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# The OmniTread OT-4 Serpentine Robot for Emergencies and Hazardous Environments

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**Abstract –** *Serpentine robots are slender, multi-segmented vehicles designed to provide greater mobility than conventional wheeled or tracked robots. Serpentine robots are thus ideally suited for urban search and rescue as well as for surveillance and inspection tasks in hazardous and hard-to-reach environments. One such serpentine robot, currently under development at the University of Michigan, is the "OmniTread OT-4." The OT-4 comprises seven segments, which are linked to each other by 2-degree-of-freedom joints. Moving tracks on all four sides of each segment assure propulsion even when the vehicle rolls over. The OT-4 is designed to climb over obstacles that are much higher than the robot itself, propel itself inside pipes of different diameters, and traverse even the most difficult terrain, such as rocks or the rubble of a collapsed structure.*

*The foremost and unique design characteristic of the OT-4 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 slender bodies of serpentine robots travel over rugged terrain.*

*This paper describes the OmniTread concept and some of its technical features in some detail. In the Experiment Results Section, photographs of successful obstacle traverses illustrate the abilities of the OT-4.*

## I INTRODUCTION

Urban Search and Rescue, as well as certain industrial inspections tasks in hazardous environments 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 small openings. 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.

Because of ambiguity in the use of the terms "snake robot" and "serpentine robot," we introduce the following definitions for the remainder of this paper.

- A "snake robot" is a multi-segment mechanism that derives propulsion from undulations (a wave-like motion of the joints only), that is, it uses no driven 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. Some researchers use the term "active skin" to describe this type of robot.

Since the focus of this paper is on serpentine robots, we limit the scope of our literature review to this type of robots only. The first serpentine robot, called KR-I, was introduced by Hirose and Morishima [1] and the improved version KR-II was presented by Hirose et al. [2]. The KR-I was large and heavy, weighing in at 350 kg.

Klaassen and Paap [3] and Paap et al. [4] 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

**Figure 1:** The OmniTread OT-4 serpentine robot slithering out of a crevice under a pile of rocks.

the vehicles orientation (i.e., its roll angle). Segments are interconnected by universal joints that are actuated by three additional electric motors through strings.

While wheeled serpentine robots can work well in smooth-walled pipes, more rugged terrain requires tracked propulsion. To this effect Takayama and Hirose [5] developed the Souryu 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.

A serpentine robot that is strikingly similar to our OmniTread design is MOIRA [6].[a] 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, because the bellows are more compact and don't require any space in the segments.

A different concept, using unpowered joints, was introduced by Kimura and Hirose [7] at the Tokyo Institute of Technology. That robot, called Genbu, is probably the only serpentine robot with unpowered joints.

Another robot incorporating a combination of passive and active joints as well as independently driven and coupled segments is KOHGA developed by Kamegawa et al.

[8]. This robot implements a smart design feature: Besides a camera in the front segment there is a second camera in the tail section that can be pointed forward, in the way a scorpion points its tail forward and over-head. This "tail-view" greatly helps teleoperating the robot.

Of course, we should mention in this introduction that the OmniTread OT-4 is the successor of our earlier-developed OmniTread OT-8, shown in Figure 2. The OT-8 is so designated because it can fit through a hole 8 inches in diameter, while the OT-4 can fit through a hole 4 inches in diameter. Our paper [15] describes the OT-8 in detail.

## II THE OMNITREAD CONCEPT

The OmniTread OT-4 comprises seven segments and six 2-DOF joints, as shown in Figure 3. The segment in the

**Figure 2:** Our earlier-developed and larger OmniTread OT-8 can fit through an 8-inch diameter hole.

center is called "Motor Segment" because it houses the single drive motor. All other segments are called "Actuation Segments" because they house, among others, the control components for the pneumatic actuators. Segments #1 and #7 will be able to hold some payload, such as cameras, microphones, and speakers. Segments #2 and #6 will hold $CO_2$ tanks and a micro air-compressor, respectively, for pneumatic power. Segments #3 and #5 will hold Li-Polymer batteries. Table I lists some of the OT-4's key specifications.

The OT-4 is designed to carry onboard energy resources for up to one hour of continuous, untethered operation. This important feature, however, was not yet fully functional at the time of writing this paper. We expect this feature to be functional when we demonstrate the OT-4 at this conference within the framework of the *Judged Robot Showcase*.

The OT-8 and OT-4 share these mostly unique features:

1. *Tracks-all-around* each segment. This design aims at maximizing the coverage of the whole robot body with moving tracks. This feature is tremendously important, since the long, slender body of serpentine robots rolls over easily in difficult terrain that may not allow the robot to upright itself immediately.
2. The 2-DOF joints are actuated by *pneumatic bellows*, which produce sufficient torque to lift the three leading or trailing segments up and over obstacles. More

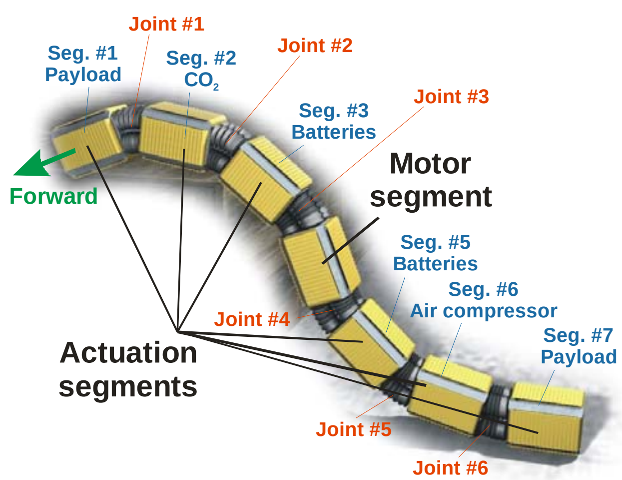


**Figure 3:** Nomenclature for segments and joints.

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[a] 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.

**Table I:** Specifications for the OmniTread OT-4.

| | |
|---|---|
| **Structure:** | Seven segments, six 2-DOF rotary joints |
| **Dimensions:** | |
| L×WxH: | 94 cm (37”) x 8.2 cm (3.2”) x 8.2 cm (3.2”) |
| Weight: | 3.6 Kg (8.0 lbs) |
| Motor Seg. length: | 10.9 cm (4.3”) |
| Actuator Seg. length: | 10.3 cm (4.0”) |
| Joint length: | 3.6 cm (1.4”) |
| **Performance:** | |
| Diameter: | Can pass through a 10-cm (4.0”) dia. hole |
| Lifting power: | When stretched out horizontally, OT-4 can lift three segments off the ground. |
| Flexibility: | Joints bend at least ±33° in any direction but ±41° in principal directions. |
| Turning radius | Outside: 22.9 (9”)<br>Inside: 15.2 cm (6”) |
| Speed: | 10 cm/sec (4 in/sec) |
| **Control:** | Off-board PC, connected through electric tether. Full proportional control over angular position of joints, stiffness, and forward/backward drive speed.<br>Currently, 3 operators are needed to operate six joysticks for the six 2-DOF joints. |
| **Design features that enable tetherless operation** | |
| **Pneumatic power:** | Obtained from liquid $CO_2$ tanks and miniature air compressor. |
| **Electric power:** | Obtained from onboard Li-Pol batteries. Sufficient for >60 minutes of operation. |
| **Micro-clutches:** | Any track can be individually engaged or disengaged under computer control, resulting in significant power savings. |

importantly, pneumatic bellows provide natural compliance with the terrain. This assures optimal traction on most terrains.

3. A single electric drive\ motor in the center segment provides rotary power to each segment through a so-called “drive shaft spine” that runs through the whole length of the robot. We believe this design to be more weight and power efficient than individual motors in each segment. The penalty with this design is a slight inefficiency when articulating the joints.

In the remainder of this section we discuss features (1) and (2) in more detail. Feature (3) is straightforward and does not warrant an in-depth explanation.

## II.A Tracks-all-around

One doctrine in the design of all OmniTread models is the maximal coverage of all sides of the robot with moving tracks. This doctrine is based on two reasons:

1. Serpentine robots inevitable roll over when traveling over rugged terrain. Since terrain conditions may not allow the robot to upright itself immediately, only coverage of *all* sides with propulsion elements can assure continuation of the mission after a roll over.
2. 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 produces motion. To express this relation quantitatively, we define the term “*Propulsion Ratio,*[b]” $P_r$. $P_r$ is measured as the surface area that provides propulsion, $A_p$, divided by the total surface area, $A_p+A_i$

$$P_r = A_p/( A_p + A_i) \qquad (1)$$

where $A_i$ is the inert surface area of the body. To further clarify, $A_p$ is the sum of all surface areas that *could* provide propulsion if in contact with the environment, while $A_i$ is the sum of all surface areas that could not.

$P_r$ is not only a function of the robot’s geometry, but also of the application domain. For example, on flat and hard terrain, $P_r$ for a conventional automobile is 1.0 since only the wheels can be in contact with the terrain. That’s because in a car no inert area of the periphery could possibly be in contact with the ground, that is, $A_i = 0$. However, on soft terrain the wheels sink into the ground and on rugged terrain obstacles protrude out of the ground, resulting in potential contact between the ground and portions of the inert body periphery. In this case the propulsion ratio $P_r$ is undesirably low.

In practice, 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 (as is also advised by Blitch [10]. We also took extensive measures to reduce the space (and thus, the inert area $A_i$) between the segments. Environments, in which robots with high propulsion ratios excel, are dense underbrush, rubble, and rocks. In these environments contact can occur anywhere, and robots that have propulsion surfaces only on the bottom are always at risk of being stalled due to excessive, non-propelling contact. The propulsion ratio for the OT-4 is 0.59 while that of our earlier OmniTread OT-8 is 0.42.

## II.B Pneumatic Joint Actuation

The foremost reason for actuating joints pneumatically is the natural and controllable compliance afforded by this method. Natural compliance is of critical importance, since propulsion depends on optimal traction between propelling surfaces and arbitrarily shaped terrain features. On rugged terrain, maximal traction is achieved by letting

[b] In an earlier paper, John Blitch, former Program Director of the DARPA TMR program and currently Director of the Alliance for Robot Assisted Crisis Assessment and Response, developed the notion of “Traction Fraction” [2003]. The Traction Fraction concept is very similar to the “Propulsion Ratio” concept described here, although both concepts were developed independently. Our first formal formulation of the “Propulsion Ratio” concept was included in a report to our sponsors at the U.S. Department of Energy, in Sept. 2002 – see http://www.engin.umich.edu/research/mrl/urpr/Reports/2002-Monthly-09.pdf.

We consider the significant similarity between the two independently conceived concepts as support for – but not proof of – their validity.

joints go limp, allowing the robot's body to conform compliantly to the terrain. Without natural compliance, extremely complex sensor/actuator control algorithms must produce artificial compliance to emulate joint compliance.

One major problem with pneumatic joint actuation is the difficulty of controlling the somewhat uncommon pneumatic joint actuators. Many more roboticists are familiar with the control of electric motors than with the control of pneumatic actuators.

In order to address the joint control problem methodically, we spent almost two years of dedicated efforts studying this problem and solutions. As a result we developed a unique and recently patented pneumatic joint controller. This controller can simultaneously control both the position (i.e., angular deflection) as well as the stiffness of each 2-DOF joint. Furthermore, our controller is optimized for the preservation of compressed air, or, as in the case of the OT-4, which is designed for tetherless operation, preservation of on-board $CO_2$. When we tested the air consumption of conventional pneumatic position-control circuits with our optimized control system, we found that our system reduced air consumption by a factor of 30. Details on our joint actuation system are provided in our papers [11], [12].

There are three well-known types of pneumatic actuators, as shown in Figure 4:

- Pneumatic cylinder – This is the most widely used pneumatic actuator. One disadvantage of pneumatic cylinders is their limited *strain* (the ration in length between the fully extended state and the fully retracted state). Because of their design, pneumatic cylinders cannot have a strain greater than 2.0.
- Pneumatic muscle ("McKibben Muscle") – This actuator comprises an airtight liner, surrounded by a mesh. When the liner is inflated, it balloons, forcing an increase in the diameter of the mesh. Because of the construction of the mesh from diagonally woven fibers, the increase in diameter forces a decrease in length. Thus, inflation of this actuator results in axial contraction. While very forceful, the strain of pneumatic muscles is limited to about 1.3.
- Pneumatic bellows – this actuator is made of an elastic, airtight tube, usually rubber. The wall of the tube is pre-shaped into characteristic convolutes that make it easy for the tube to expand axially when inflated. The convolutes also help the bellows fold neatly when axially compressed by external forces. Because of their ability to fold into a compact shape, pneumatic bellows have a strain of up to 4.0. That is, their expanded length can be up to four times their fully compressed length. The bellows is in Figure 4b have fiber-reinforced walls, and metal rings around the inner convolutes prevent the bellows from ballooning. If a bellows was allowed to balloon, it would rupture.

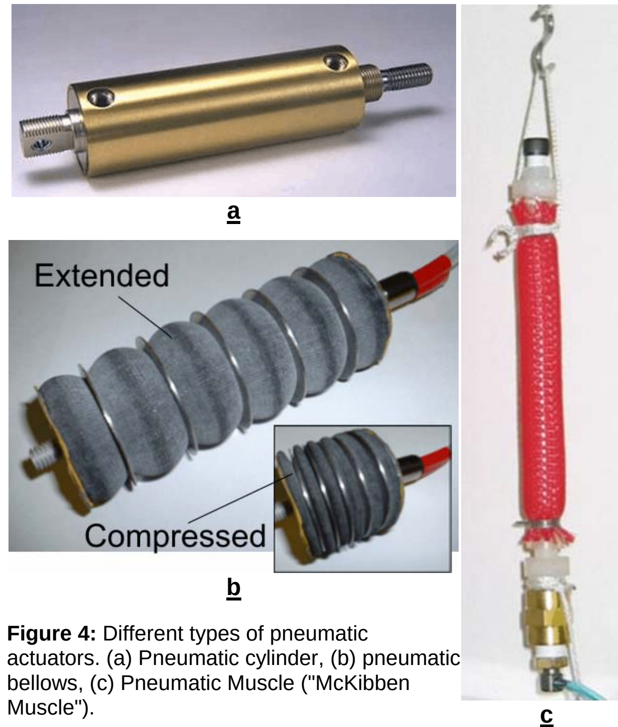


**Figure 4:** Different types of pneumatic actuators. (a) Pneumatic cylinder, (b) pneumatic bellows, (c) Pneumatic Muscle ("McKibben Muscle").

In the OmniTread line of serpentine robots, we chose pneumatic bellows as the joint actuators, since their superior strain allows them to fit entirely into the space of the joint, without taking up any of the very limited space inside the segments.

## III Design Details

One key design feature of our OmniTread robots is the placement of a single drive motor in the center segment. With the motor taking up space only in on segment, all other segments have space for a manifold, valves, and an electronic control board. In addition, there is a rather large space (shown as the red block in Figure 5) that is available for energy storage or for a payload.

In the remainder of this section, we discuss the design of individual functional components. Where applicable, we refer to earlier publications, to avoid duplication.

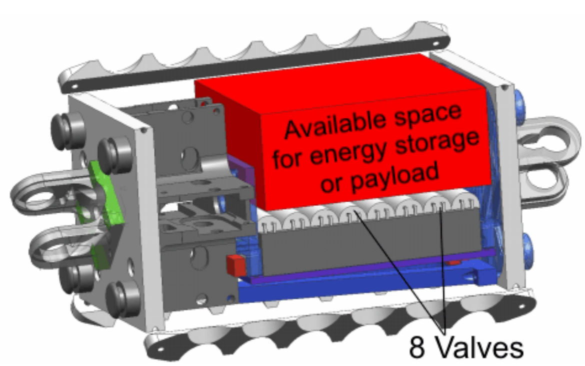


**Figure 5:** All six non-motor segments, called "Actuation Segments," have this space allocation.

### *III.A Gear Train*

The single electric motor in the motor segment powers the so-called "drive shaft spine" that runs the length of the robot. The drive shaft spine comprises seven rigid shafts that are connected by six universal joints. The universal joints are concentrically located within the gimbal joints that link the segments.

On each shaft segment is a worm. Four worm gears feed off that worm on the drive shaft as shown in Figure 6. Each worm gear drives a chain that drives the track sprocket. The drive shaft is supported by two ball bearings on each end of the gearbox to retain good tolerances within the gearbox. The other end of the drive shaft is floating and only supported by the universal joint. Not constraining the shaft at three points prevents the driveshaft from flexing too much, if the structure of the segment warps under high loads.

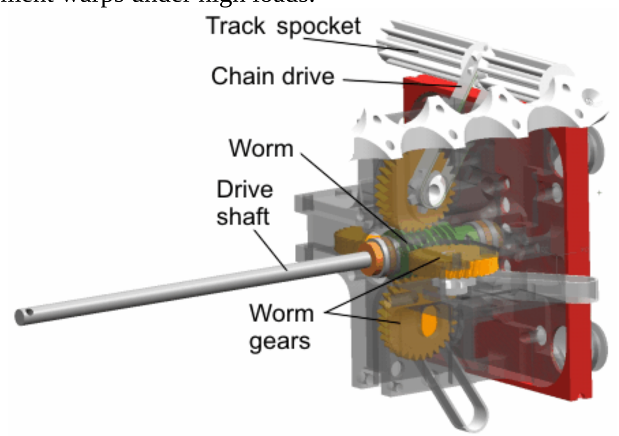


**Figure 6:** The track sprocket (white) is driven by the driveshaft via a worm (green), worm gear (orange), and chain drive (grey).

The motor is mounted on a sliding fixture that allows us to quickly change motors and gear ratios without any mechanical redesign. The motor itself also has a gear head for an added reduction stage, which can be chosen from a wide variety of gear heads offered by the manufacturer.

### *III.B Tracks*

To simplify the gearbox, the chain is run off a sprocket mounted directly on the side of the worm gear. The chain drive is therefore off-center with respect to the driveshaft and the two tracks per side are therefore not of equal width (see Figure 7). The tracks are molded in-house from a silicon mold. That mold is made from a Stereolithographic (SLA) rapid prototype, based on a CAD model, which we also developed in-house.

The grousers have twice the pitch of the track teeth to better engage features of the obstacle being scaled. Keeping the grouser pitch a function of the tooth pitch reduces the stiffness of the track as most of the flexibility of the track comes from the thin area between the teeth.

In order to increase the stability of the robot to minimize roll-overs, it is desirable to make the tracks as wide as possible. This is especially important considering the large deflection of the center of gravity we can impose on the robot by raising three segments in the air.

**Figure 7:** Front view of the OT-4. The extra-wide track areas add stability and reduce the risk of roll-overs.

On the other hand, our design goal was to let the OT-4 pass through a 4-inch diameter hole – clearly a requirement that conflicted with making the tracks as wide as possible. To meet both goals, we had to minimize the sprocket diameter, as is evident from Figure 7. The disadvantage of small sprockets is the greater roll resistance as well as a reduced ability to transfer torque between the sprocket and the track. In order to transfer more torque, the tooth profile was kept similar to that of a timing belt, i.e., we maximized the number of engaging teeth.

### *III.C Chassis Design*

Due to the small size of the OT-4, significant efforts had to be made to organize the internal components for space efficiency and accessibility. Cables and pneumatic lines are routed with these goals in mind. For example, the electronic circuit board on each segment has a connector on each end, with the wires coming from the neighboring segments plugging into the closer side. This design eliminated the need for wire runs all the way through the segment. Similarly, instead of using air hoses we integrated all pneumatic pathways into the chassis. This was possible thanks to SLA rapid prototyping techniques, which build the parts in layers and allows for such internal features. The chassis with integrated manifold and "etched-in" pneumatic pathways is shown in Figure 8.

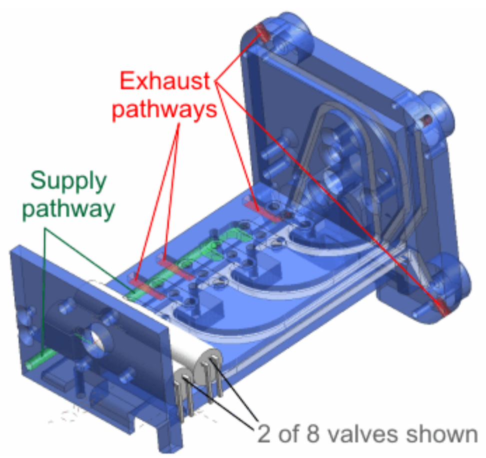


**Figure 8:** Manifold with two of the eight valves (white) mounted. Exhaust and supply pathways from and to the bellows are shown in red and green, respectively.

SLA rapid prototyping allowed us to create very complex, and otherwise difficult to machine structures. The SLA technique also allowed us to design parts for ease of assembly, maintenance, and space savings. However, SLA resins tend to warp with time, which is why they are normally used for prototyping only. In our early OT-4 prototypes, components that were under constant load would creep with time and would cause problems, especially in the case of the seal between the valves and the manifold. Aluminum reinforcements were therefore added to the endwalls, joints and manifold at key points where creep and deformation during load was becoming an issue. The reinforcements can be seen below in red:

As shown in Figure 9, the endwalls were reinforced with a thin aluminum shell and the manifold was reinforced with a bar screwed on at both ends. The result was a much stiffer segment at a minor (2.5%) weight penalty.

## *III.D Joints*

Between any two segments are two concentric universal joints referred to as the "outer" and "inner" universal joint. The outer universal joint connects the two adjacent segments. It is made of two forks and a ball-bearing-mounted gimbal connecting the two forks, as shown in Figure 10. The inner universal joint (not shown) connects adjacent segments of the drive shaft spine and is concentrically located inside the gimbal. All components of the outer universal joint are made from aluminum and each fork is screwed onto the adjacent segment endwalls. Two potentiometers mounted on one arm of each fork, respectively, provide position feedback for the control of the joint angles.

The joint can be actuated at least 33° in any direction and up to 41° in the four principal directions (up, down and side to side). Wiring and pneumatic lines between the segments pass through four holes at the corners of the gimbal and the bases of the forks.

Each joint is orientated with respect to each other in a way so as to compensate for gimbal error, the angular 'twisting' deviation that occurs between the two ends of a universal joint as it is articulated. Without this, three fully articulated joints would lead to each progressive segment being 'twisted' about the drive spine axis leading to instability and making traversing obstacles difficult.

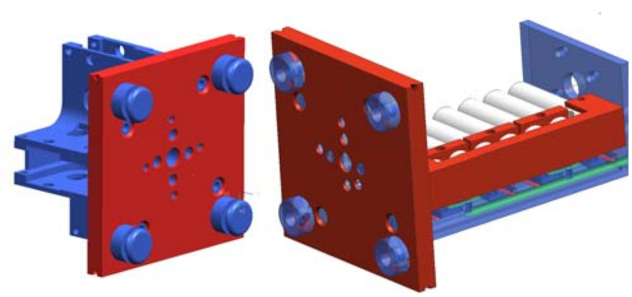


**Figure 9:** Aluminum reinforcements for SLA parts. Blue: SLA; Red: Thin aluminum reinforcement shells covering the original SLA. (a) Front of gearbox; (b) front of manifold.

## *III.E Pneumatic Bellows*

Pneumatic bellows develop axial force according to

$$F = PA \tag{2}$$

where $P$ is the pressure of the compressed air and $A$ is the area of the bellows surface that is normal to the axial direction, that is, the area of the cross section. One problem with Eq. (2) is the difficulty in determining exactly what the area $A$ is. For example, in the bellows shown in Figure 4b (in Section II.B), the convolutes change the diameter and thus the area of the cross section along the bellows. Of particular concern is the minimal cross section area, $A_{min}$, which corresponds to the inner whorl of the convolutes. For a given pressure $P$, the axial force that the bellows can apply is limited by the cross section area of the inner whorls, $A_{min}$. Yet, the volume of space that the bellows requires is determined by the diameter of its outer whorls. In the relatively large OT-8, the ratio between inner and outer diameter of the whorls (we refer to this ratio as "*bellows efficiency*") is fairly close to 1.0. However, in the smaller bellows of the OT-4, the bellows efficiency is much smaller than 1.0. In many conventional bellows the diameter of the inner whorl increases when inflated, thereby improving that bellows' efficiency. However, our OT-8 bellows design uses a metal ring around the inner whorls to prevent the bellows from ballooning. At the same time, these rings prevent the inner whorls from growing in diameter, thereby keeping the bellows efficiency low.

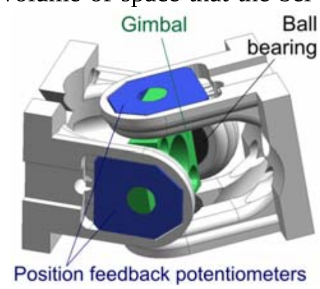


**Figure 10:** Outer universal joint, with potentiometers (blue), gimbal (green) and ball bearings (black).

To overcome this problem in the small-sized OT-4 bellows, we abandoned the metal rings altogether. Instead, we encased the OT-4 bellows in a tubular polyester mesh. To distinguish between these parts, we call the air-tight, elastic part of the bellows "liner," and the outer part "mesh."

The new two-part bellows of the OT-4, shown in Figure 11, has the significant advantage of allowing the diameter of the inner whorl to grow when pressurized, until the inner whorl is practically flush with the mesh (see Figure 12). The result is a bellows that has an efficiency of close to 1.0, when fully pressurized.

There is, however, one problem with all bellows designs: When the bellows extends beyond the natural length of the liner, the axial extension force $F = PA$ has to work against the elasticity of the liner. Similarly, when a bellows in a joint is compressed beyond a certain limit (e.g., because the bellows on the opposite site is expanding), its liner and mesh develop elastic forces that resist further compression with increasing force. Conversely, the bellows on the side of the joint that is being compressed resist further compression, thereby making it harder for the opposing bellows to expand.

As a result of these effects, the moment produced by the bellows when installed inside a joint is neither constant nor depending only on the applied pressure differential. Rather, the produced moment is a non-linear function of the joint's momentary angle. For extreme joint angles, the moment produces by the joints may be reduced by as much as 50% compared to the maximal moment that's available when the joint is in its neutral position. In the OT-4, however, we dimensioned the bellows so as to be powerful enough to lift three segments even at near-maximal joint angles.

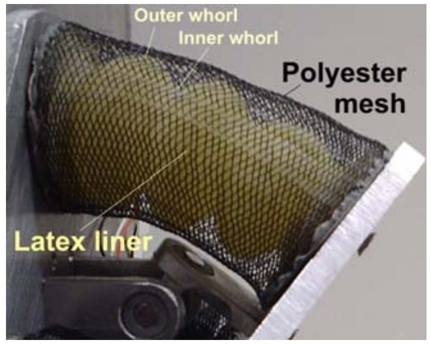


**Figure 11:** OT-4 bellows comprising a liner and a mesh. We chose yellow latex liner material for this photograph because it contrasts better with the black mesh. However the actual OT-4 bellows have neoprene (black) liners.

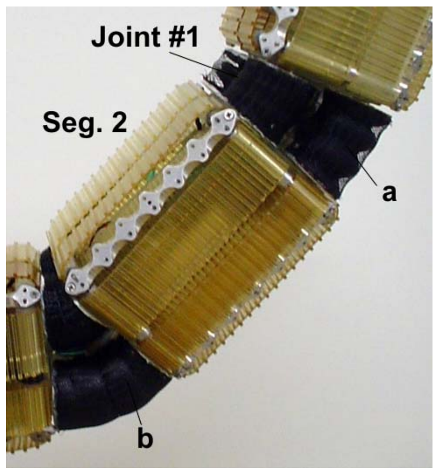


**Figure 12:** OT-4 bellows at different levels of internal pressure. Bellows 'a' in Joint #1 is pressurized to a moderate level. Bellows 'b', is inflated to the maximal pressure of 30 psi.

## IV Experimental Results

The OmniTread OT-4 will be demonstrated at this conference for three days, and it will also be demonstrated in the Judged Competition at this conference. A library of high-resolution video clips and photographs is available at
http://www.engin.umich.edu/research/mrl/00MoRob_6.html

Real-life demonstrations at this conference and the rich media resources available at the above web site are far more suitable for conveying the mobility performance of a serpentine robot than a written description. For this reason, we report experimental results in this paper by just a few photographs of the OT-4 (see Figure 13) in various test environments. All of the photographs in this section are frames of video footage taken during the actual and successful traversal of the depicted environment. In other words, none of the photographs is staged.

## V Conclusions

This paper describes the design and features of the "OT-4" serpentine robot, which is part of the family of so-called "OmniTread" robots that are being built at our lab. Key features of the OmniTreads are (1) joint actuation with pneumatic bellows, (2) body surrounded by extra-wide tracks on all sides, and (3) a single drive motor powers all tracks.

In contrast to our earlier OmniTread model OT-8, the smaller OT-4 is designed to carry onboard energy resources (electric batteries and tanks with liquid, pressurized $CO_2$) for up to one hour of untethered operation.


Acknowledgements

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We are also grateful to Dr. William Hutchison who developed the "7G" computerized learning program. This program produced the sophisticated and complex motion strategies used for traversing the two wooden obstacle courses in Figure 13.


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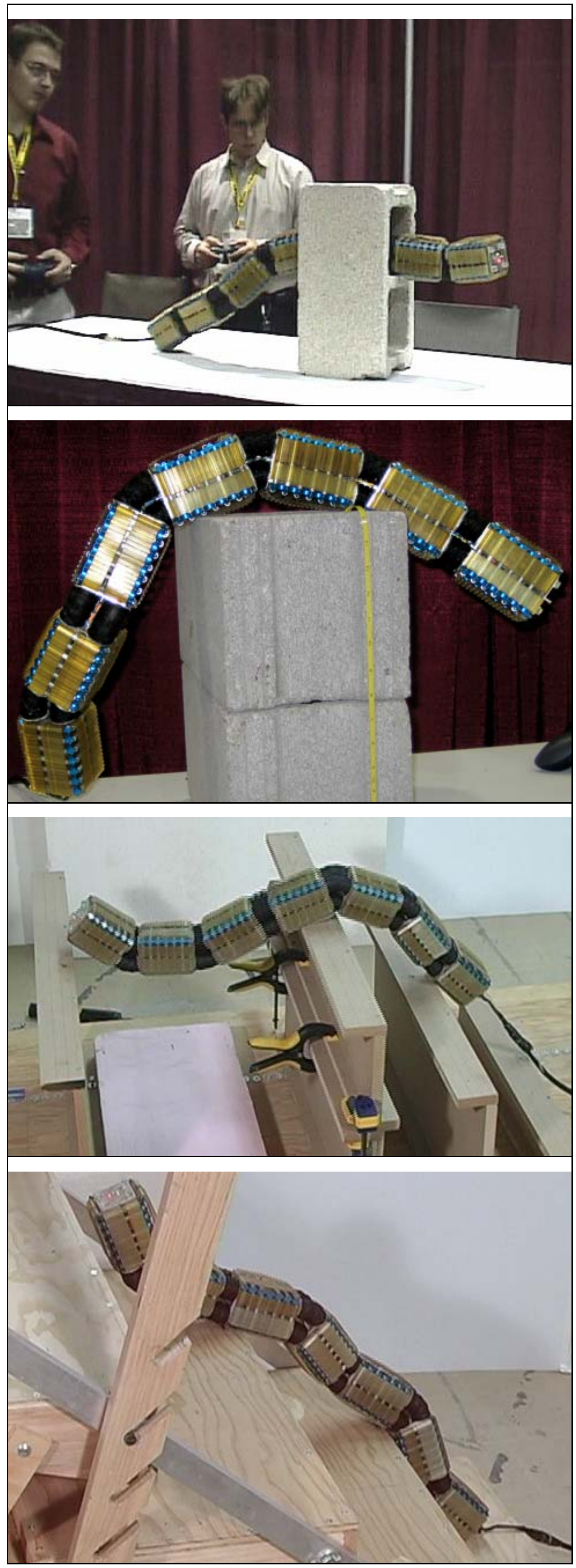

**Figure 13:** Snapshots of successful traversal of different obstacle courses. **Above:** OT-4 driving up the inside of a 4-inch diameter pipe, at a 45-degree incline. We have also successfully demonstrated a climb inside a *vertical* 4-inch pipe.

**Right-hand column, top to bottom**: (1) OT-4 climbing up and through the narrow opening in a cinder block; (2) OT-4 successfully climbing over an obstacle just under 40-cm high (4.7 times the height of the OT-4 itself); (3) OT-4 climbing over an obstacle course of parallel bars; (4) OT-4 climbing up a staircase with a 10-in tread and 8¼-in rise (40° slope).