Proc. of the SPIE Defense and Security Conference, Unmanned Ground Vehicle Technology VII, Orlando, FL, March 28th to April 1st, 2005.

The OmniTread Serpentine Robot – Design and Field Performance

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ABSTRACT

This paper describes the design and performance of the *OmniTread* serpentine robot, developed at the University of Michigan. Serpentine robots are mobile robots that comprise of multiple rigid segments, connected by actuated joints. The segments usually have drive elements, such as wheels or tracks.

To date, we have developed two versions of the OmniTread. The larger version, called "OT-8," has five rigid segments and four 2-Degree-of-Freedom (2-DOF) joints, and it can drive through an 8-inch diameter opening. The OT8 is fully functional and this paper documents experimental results for the OT-8. The smaller and newer version, called "OT-4," will have seven segments, six 2- DOF joints, and it will fit through a 4-inch diameter hole. The OT-4 is not yet completely built, but its design is mostly completed and key improvements over the OT-8 have been bench tested.

The foremost and unique design characteristic of the OmniTread is the use of pneumatic bellows to actuate the joints. The pneumatic bellows allow the simultaneous control of position and stiffness for each joint. Controllable stiffness is of crucial importance in serpentine robots, which require stiff joints to cross gaps and compliant joints to conform to rough terrain for effective propulsion.

Another unique feature of the OmniTread design is the *maximal* coverage of all four sides of each segment with driven tracks. This design makes the robot indifferent to roll-overs, which are bound to happen when the long and slender bodies of serpentine robots travel over rugged terrain.

Keywords: Serpentine robot, snake robot, pneumatic, multi-segment, multi-joint, hypermobility, hyper-redundant, active skin.

1 INTRODUCTION

Urban Search and Rescue, industrial inspections in hazardous environments, and military intelligence have one need in common: small-sized mobile robots that can travel across the rubble of a collapsed building, squeeze through small crawl-spaces, and slither into the shelter of insurgents to gather intelligence. One species of mobile robots that promises to deliver such *hypermobility* is the so-called serpentine or snake robot (see Figure 1). Serpentine robots typically comprise of three or more rigid segments that are connected by 2- or 3-degree-of-freedom (DOF) joints. The segments typically have powered wheels, tracks, or legs to propel the vehicle forward, while the joints may be powered or unpowered.

Figure 1: The OmniTread serpentine robot model OT-8, developed at the University fo Michigan.

[1)] This work was conducted at the University of Michigan's Mobile Robotics Lab

Because of ambiguity in the use of the terms “snake robot” (or “snake-like robot”) and “serpentine robot,” we introduce the following definition for the remainder of this paper.

- A “snake robot” or (snake-like robot) is a multi-segment mechanism that derives propulsion from undulations (a wave-like motion of the joints only), that is, it uses no wheels, legs, or tracks for propulsion.
- A “serpentine robot” is a multi-segment mechanism that derives propulsion from wheels, legs, or tracks. Joints connecting the segments may be either powered or unpowered.

Snake-like robots have been attracting the attention of researchers since the seventies. Around that time Shigeo Hirose from the Tokyo Institute of Technology developed his Active Cord Mechanism, which mimicked snake movements. The latest incarnation of this idea is the ACM-R3 robot, which is capable of performing new types of three-dimensional undulations [Mori and Hirose, 2002].

In the nineties, research on snake-like robots increased dramatically as documented by Dowling [1997]. Muth and Grant [2000] developed the MOCASIN II pipe crawler. This snake-like robot uses joint actuators for active propulsion while actuators embedded in the segments are used for holding consecutive links in place. Another snake-like robot that uses pneumatic power for actuating its joints is the Slime Robot (SR) developed by Ohno and Hirose [2000]. Metal bellows used in the initial prototype were exchanged for bridle bellows in the latest version, called SSR-II [Aoki et al. 2002].

The focus of this paper, however, is on serpentine robots. The first serpentine robot, called KR-I, was introduced by Hirose and Morishima [1990] and the improved version KR-II was presented by Hirose et al. [1991]. The KR-I was large and heavy, weighing in at 350 kg. The KR-robots comprised of multiple vertical cylindrical segments on powered tracks or wheels, which give them a train-like appearance. Vertical joint actuators allow a segment to lift its neighbors up, in order to negotiate steps or span gaps.

More recently, Klaassen and Paap [1999] and Paap et al. [2000] at the German Institute for System Design Technology (GMD) developed the Snake2 vehicle, which contains six active segments and a head. Each round segment has an array of 12 electrically driven wheels evenly spaced around its periphery. These wheels provide propulsion regardless of the vehicles orientation (i.e., its roll angle). Segments are interconnected by universal joints that are actuated by three additional electric motors through strings.

Another serpentine robot designed for sewer inspection was developed by Scholl et al. [2000]. Its segments use only two wheels but the actuated 3-DOF joints allow full control over each segment’s spatial orientation. The sensor suite of this robot is similar to that of Snake2. The robot is able to negotiate tight 90° angled pipes and climb over 55 cm high obstacles. One segment and its joint are about 20 cm long.

While wheeled serpentine robots can work well in smooth-walled pipes, more rugged terrain requires tracked propulsion. To this effect Takayama and Hirose [2000] developed the Soruyu-I crawler, which consists of three segments. Each segment is driven by a pair of tracks, which, in turn, are all powered simultaneously by a single motor, located in the center segment. Torque is provided to the two distal segments through a rotary shaft and universal joints. Each distal segment is connected to the center segment by a special 2-DOF joint mechanism, which is actuated by two lead screws driven by two electric motors. The robot can move forward and backward, and it can change the orientation of the two distal segments in yaw and pitch symmetrically to the center segment. One interesting feature is this robot’s ability to adapt to irregular terrain through the elasticity of its joints. This elasticity is provided by springs and cannot be actively controlled.

A serpentine robot that is strikingly similar to our OmniTread design is MOIRA [Osuka and Kitajima, 2003][2]. MOIRA comprises four segments, and each segment has two longitudinal tracks on each of its four sides, for a total of eight tracks per segment. The 2-DOF joints between segments are actuated by pneumatic cylinders. We believe that the bellows-based joint actuators used in our OmniTread have a substantial advantage over a cylinder-based design, as the discussion of our approach in Section 2.2 will show.

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2) Osuka and Kitajimas effort and ours are independent. We became aware of their work through their presentation/publication in October 2003. However, the development of our two serpentine robots, OmniPede and OmniTread, began in 1998 and September 2002, respectively. We also hold U.S. patent (#6,774,597, issued August 10, 2004) on the tracks-all-around-the-body design feature.

A different concept, using unpowered joints was introduced by Kimura and Hirose [2002] at the Tokyo Institute of Technology. That robot, called Genbu, is probably the only serpentine robot with unpowered joints. The stability of the robot and its high mobility on rough terrain are preserved by large-diameter wheels (220 mm). The control system employs position and torque feedback sensors for the passive but rigid joints. Specially designed self-contained wheels with gear-head protectors provide robustness on rough terrain. As in Hirose's other design above, springs are used to protect the electric motors from impact, although the stiffness of the springs cannot be controlled during operation.

Another robot incorporating combination of passive and active joints as well as independently driven and coupled segments is KOHGA developed by Kamegawa et al. [2004]. This robot implements a smart design feature: Besides a camera in the front segment there is a second camera in the tails section that can be pointed forward, in the way a scorpion points its tail forward and over-head. This "tail-view" greatly helps with teleoperating the robot.

The concept of joining several small robots into a train to overcome larger obstacles was used by Brown et al. [2002] in their Millibot Train. The robot has been demonstrated to climb up a regular staircase and even higher steps. However, with only one DOF in each joint the vehicle is kinematically limited.

2 THE OMNITREAD DESIGN

The OmniTread design offers two unique and fundamentally important advantages over all other serpentine robots described in the scientific literature to date. These features are: (1) *maximal* coverage of the robot's surface with propulsion elements and (2) joint actuation with pneumatic bellows. The rationale for these features is detailed below.

2.1 Complete coverage of all sides with propulsion elements

This patented design feature makes the serpentine robot indifferent to rolling over – a condition that is inevitable when the slender bodies of serpentine robots travel over rugged terrain. Another reason for the use of wide tracks on each side of each segment is our fundamental design doctrine that calls for covering the largest possible surface area of the robot with propulsion elements. The reason is that any contact between an environmental feature and a robot's inert (i.e., not propelling) surface impedes motion or entirely stops the robot (i.e., the robot gets "stuck"). In contrast, any contact between an environmental feature and a propulsion surface supports motion. We define the term "Propulsion Ratio," P_r, measured as the surface area that provides propulsion, A_p, divided by the total surface area, A_p+A_i, where A_i is the inert (non-moving) surface area of the body. Our design goal is to maximize P_r.

Commonsense, supported by our experience, suggests that serpentine robots with a low propulsion ratio get stuck very easily when trying to move over rugged terrain. In order to increase the propulsion area A_p and thus the propulsion ratio P_r, we cover *all sides* of the OmniTread with extra-wide tracks. We also took extensive measures to reduce the space (and thus, the inert area A_i) between the segments, as will be explained in the next section.

2.2 Joint actuation with pneumatic bellows

We begin this section by an informal discussion on the particular joint actuation requirements of serpentine robots. Thereafter, we explain our choice of pneumatic bellows for joint actuation in view of these requirements.

By definition, serpentine robots are relatively long compared to their diameter, so that they can reach up and over high obstacles while still being able to fit through small openings. However, lifting the lead segments requires a significant amount of torque, which is particularly difficult to generate in slender serpentine robots, where the lever arm for a longitudinal lifting force is limited by the robot's small diameter. Thus, one key requirement for serpentine robots is that they employ joint actuators of sufficient strength to lift two or more of its lead or tail segments.

Another key requirement is that serpentine robots should conform to the terrain *naturally* (i.e., compliantly). This ensures that as many driving segments as possible are in contact with the ground at all times and provides effective propulsion. Serpentine robots that don't conform to the terrain naturally require extremely complex control systems to measure contact forces and to command momentary angles for each non-compliant joint to force ground contact. Such actively controlled compliance has not yet been successfully demonstrated and may well be unfeasible for many more years.

At other times, it is necessary to increase the stiffness of a joint, for example, for crossing a gap or for reaching over an obstacle. Alternatively, it may be necessary to adjust the stiffness on-the-fly and to various intermediate levels, for example, when climbing up a flight of stairs, as shown in Figure 2.

Figure 2: OmniTread OT-8 climbing up a flight of wooden stairs.

Thus, serpentine robots must be capable of adjusting the position *and* stiffness of every DOF individually and proportionally.

Furthermore, large amounts of space dedicated to joints (we call this space "Joint Space") dramatically increase the amount of inert surface area. Therefore, joint actuators should take up as little space as possible to reduce the size of Joint Space (if the actuator is located in Joint Space), or to reduce the volume they take up in Segment Space.

Extensive studies of these requirements and of joint actuators potentially meeting these requirements [Granosik and Borenstein, 2005] led us to the second unique (and patent pending) design feature of the OmniTread: the use of pneumatic bellows for actuating the joints. Our research showed that pneumatic bellows meet all four of the above requirements better than any other type of actuator. In particular, pneumatic bellows provide a tremendous force-to-weight ratio, and they fit perfectly into the otherwise unusable (since varying) space between segments.

The latter point is illustrated in Figure 3, which shows that parts of Joint Space may be small at one moment, and large at the next, depending on which way the joint is bending. If we wanted to use Joint Space for housing electronics or other rigid components, then the size of that component would be limited by the dimensions of the "minimal space" shown in Figure 3. Contrary to rigid components, pneumatic bellows fit into such varying spaces perfectly: bellows expand and contract as part of their intended function, and they happen to be smallest when the available space is minimal and largest when the available space is maximal. From the point of space utilization, pneumatic bellows are thus a superbly elegant solution, because joint actuators take up *only* Joint Space, and very little of it, for that matter. In contrast, pneumatic cylinders or McKibben muscles, as well as electric or hydraulic actuators, would all require space within the volume of the segments. One exception is the earlier-cited MOIRA serpentine robot [Osuka and Kitajima, 2003], which uses pneumatic cylinders fitted entirely into Joint Space (see Figure 4), albeit at the cost of making Joint Space much larger. Since the surfaces of Joint Space are inert (i.e., don't provide propulsion), the result is a dramatic reduction in the MOIRA's propulsion ratio P_r. To further illustrate our point about small versus large Joint Spaces, we included Figure 5, which shows how the OmniTread successfully traverses a narrow-edge obstacle, thanks to its very short joints. If the joints were longer than the rail's width, then the robot would necessarily get stuck on it.

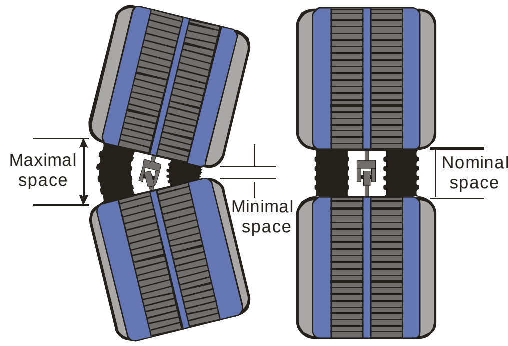

Figure 3: Pneumatic bellows fit perfectly into Joint Space. Therefore they don't take up valuable space inside the segments, and they don't enlarge Joint Space (which would result in large inert surface areas).

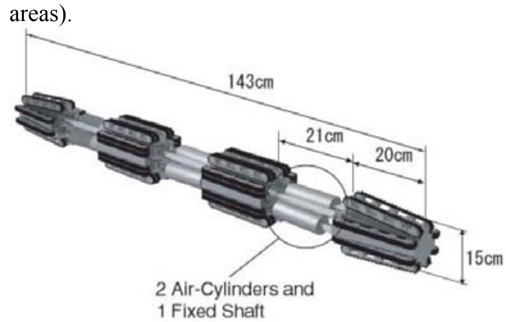

Figure 4: The MOIRA serpentine robot [Osuka and Kitajima, 2003] fitted pneumatic cylinders entirely into Joint Space. This design results in large inert surface areas.

Figure 5: In the OT-8, Joint Space is only 6.8 cm long while segments are 20 cm long. This design helps produce a very favorable Propulsion Ratio P_r. The obvious advantage is the OT-8's ability to cross a narrow-edged obstacle, such as this railroad rail. Robots with long inert Joint Spaces will get stuck on this narrow obstacle.

2.3 The OmniTread OT-8

The OmniTread OT-8 was developed in over six years of research at the University of Michigan (UM) and was tested with considerable success at the Southwest Research Institute (SwRI) in February 2004.

The OT-8 has five segments and four pneumatically actuated 2-degree-of-freedom (DOF) joints. The size of each segment is 20×18.6×18.6 cm (length × width × height). Each Joint Space is 6.8 cm long. The entire robot is 127 cm long and weighs about 13.6 kg. A single drive motor located in the center segment provides torque to all tracks on all five segments via a so-called *drive shaft spine* running through the center of the segments. The four joints are actuated by a total of 16 pneumatic bellows. With this unique design the OmniTread has 33 individually and proportionally controllable parameters: 16 × position, 16 × stiffness, and 1 × forward/backward speed.

In order to control the OmniTread we developed a microprocessor-based distributed control system consisting of five local controllers – one for each of the OT-8's four joints and a fifth controller for the electric drive motor. Each local controller is based on a 16-bit Motorola microcontroller MC9S12DP256B and all five controllers communicate with a master PC via CAN bus. Each local controller can receive new position and stiffness commands and return feedback data (two positions and four pressures) every 10 ms. Upon receiving a command, the local controllers for the joints then sends pulse width modulation (PWM) signals to eight on-off pneumatic valves (two for each bellows and there are four bellows per 2-DOF joint). The controllers implement the simultaneous proportional stiffness and position controller that we developed earlier [Granosik and Borenstein, 2004; 2005]. A more detailed technical description of the OT-8 is given in [Granosik, Hansen, Borenstein, 2005].

Figure 6: OT-8 successfully climbing up and over a 46 cm (18-inch) high vertical wall.

3 EXPERIMENTAL RESULTS

In February of 2004 the OmniTread OT-8 was tested for three days at the Southwest Research Institute (SwRI). During these tests the OmniTread was continuously controlled by two operators who had audio and visual contact with the robot, allowing them to monitor the robots behavior at all times. Numerous capabilities were tested including climbing over high steps, ascending through the inside of pipes, and traversing wide gaps. Some numeric results are shown in Table I, and the following photographs further document the testing.

Error! Reference source not found. illustrates the Omni Tread's ability to climb a 45.7 cm high curb. This height is over 36% of the robot's length or over 240% of its own height. Such obstacle traversion capabilities are possible only with serpentine robots.

The advantages of the "tracks-all-around" design become apparent in SwRI's dense underbrush environment (see Figure 7). In that environment branches touch the robot from all sides and could easily stall a robot with a low propulsion ratio (e.g., a robot that has tracks only on the bottom). In the OT-8, branches touching the large propulsion surfaces help the robot, rather than impeding it. Additional experiments are documented in [Granosik, Hansen, and

Figure 7: OT-8 driving through dense underbrush. Powered tracks-all-around provide propulsion wherever branches come in contact with the body. Robots with tracks only on the bottom can easily get stuck in this environment.

Table I: Select Performance Measures for the OT-8

Maximum velocity	10 cm/s
Minimum turning radius	53 cm
Maximum angle of slope	30 deg
Maximum height of curb	45.7 cm (36% of robot's length or 240% of robot's height)
Maximum width of trench	66 cm (51% of robot's length)

Borenstein, 2005] and are omitted here to avoid duplication.

4 WORK IN PROGRESS: THE OT-4

Since May 2004 we have been working on the next version of the OmniTread. The new version is called “OT-4” because it is designed to fit through an opening 4 inches (10 cm) in diameter, whereas the OT-8 can fit through an 8-inch diameter opening.

The OT-4 hardware is not yet fully built, although most components are already designed and bench tested. We expect to have three segments and two joints running at the time of presenting this paper. Once completed, the OT-4 will look as shown in the CAD model of Figure 8.

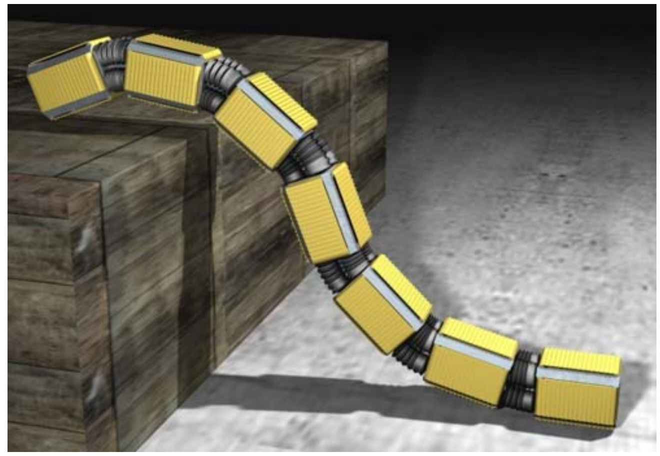

Figure 8: CAD model of the OmniTread OT-4.

Common to the OT-8 and the OT-4 are these already proven design features:

1. pneumatic bellows to actuate the joints;
2. powered tracks on all four sides of all segments;
3. single drive motor powering all tracks on all segments via a drive shaft spine.

However, the OT-4 will have seven segments with six 2-DOF joints and it will feature numerous improvements over the OT-8.

4.1 New Features in the OT-4

Although the OT-4 retains key features of the OT-8, we are also incorporating in the OT-4 major improvements over the OT-8. For example, and since the OT-8 was meant to serve as a proof-of-concept prototype only, we had made no effort to supply electric and pneumatic power on-board. In contrast, the OT-4 will be fully self-contained, and several of its new features aim at reducing power consumption. Table II compares the features of the two models side-by-side.

4.1.1 Self-contained power sources

The OT-4 will carry onboard electric power for over one hour of continuous operation. Three AAA-sized batteries will fit into segments #2, #3, #5, and #6. The lead and tail segments (#1 and #7, respectively) will carry payload and segment #4 will house the electric drive motor. In addition, pneumatic power will be stored in the form of liquid CO_2 cartridges.

Table II: Side-by-side comparison of salient features of the OT-8 and OT-4.

OmniTread OT-8 Can pass through 8-inch (20 cm) diameter hole. 5 segments, four 2-DOF joints. Length: 116 cm (46”), weight: 12 Kg (26 lbs). 	**OmniTread OT-4** Can pass through 4-inch (10 cm) diameter hole. 7 segments, six 2-DOF joints. Length: 88 cm (35”), weight: 2.5 Kg (5.5 lbs) 
Requires tether for compressed air and electric power.	*Untethered*, carries onboard compressed gas and electric power for >60 minutes of operation. Fiber optic tether is optional and for remote control only.
All tracks on all segments are permanently engaged with the drive shaft spine, thus continuously consuming motor power.	Ability to selectively disengage individual tracks from the drive shaft spine for substantial savings in power consumption.
No propellant-saving technology for pneumatic system	Uses inert floaters in bellows to reduce CO_2 consumption.
No linear object latching capability	Ability to latch on to and travel along linear large or small diameter objects such as poles, pipes, and electric conduits.

Such cartridges are commercially available. A standard size is the 8-gram cartridge, one of which will fit into each of Segments #2, #3, #5, and #6. Preliminary results suggest that these four cartridges will power the joints for over one hour of operation, under typical duty cycle conditions.

4.1.2 Individual clutches for each track

The OT-4 will have one electrically actuated, bi-stable clutch for each of its nominally 7×4 = 28 tracks. These clutches will allow the operator to engage or disengage each track individually. Thus, tracks not in contact with the environment can be disengaged to reduce drag and waste of energy. Disengagement of tracks is also useful if a track is jammed or otherwise disabled. If the robot rolls over, the tracks that come into contact with the ground can be re-engaged by the operator. On flat ground only three tracks need to be engaged: the ones on the bottom of Segments #1, #4, and #7, while the other segments stay off the ground. This configuration provides stable, 3-point contact at minimal power consumption.

Figure 9 shows a prototype of the micro-clutch mechanism. The 6-mm diameter micro-motor turns a 1-mm diameter lead-screw, which moves joint ‘O’ of a 4-bar mechanism toward or away from the motor. In the position shown, worm gear WG is engaged with worm W, which permanently rotates with the drive shaft spine. If joint ‘O’ is pushed away from the motor, the 4-bar mechanism raises the worm gear WG and disengages it from the worm W. Electric contacts, not shown here, function as limit stops. Once either limit is reached, the micro-motor stops and no power is needed to hold the clutch in its position. Figure 10 shows a CAD drawing of one segment and Figure 11 shows a fully functional prototype segment. The prototype segment has four micro-clutches and performs flawlessly.

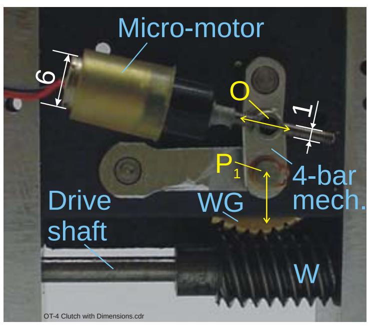

Figure 9: Prototype of the micro-clutch that disengages drive tracks from the drive shaft spine.

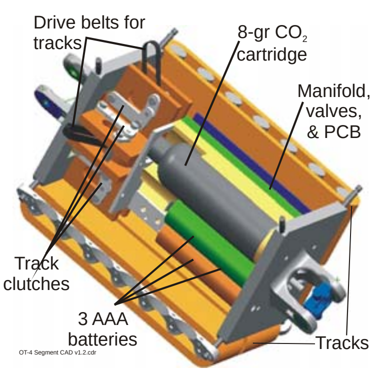

Figure 10: CAD model of one OT-4 segment (tracks on top and side removed to reveal internal components).

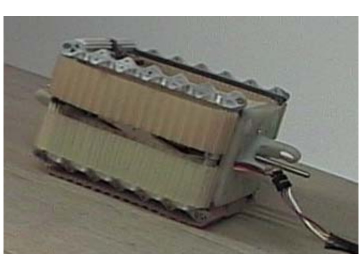
Figure 11: Fully functional OT-4 motor segment during test run (top track removed for testing).

4.1.3 Inert floaters in bellows

This unique innovation aims at minimizing the consumption of CO_2 during operation of the joints. When a bellows changes state from completely compressed (exhausted) to completely extended (inflated), the CO_2 cartridges must supply roughly the amount of gas needed to fill the fully extended volume (V_e) of the bellows with gas at the working pressure of 45 psi. When the bellows is fully deflated, it exhausts its whole volume worth of pressurized gas, V_e, to the ambient air. Even in the fully compressed state, the volume inside the bellows, V_c, is not zero, but rather quite large: $V_c \cong ½V_e$ (see Figure 12). Also, after exhausting, the gas remaining in the bellows fills the volume of V_c, but it has the pressure of the ambient air and thus no energetic value.

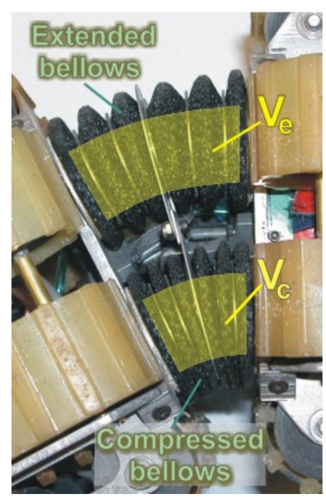

Figure 12: Comparison of the internal volume of a fully extended (V_e) and a fully compressed bellows (V_c). Volumes are indicated by yellow shading.

This approach is wasteful of the limited resource of CO_2, because in every cycle of inflation and exhaustion all of the gas that filled V_e at 45 psi is spent. In order to minimize the amount of gas spent in a given cycle, we developed an innovative approach using what we call “*inert floaters*.” An inert floater, shaped like the internal space of the bellows in the fully compressed state (but about 10% smaller), is permanently sealed inside the bellows. Thus, when the bellows is fully compressed, there is only very little gas left in it, since most of V_c is taken up by the floater. In order to fully extend the bellows, compressed gas has to fill up only the volume of V_e - V_c, which is about ½ V_e. The result is a saving of 45-90% (!) of CO_2 compared to the conventional operation of the bellows[3], without inert floater. The inert floater will be a lightweight deformable liquid or gel in a plastic pouch that will conform to any shape of the inside volume, but without being compressed. It is, of course, well known from the field of fluid mechanics that the bellows' axial force, *F,* is completely unaffected by the inert floater. This is because *F* depends solely on the pressure of the gas and the surface area of the bellows' end plates.

5 CONCLUSIONS

This paper introduced the design of two versions of our OmniTread serpentine robot: OT-8 and OT-4. The larger one, OT-8, was tested at the Southwest Research Institute and we provided some of the experimental results here.

After validating the unique features of the OmniTread design, we designed a smaller and more advanced version, called OT-4. To date we have not yet built a full-sized OT-4, but we have successfully tested some of the key innovation in this design, such as individual clutches for each track, provision of pneumatic power from liquid CO_2 cartridges, and reduction of pneumatic power consumption with inert floaters. We expect to have a rudimentary but fully functional OT-4 built by the end of Summer of 2005.

We believe that serpentine robots based on the OmniTread design can provide hitherto unattainable capabilities, such as climbing over high steps, ascending through the inside of pipes, or traversing wide gaps.

Acknowledgements

This work was funded by the U.S. Dept. of Energy under Award No. DE-FG04-86NE3796 as well as by the Intelligence Technology Innovation Center (ITIC) through Southwest Research Institute under CONTRACT No. F009822.

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[3] The extreme savings of 90% would be realized if, for example, a bellows was commanded to change its state from completely compliant to completely stiff, while keeping its fully compressed position constant. This is because in this case only the difference between V_c and the volume of the inert floater has to be filled with pressurized gas.

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