitry was located in the "head" of the snake. NiCad batteries were proposed as a power source, but external power was used in the actual implementation. Additionally, a CCD camera was mounted on the head unit. An interesting feature of this robot was that the use of "skin" was investigated to provide desirable friction characteristics. Dowling proposed covering the entire robot in a fabric or material that would provide good friction characteristics in order to propel the snake forward. Several candidate materials were discussed and evaluated.

5.3 PolyBot Reconfigurable Robots

Another example of reconfigurable robots developed by Yim et al. 2000 is called PolyBot, illustrated in Figure 15 in a snake configuration [39]. The PolyBot mechanisms could be arranged in a form to mimic snake-inspired robot motion. The design philosophy behind PolyBot was that a number of small modules can be assembled into complex systems which could achieve complex tasks, even though the modules themselves are very simple. The segment module could be divided into three subsystems: 1) structure and actuation, 2) sensing, computation and communication, and 3) connection plate. The structure was made of a laser-cut stainless steel sheet and was basically cube shaped. The module's one DOF allowed these two faces to be rotated so they are no longer parallel. Each segment had two connection plates. The connection plate served two purposes. One was to attach two modules physically together. The other was to attach two modules electrically together as both power and communications are passed from module to module. PolyBot allowed two connection plates to mate in 90 deg increments which allowed two modules to act together in-plane or out-of-plane. The modules were used to simulate various locomotion types such as sinusoid snake-like locomotion, a rolling track, and a three-legged caterpillar-like locomotion. It is worth noting that this is an inactive project at Palo Alto Research Center (PARC) does not represent their most current work in reconfigurable robotics, such as, the Proteo and Digital Clay projects.

The primary purpose for the robot's development was to investigate the concept of developing modules which promised to be versatile, robust, and low cost, yet still could be used to assemble complex constructs. Each module was a 50 mm by 50 mm by 50 mm cube. A brushless DC motor with a 4 stage 134:1 gear reduction sat in the middle of the segment on the axis of rotation. Future plans included the use of a form of harmonic drive to reduce gear box space allowing the motor to sit within the module. In a snake-like configuration, the modules executed a sinusoid serpentine-like locomotion, which was demonstrated over a variety of obstacles including: crawling in 101.6 mm diameter aluminum ducting, up ramps (up to 30 deg), climbing 44.5 mm steps, and traversing over loose debris and wooden pallets.

5.4 CMU's Modular Snake Robots

Several modular snake robots, such as the robot illustrated in Figure 16, were designed and built by students from Carnegie Mellon University (CMU) [40-42]. These modular robots were used to demonstrate several snake-inspired gaits for accomplishing difficult tasks such as climbing, swimming, and crossing gaps. The each module consisted of a single servomotor, which created half of the structure of the module and provided the torque to move and maintain angles while resisting forces from the environment. To complete the other half of the joint a component was created, called the U case, which attaches to the output arm. The U case had one arm attached to the output of the servo and the other attached to the back of the servo to add strength. In addition to their mechanical design, the robots also utilized modifications to their outer surface to enhance performance in a number of environments. These modifications took the form of a full, possibly sealed, covering called skin or the adherence of additional material to the modules themselves, called compliance. The robot illustrated in Figure 16 is an example of a CMU snake robot utilizing skin covering. It should be noted that the decision to use either compliance or a skin did not impact the mechanical design and each skin could be interchanged. The compliance material may serve to increase the coefficient of friction between the robot and the surface in order to better simulate the function of a snake's scales in contact with the terrain.

The family of robots appeared to be primarily designed to support CMU's research into various snake-inspired gaits. These gaits fell into one of two categories: differentiable gaits, which could be described by a differentiable function, and more complex piecewise differentiable gaits, in which the time varying backbone curve they approximate was piecewise differentiable. The robot, Breadstick, was the lab's first metal snake robot, finished in late 2005. With the exception of the 1060 aluminum housing, the robot used many of the electronics and components from previous CMU plastic snake robot versions. The robot had a cross-section of 50.8 mm by 50.8 mm and a total length of 838.2 mm. The robot's total weight was 1.26 kg. The robot utilized 4.8-6V Hitec 645 Servos, which had a maximum torque of 0.94 Nm and a maximum rotational speed of 300 deg/s. The forward velocity of the robot was approximately 101.6 mm/s (based on observations from demonstration videos).

6. CATEGORY V: ROBOTS BASED ON UNDULATION USING LINEAR EXPANSION

The robots reported in Section 5 utilized rectilinear motion based on vertical waves formed by the robot's body to progress forward. However, rectilinear motion can also be achieved by linear expansion and contraction of the robot's body to form a gait similar to the gaits utilized by real snakes. In rectilinear motion demonstrated by snakes, lateral bending of the body and lateral resistances do not contribute to the motion in contrast to the other locomotion modes [3]. Instead, waves of muscular contraction travel through the snake in forward direction. These muscular contractions are capable of producing tensions between the vertebral column and the ventral skin and thus propel the ventral surface forward against frictional resistance.

In this section, we will discuss the following three robot designs in detail: the Slim Slime robot, Yeo's Planar Inchworm robot and the Telecubes. Another example of a robot which utilize linear actuation-based rectilinear motion is the inchworm robot introduced by Chen et al. 1999 [43]. The robot consisted of interconnected actuating modules that can either deform in the direction of travel (extensors) or grip against walls in the robot's environment (grippers). The robot was designed for use in traveling and conducting tasks in narrow and highly constrained environments, such as pipes and conduits in industrial plants. Each module had a cart-like geometry moving along a horizontal track. The robot also served as the first iteration for the design of a planar inchworm robot, discussed in Section 6.2, which was able to change directions and climb smooth surfaces using pneumatics.

6.1 Slim Slime Robot

The Slim Slime robot, pictured in Figure 17, was an ACM composed of serially-connected modules driven by pneumatic actuators, which allowed it to perform in a 3D workspace [11, 44]. Slim Slime robot was composed of six expandable modules. The robot maintained a high degree of freedom, while being pneumatically-driven without the use many air supply lines. Three flexible pneumatic actuators, known as bellows and a main distribution tube made up the actuation system of each module of the robot. Compressed air was provided into each bellows from the main tube through an inlet valve built in bellows. Inlet and outlet valves built in each bellows made the bellows stretch, shrink and lock its length; therefore the module could stretch and bend in any direction actively.

The robot was developed to perform operations dangerous to a human worker such as in-pipe inspection at chemical or nuclear energy plants, or the rescue of victims under collapsed houses by making use of its shape and using the ability to distribute its weight evenly to perform mine detection. Each Slim Slime robot module had a compressed length of 114 mm and a full extended length of 177.6 mm. The total extended length of the robot was 1120 mm, with a total compressed length of 730 mm. The robot had a diameter of 128 mm. The Slim Slime had a total mass of 12 kg. Through testing, the Slim Slime robot had demonstrated various locomotion types including: the creep motion of a snake, the pedal wave motion of a snail and limpet, lateral rolling and pivot turning. Slim Slime Robot was capable of a maximum forward velocity of approximately 60 mm/s.

6.2 Planar Walker: Planar Inchworm Robot Introduced by Yeo et al.

The design of the inchworm robot by Chen et al. 1996 led to the development a planar inchworm robot, shown in Figure 18, based on the basic inchworm motion [45, 46]. The planar inchworm could mimic snake or inchworm-like creeping motions. In addition, the unique mechanical arrangement of the actuators allowed for quick change in travel direction and permitted rotational movement. The robot design was inspired by interest for walking/climbing systems for large surface inspection and maintenance tasks on ship hulls and oil tanks. The prototype system was based on pneumatic power and called a Planar Walker. The unit featured a simple closed-loop planar 8-bar mechanism formed by four linear cylinders and four revolute joints. When the four cylinders were actuated independently, the shape of the mechanism changed to a square, a rectangle, or an irregular quadrilateral. Four pneumatic suction/gripper modules were mounted below each of the revolute joint to hold the robot to the working surface. The robot was designed to be able to traverse forward, backward, and sideways a fixed distance or turn at a fixed angle. Based on the symmetry of the robot, the translation and rotation of the robot were decoupled; therefore, the robot could change its direction of travel very rapidly.

The robot was designed to explore locomotion principles and navigation of this robot configuration. The robot was 500 mm by 500 mm in size and had a total weight of 6 kg. The robot system consisted of two major modules: the locomotion mechanism module and the system control module. Four pneumatic cylinders were connected through pivot joints. The cylinders had a bore size of 16 mm with a stroke length of 45 mm. The overall length of the pistons between the two pivot joints was 175.5 mm. The crossbar frame had a central revolve joint so that the two crossbars could rotate with respect to each other with no restriction. The crossbar frame consisted of four sliding units that are integrated with the pivot joints. A gripper unit was attached to each slider unit to provide the vacuum suction force to the surface. The robot had a maximum transverse stride length of 32 mm/cycle and a maximum turning angle of 25 deg/cycle. The robot achieved a maximum transverse speed of 1.07 mm/s (30 s per cycle) and a maximum turning gait speed of 0.42 deg/s (60 s per cycle).

6.3 Telecubes: Self-Reconfigurable Robots

The Telecubes, shown in Figure 19, were another example of self-reconfigurable robots which were able to assemble in configurations that could mimic snake-inspired locomotion [47]. Each

Telecube robot module had two basic mechanical functions: contracting/expanding and connecting/disconnecting from the faces of neighboring modules. Each robot possessed six DOF through six prismatic joint which could individually expand or contract each face of the cube. Each face, known as a connection plate, had a mechanism and means to reversibly clamp onto the neighboring robot's connection plate and transmit power and data to the neighboring robot. The two principle design goals of the robot were to achieve a 2:1 expanded-to-contracted ratio and maintain a design with relatively small overall dimensions. The designer believed these goals would allow the units to have a relatively low cost to support manufacturing in large quantities, providing numbers of cheap, simple robots which can perform complex tasking. It is worth noting that this is an inactive project at Palo Alto Research Center (PARC) does not represent their most current work in reconfigurable robotics, such as, the Proteo and Digital Clay projects.

The robot system was designed to support experiments which explore local control methods, distributed sensing and actuation. Each Telecube robot was designed to be a 60 mm by 60 mm by 60 mm cube in dimensions. The robot mass was to be under 0.3 kg. Each prismatic joint, known as a telescoping-tube linear actuator was a lead screw assembly powered by a brushless 1.2W DC motor. The prismatic actuator was designed to achieve a 36-40 mm extension at a rate of 8-10 mm/s with maximum force output of 12 N. The docking mechanism of each cube consisted of a set of two "switching" permanent magnet devices and two mating metal plate on each face of the cube. The system allowed for passive and active docking between cubes. The docking system had about 5 kg force of holding force per face. Each robot was designed be equipped with a set of IR sensors and emitters on each face to provide communication between robot modules.

7. DISCUSSION

Various snake-inspired robot designs share many aspects which allow them to be easily grouped under the general classification of a snake robot, as well as the more detailed categories such as the ones presented in this paper. However, the process of using metrics to compare the performance of these designs is a much more challenging endeavor. For example, if a simple performance metric, such as maximum forward velocity, was used to compare all the robots presented in the survey, it may lead to erroneous conclusions. In this work, the term forward velocity is meant to describe the general forward progression of the robot, regardless of gait type, in comparison to other functional velocities such as turning. Forward velocity may be strongly correlated to the robot size. Hence, this discussion will attempt to characterize the performance tradeoffs of forward velocity due to changes in configuration of snake-inspired robots, based on actual performance data from representative designs. The performance metric of forward velocity was chosen due to its impact on a snake-inspired robot's usefulness in various applications, such as search and rescue. To attempt to provide a better performance comparison between the presented robot designs and draw some general conclusions regarding snake-inspired robots, the maximum velocity metric for a sample of the robots will be plotted against robot configuration metrics: total robot length, robot cross-section, and total robot weight. The data for the robots to be compared is presented in Table 1. The only selection criterion for the robots chosen for this comparison was the availability of information. The data in Table 1 was plotted and presented in Figures 20-22.

The velocity-length plot, in Figure 20, shows a general positive relationship between the robot speed and length, i.e. longer robots are generally faster. Upon closer inspection, the designer would realize that KR II, the fastest and longest robot, is a powered wheeled type, however, the next fastest is ACM III, a passive wheel type. Although this does not provide any conclusive evidence to determine which robot class is generally faster, it does support the general assumption that more segments equates to a higher speed capability. The assumption make sense when one considers that the addition of more well-designed segments may provide a greater increase to the robot's propulsive force compared to the increase in robot load due to the inclusion of the additional segments. The assumption is further supported by the fact that the slowest robots, Planar Inchworm and Kotay's Inchworm, only possess one active segment. Although the robots have multiple moving parts, there is only relative motion between one part of the robot and the remaining stationary portion of the robot with respect to the terrain at any given time. Note the AB II robot appears to be an outlier data point. According the authors, a possible reason why this relatively short and small volume robot has such high forward velocity compared to the other robots is its choice of actuation motor. The configuration of the AmphiBot II is the same as the AmphiBot I with slight larger segment dimensions, however, the AmphiBot II is utilized a 2.83W DC motor in its actuation system compared to the AmphiBot I robot's 0.75W DC motor. This significant increase in available power in a comparable package gives the robot a much greater joint response time which apparently results in a greater forward velocity. In general however, designers should be careful about simply replacing the actuation system of a robot with a more powerful one without properly modifying the rest of the robot, as this may lead to reliability, performance and structure integrity issues for the robot in the field.

Although the velocity-cross-section plot, in Figure 21, does not provide any general trends for snake-inspired robots, it does provide the designer with supporting information to make a comparison between robots with similar velocities and lengths. For example, observing the velocity-length plot, one can determine that OT-4 and JL-I have comparable lengths and forward velocities. However, observing the velocity-cross-section plot, one can determine that OT-4 has a much small cross-section than JL-I. This leads to the conclusion that OT-4 can traverse tighter spaces than JL-I. Upon further investigation, the designer would realize that although both robots are active tread types, JL-I is truly modular, meaning that the modules could by separated and robot still functions. This requires that each module be equipped with its own power supply, power train and communication and control equipment making the robot bulkier. OT-4 on the other hand, distributes the required components among segments, for example, the power train is in the middle segment (segment 5) while the power supply is located in segments 4 and 6. If the designer has no need for true modularity, then a configuration similar to the OT-4 may be more appropriate. Note that the robot KR-II, with a cross-section of 0.497 m^2 and a velocity of 500 mm/s, was not included in the velocity-cross-section plot simply because its inclusion skewed the difference between the other robot designs. Also note that the AB I and II robots were not included in the cross-section plot because the cross-section data does not reflect the inclusion of the removal wheel sets necessary for locomotion on a surface.

The third and final plot generated from the robot performance data is the velocity-weight plot, shown in Figure 22. Like the velocity-cross-section plot, this graph provides the designer with greater insight to the difference in a robot configuration beyond the velocity performance metric. For instance, robots with similar lengths and speeds but significantly different total weights may indicate additional capability in the higher weight robot or inefficiency. The higher weight robot may have higher greater load capacity or may be carrying electronics which allow it to be tether-less. An example of this are ACM III and KR I robots. In the velocity-length plot, the ACM III is both longer and faster than KR I, however, the velocity-weight plot indicates that the two designs have nearly identical weights. This would seem to indicate a significant inefficiency in the KR I design. However, upon closer observation, the designer would realize that the KR I has an additional DOF compared to the ACM III. The ACM III is a planar robot, meaning it can only traverse flat terrain types. The KR I was a spatial robot meaning it can traverse terrain types that have limited sharp elevations throughout the terrain, which may of some or no value to the designer. Note that the robot KR-II, with a weight of 370 kg and a velocity of 500 mm/s, was not included in the velocity-weight plot simply because its inclusion skewed the difference between the other robot designs.

8. CONCLUSION

Snake-inspired locomotion can be used to traverse many different and difficult terrain types, such as small holes, tunnels and gaps, which would prohibit most leg and wheel-based locomotion types. Snake-inspired robots usually have more DOF than is necessary for a given task, thereby providing the robot configuration with a certain degree of redundancy. Numerous snake-inspired robot designs have been developed, however, various robot designs differ greatly in physical configurations and purpose. Although this paper is not to be considered a comprehensive list of all published snake-inspired robot designs, it does attempt to create a taxonomy in which a significant number of published snake-inspired robot designs can be mapped. The paper divided snake-inspired robot designs into five categories: (1) robots with passive wheels, (2) robots with active wheels, (3) robots with active treads, (4) robots based on undulation using vertical waves and (5) robots based on undulation using linear expansion. In each of these categories, several robot designs were presented and selected robot designs were discussed in detail. In addition, a comparison between some representative designs of this taxonomy was presented to provide the reader with a sense of the differences between the various robot designs.

Based on the plot of robot data the following general observations can be made. First, it can be assumed from the velocity-length plot that a faster robot may have a longer length in comparison to another snake-inspired robot. This assumption may be supported by the idea that a longer robot may have additional propulsive force due to additional active joints or modules. Second, at present, snake-inspired robots executing rectilinear-based locomotion are typically slower than robots which use passive and active wheels. This assumption is based on a comparison between the Category IV and V robots and the remaining wheeled robots. It should be noted that there are not enough robots in each category to compare the categories; however, there are enough to compare pure undulation-based robots and wheel-based robot designs. Finally, it was determined that accurate comparisons between the various snake-inspired designs cannot be achieved using a single performance metric. An accurate comparison would require that the designer use several metrics to include the robot's performance, configuration, and intended operating environment.

Although snake-inspired robot designs have demonstrated general functionality and a number of useful gaits, the current designs still have not been placed into widespread use. Even with better understanding of the current proven designs and their useful features, there are still major design challenges which future designers must resolve to increase the practicability of snake-inspired robots. There are at least four major design challenges which must be addressed to maximize the utility of snake-inspired robots: (1) very small cross-sections, (2) multi-gait functionality, (3) high velocities, and (4) much longer operational time. Currently, fully operational, tether-less snake-inspired designs have achieved cross-sectional areas as low as 0.002 m^2. While robots with these cross-sectional areas may be very useful in activities such as searching for survivors through rubble, even smaller cross-sectional areas may enable more opportunities in activities such as military reconnaissance. Many snake-inspired robot designs are capable of demonstrating multiple gaits, although, almost all these robot designs only possess programming sophisticated enough to execute one gait while in operation. In actual snakes, the animal frequently changes between multiple gaits depending on the terrain encountered to maximize its effectiveness at traversing the new terrain type. In much the same way, future snake-inspired robots will need to be able to switch between multiple preprogrammed gaits types while in operation to adapt to unexpected changes in the terrain. In addition, gaits will need to be optimized during the operations [48]. Future snake-inspired robot designs will also need to be able to achieve much higher forward and turning velocities than what is currently possible. In many applications, robot designs will need to be capable of at least keeping pace with human personnel. Finally, snake inspired robot designs will need to achieve much longer operational time despite reduction in size. If a robot were capable of only an hour of operational time, it may only be capable of several minutes of actually performing its given task when the time to travel to the desired location and return to the recharging point is considered.

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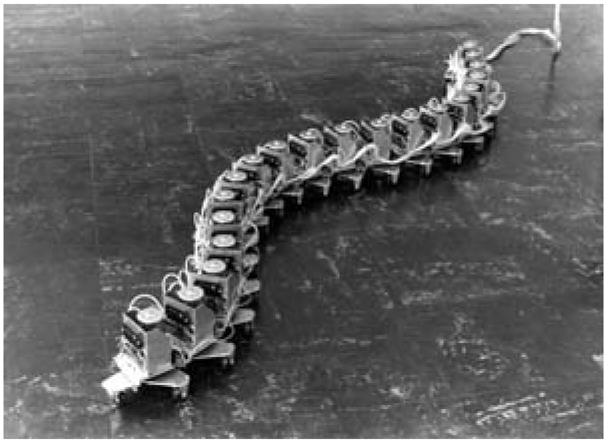


Figure 1: ACM III
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

Figure 2: ACM-R3
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

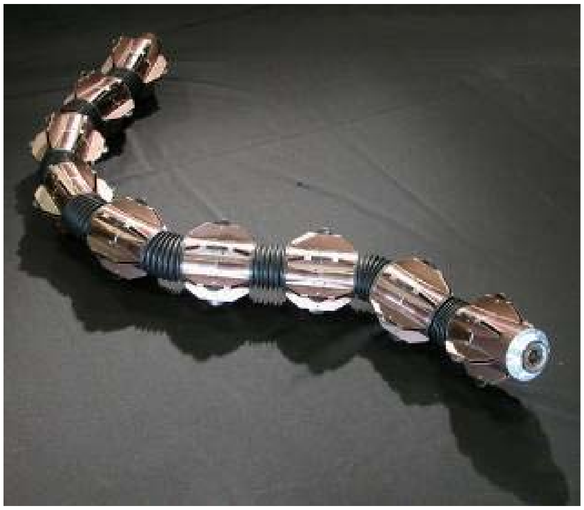


Figure 3: ACM-R5
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

Figure 4: AmphiBot I
(Courtesy of Alessandro Crespi, Biologically Inspired Robotics Group at Ecole Polytechnique Fédérale de Lausanne)

Figure 5: AmphiBot II
(Courtesy of Alessandro Crespi, Biologically Inspired Robotics Group at Ecole Polytechnique Fédérale de Lausanne)

Figure 6: Koryu-II
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

Figure 7: GMD-Snake2
(Courtesy of Rainer Worst, Fraunhofer IAIS)

Figure 8: ACM-R4
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

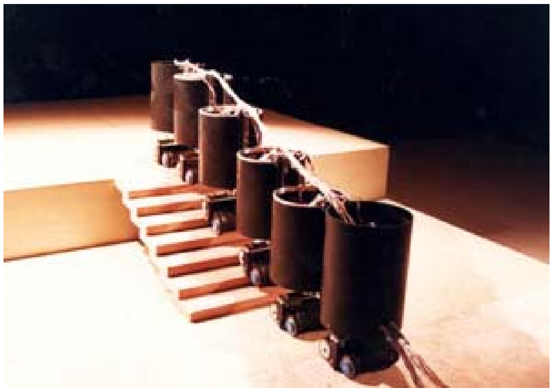
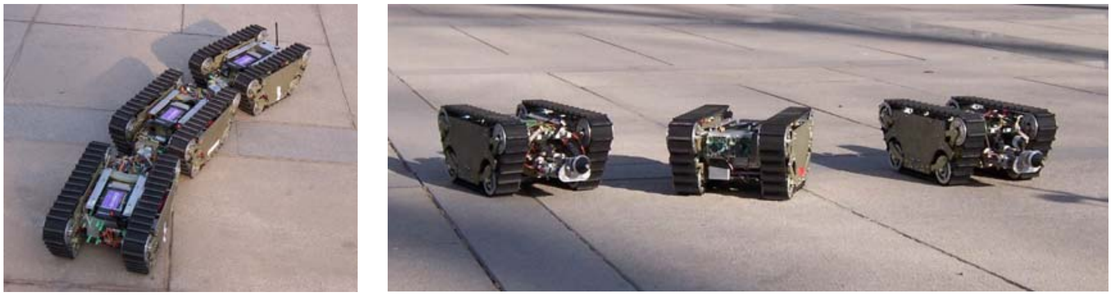


Figure 9: Koryu-I
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

Figure 10: OmniTread OT-8
(Courtesy of Johann Borenstein, University of Michigan)

Figure 11: OmniTread OT-4
(Courtesy of Johann Borenstein, University of Michigan)



(a) (b)

Figure 12: (a) Reconfigurable Robot JL-I and (b) Separate Modules
(Courtesy of Houxiang Zhang, University of Hamburg)

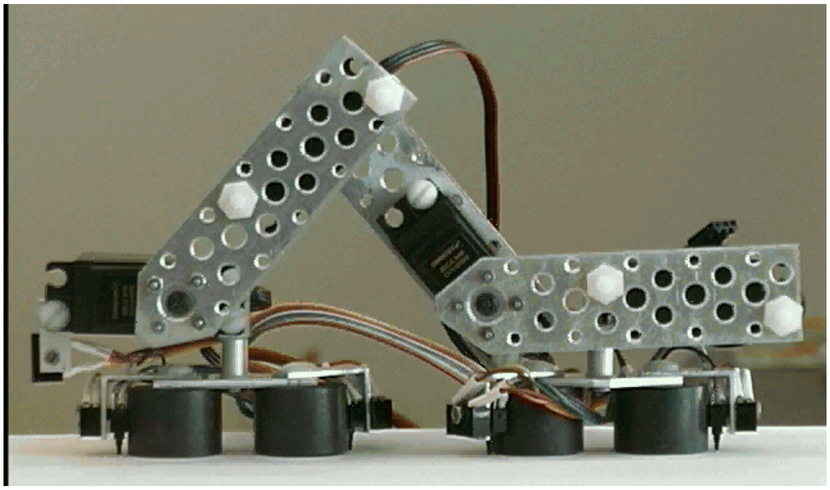


Figure 13: Inchworm Robot by Kotay and Rus 1996
(Courtesy of Daniela Rus, MIT Computer Science and Artificial Intelligence Laboratory)

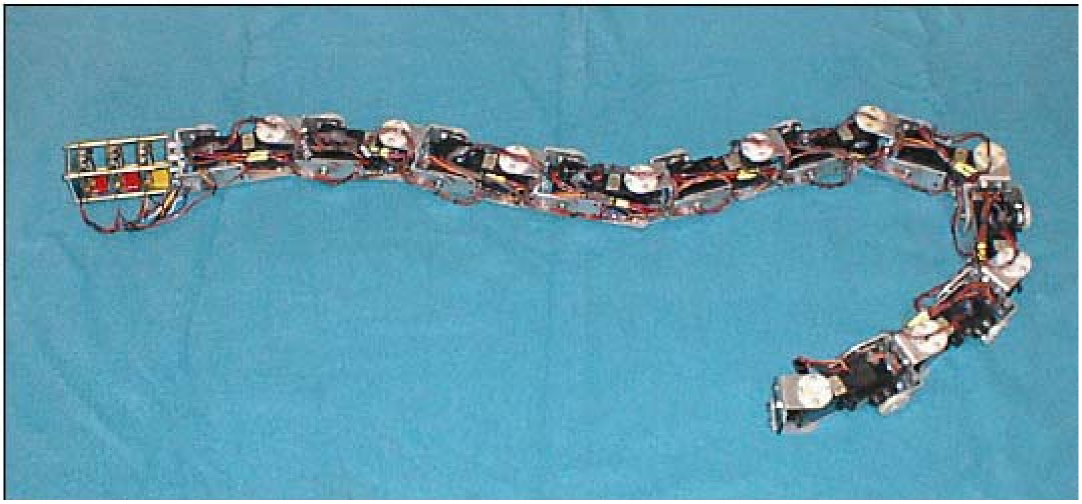


Figure 14: Dowling’s Complete Snake Robot
(Courtesy of Kevin Dowling)

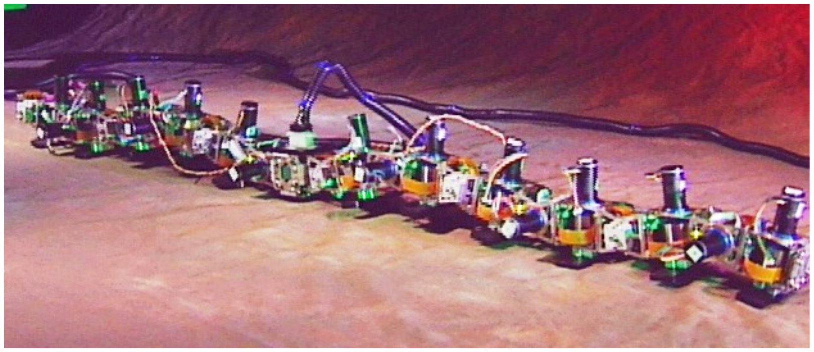
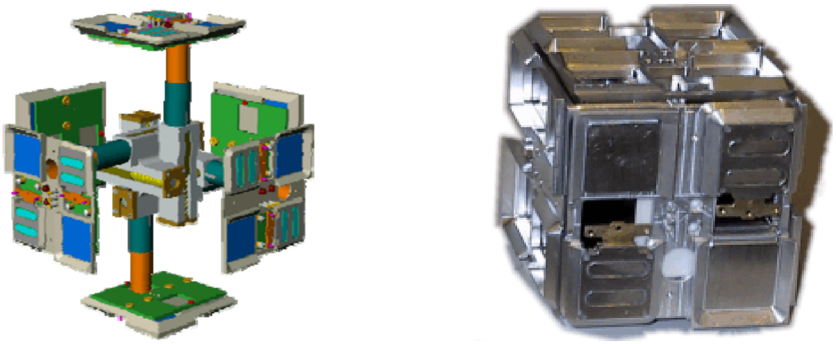


Figure 15: Reconfigurable Robot, PolyBot
(Courtesy of Linda Jacobson, Palo Alto Research Center, Inc.)

Figure 16: CMU Snake Robot
(Courtesy of Howie Choset, Carnegie Mellon University Biorobotics Laboratory)

Figure 17: Slim Slime Robot
(Courtesy of Shigeo Hirose, Hirose-Fukushima Robotics Lab)

Figure 18: Planar Inchworm Robot: Planar Walker
(Courtesy of Yeo Song Huat, Robotics Research Center Nanyang Technological University)



(a)　(b)

Figure 19: Telecube: (a) CAD model fully extended and (b) prototype fully contracted
(Courtesy of Linda Jacobson, Palo Alto Research Center, Inc.)

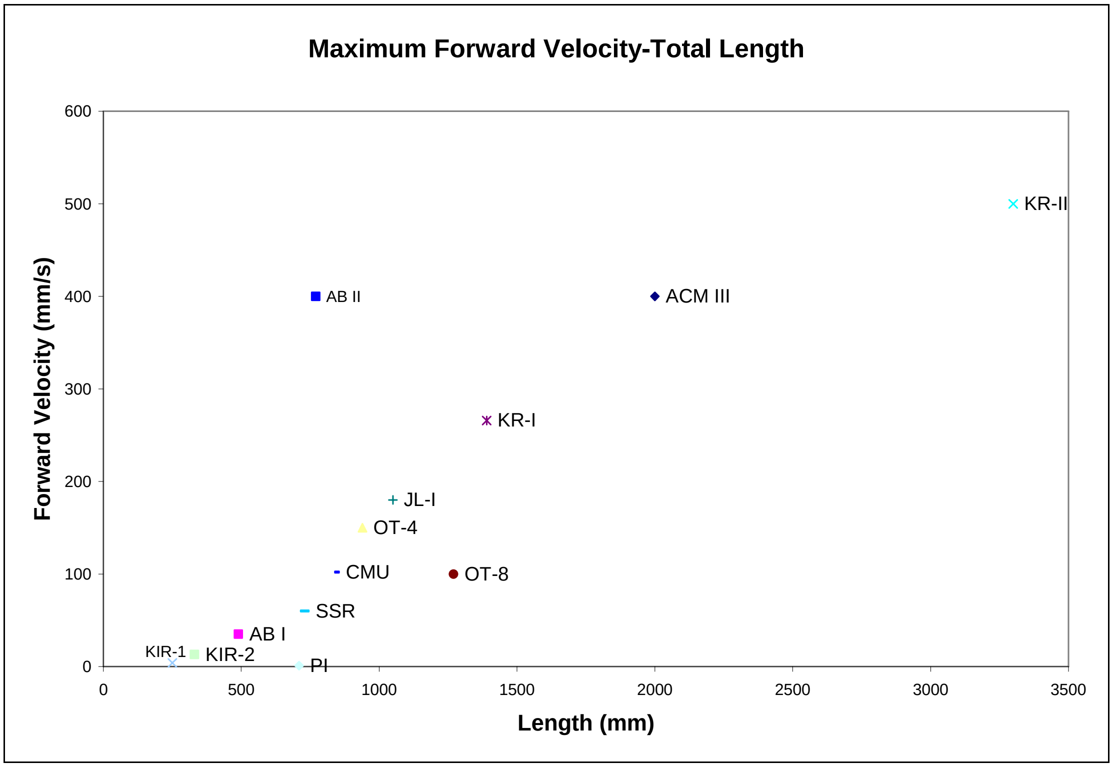


Figure 20: Maximum Forward Velocity-Total Length Plot for Sampled Robots

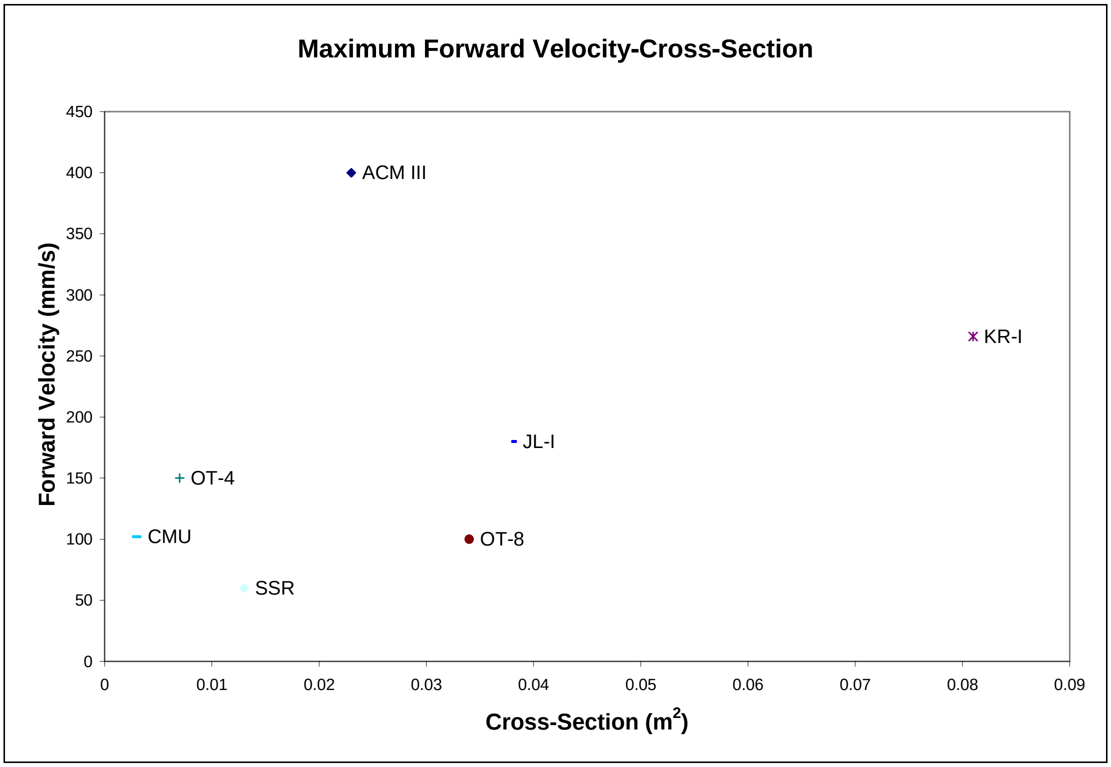


Figure 21: Maximum Forward Velocity –Cross-Sectional Area Plot for Sampled Robots

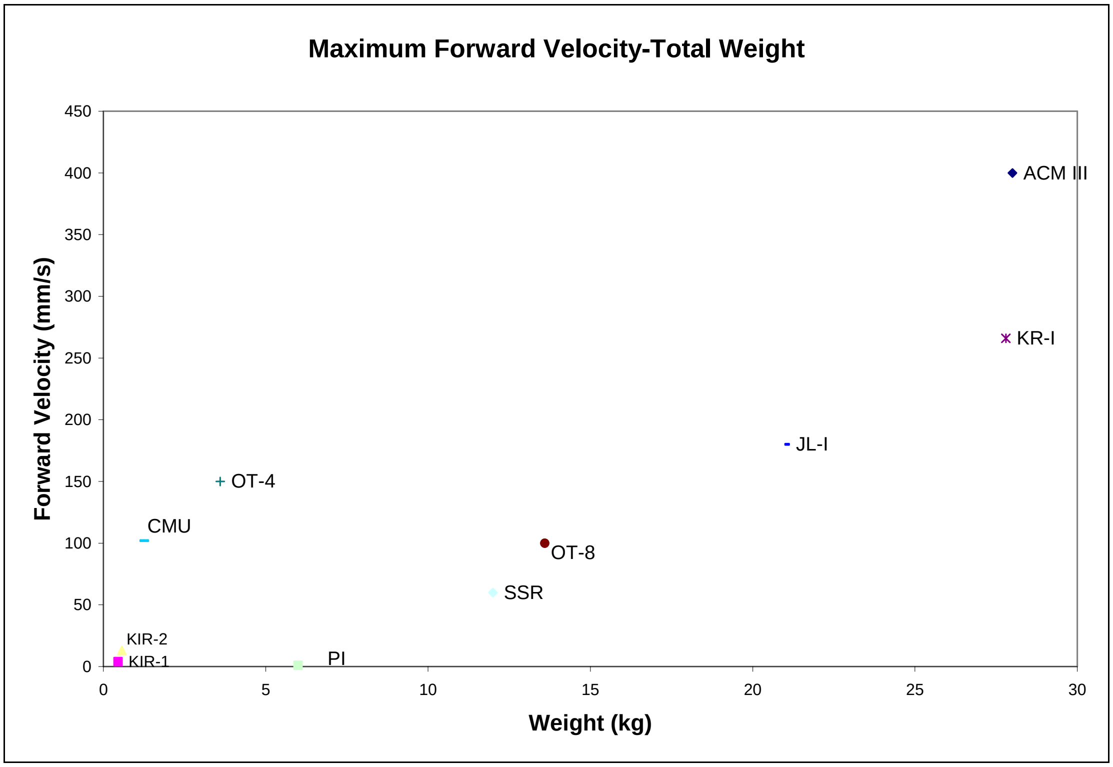


Figure 22: Maximum Forward Velocity -Total Weight Plot for Sampled Robots

Robot	**Category (I-V)**	**Length (mm)**	**Cross Section (m^2)**	**Weight (kg)**	**Velocity (mm/s)**
ACM III	I	2000	0.023	28	400
AmphiBot I (AB I)	I	490	0.002[1]	---	35
AmphiBot II (AB II)	I	770	0.002[1]	---	400
KR-II	II	3300	0.497	370	500
KR-I	III	1390	0.081	27.8	266
OmniTread (OT-8)	III	1270	0.034	13.6	100
OmniTread (OT-4)	III	940	0.007	3.6	150
JL-I	III	1050	0.038	21	180
Kotay’s Inchworm I (KIR-1)	IV	250	---	0.455	4
Kotay’s Inchworm II (KIR-2)	IV	330	---	0.566	13
CMU (M1)	IV	840	0.003	1.26	102[2]
Slim Slime Robot (SSR)	V	730	0.013	12	60
Planar Inchworm (PI)	V	710	---	6	1

[1] Note: These cross-section values do not include the removable wheel sets.
[2] Note: Approximated based on demonstration video media.

Table 1: Snake-Inspired Robot Dimensions and Performance