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The OmniTread Serpentine Robot for Industrial Inspection and Surveillance[1]

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Keywords

Serpentine robot, snake robot, pneumatic, multi-segment, multi-joint, hypermobility, hyper-redundant.

Abstract

Many industrial applications require inspections and surveillance in hard-to-reach and sometimes even hazardous areas. A relatively new kind of robotic mechanism, called a "serpentine robot," may be able to provide a solution to some of these applications.

Serpentine robots are slender, multi-segmented vehicles designed to provide greater mobility than conventional wheeled or tracked robots. This paper introduces one such robot, the "OmniTread." The OmniTread serpentine robot comprises five 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 2-DOF joints are actuated by pneumatic bellows, which produce sufficient torque to lift the two leading or trailing segments up and over obstacles. This paper describes in detail the OmniTread's general design, its key mechanical elements, and its low-level control system.

The OmniTread serpentine robot was tested at the Small Robotic Vehicle Test Bed at Southwest Research Institute (SwRI). Results from these independent and objective tests are also presented in this paper.

INTRODUCTION

Many industrial inspection tasks exist, in which sensors or probes must be transported to hard-to-reach areas, for example to take measurements, perform visual inspections, or to conduct surveillance. Some of these areas are not only difficult to reach, but may also present safety and health hazards to human inspectors. Examples are the numerous radioactive waste processing and storage facilities managed by the U.S. Department of Energy.

A small mobile robot capable of carrying sensor payloads into hard-to-reach areas would be a very desirable solution for such applications. The problem to date has been that many inspection sites are not accessible by small wheeled or tracked mobile robots. A so-called hypermobility robot possessing extraordinary motion capabilities is therefore needed. Desired capabilities for such a robot are:

- ability to traverse rugged terrain, such as concrete floors cluttered with debris, or unfinished floors such as those found on constructions sites;
- ability to fit through small openings;
- ability to climb up and over tall vertical steps;
- ability to travel inside and outside of horizontal, vertical, or diagonal pipes such as electric conduits or water pipes;
- ability to climb up and down stairs;
- ability to pass across wide gaps.

A relatively new type of mobile robot, called a *serpentine robot* (also sometimes called a "snake robot") promises to offer these capabilities. 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 definition for the remainder of this paper.

- A "snake robot" is a multi-segment mechanism that derives propulsion from the relative 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 powered.

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In the following section we present a review of serpentine robots. We don't include snake robots in this review, since they are less relevant for the subsequent discussion of our OmniTread serpentine robot.

1 SERPENTINE ROBOTS

The first practical realization of a 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]. This first serpentine robot was large and heavy, weighing in at 350 kg. The robot comprises of multiple vertical cylindrical segments on powered wheels (tracks in KR-I) that give the mechanism 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 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 vehicle's orientation (i.e., its roll angle). Segments are interconnected by universal joints actuated by three additional electric motors through strings. Snake2 is an example of a robot that is inspired by the physiological structure of snakes where wheels replace tiny scales observed on the bodies of some real snakes. Snake2 is equipped with six infrared distance sensors, three torque sensors, one tilt sensor, two angle sensors in every segment, and a video camera in the head segment. Snake2 was specifically designed for the inspection of sewage pipes.

Another serpentine robot designed for sewer inspection was developed by Scholl et al. [2000] at the Forschungszentrum Informatik (FZI) in Germany. 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 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 the ability of this robot to adapt to irregular terrain because of 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 serpentine robot (introduced in Section 2) 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 cylinder-type joint actuators, as the discussion of our approach in Section 3 will show.

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 for 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.

The concept of joining several small robots into a train to overcome larger obstacles was used by researchers from Carnegie Mellon University in their Millibot Train [Brown et al. 2002]. This robot consists of seven electrically driven, very compact segments. The diameter of the track sprockets is larger than the height of each segment, which allows the robot to drive upside-down. Segments are connected by couplers for active connection and disconnection of segments, but the joints have only one DOF. Each joint is actuated by an electric motor with a high-ratio harmonic gear and slip clutch. It provides sufficient torque to lift up the three front segments. 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.

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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.

2 THE OMNITREAD SERPENTINE ROBOT

Since 1998 the Mobile Robotics Lab at the University of Michigan (UM) has focused on the development of serpentine robots. Figure 1 shows our first serpentine robot, the "*OmniPede*." In the OmniPede, UM introduced three innovative functional elements: (1) propulsion elements (here: legs) *evenly located around the perimeter of each segment*; (2) *pneumatic power* for joint actuation; and (3) a single so-called "*drive shaft spine*" that transfers mechanical power to all segments from a single drive motor.

From the study of the OmniPede, and from the observed shortcomings of this legged propulsion prototype, we derived important insights about the design of serpentine robots. These insights led to the development of the far more practical "OmniTread" serpentine robot, shown in Figure 2.

2.1 Fundamental Design Considerations

The OmniTread design offers two fundamentally important advantages over its predecessor and, in fact, over all other serpentine robots described in the scientific literature to date. These features are:

1. *maximal* coverage of all sides of all segments with propulsion elements;
2. joint actuation with *pneumatic bellows*.

These innovative features are detailed below.

2.1.1 Maximal 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 percentage of the robot's surface area with propulsion elements.

The rationale behind this doctrine 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 produces motion. To express this design doctrine mathematically, we define the term "*Propulsion Ratio*," P_r. P_r is measured as the surface area that provides propulsion, A_p, divided by the inert surface area of the body, A_i

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

To further clarify, A_p is the sum of all surface areas that *would* provide propulsion if in contact with the environment, while A_i is the sum of all surface areas that would not. Note that when an inert surface point contacts the environment, it not only fails to propel the vehicle, but it actually counteracts propulsion because the contact creates friction, and the robot may even get stuck.

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 the OmniPede is infinite, because, since the feet protrude out of the body everywhere, no inert area of the periphery could possibly be in contact with the ground, that is, $A_i = 0$. However, on soft terrain the feet 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. 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.

2.1.2 Joint actuation with pneumatic bellows

During our work with serpentine robots, we spent a significant amount of time on the analysis and formulation of requirements for joint actuators in serpentine robots. Listed here are the four most important ones:

Figure 1: UM began the development of its first serpentine robot, the "*OmniPede,*" in 1998. The prototype had seven segments and uses legs for propulsion. An electric motor at the end (left in the photograph) rotates a so-called "drive shaft spine," which provides mechanical power to each foot (black parts). Segments are linked by 2-DOF articulated joints that are actuated by two pneumatic cylinders.

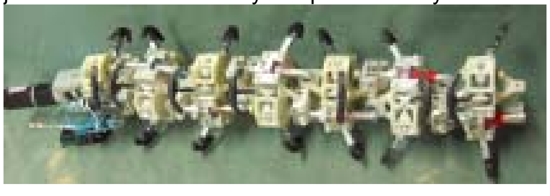
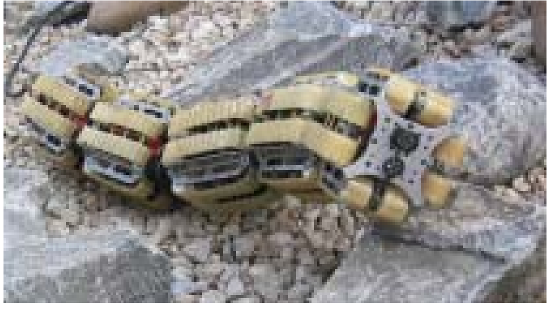


Figure 2: UM's fully functional OmniTread serpentine robot is almost completely covered with propulsion elements (tracks). At the instance this photograph was taken at SwRI, the robot was actually driving on one of its four edges, not sides, after the terrain forced it into this position. Although this position is less optimal, the OmniTread continued to move and function without a problem.



1. By definition, serpentine robots are relatively long compared to their diameter, so that their lead segments can reach up and over a high obstacle 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. One key requirement for serpentine robots is thus that they employ joint actuators of sufficient strength to lift up two or more of its lead or tail segments.
2. Another key requirement is that serpentine robots should conform to the terrain compliantly. This assures that as many driving segments as possible are in contact with the ground at all times, thereby providing effective propulsion. Serpentine robots that don't conform compliantly require extremely complex sensor systems to measure contact forces and to command a momentary angle for each non-compliant joint so as to force contact with the ground. Such actively controlled compliance has not yet been successfully demonstrated, and may well be unfeasible for many more years.
3. At times it is necessary to increase the stiffness of a joint, for example to reach over an obstacle (Figure 3), or for crossing a gap (Figure 4). Alternatively, it may be necessary to adjust the stiffness to an intermediate level, for example, when the lead segment leans against a vertical wall while being pushed up that wall by the following segments. Thus, serpentine robots must be capable of adjusting the stiffness of every DOF individually and proportionally.
4. Large amounts of space dedicated to joints dramatically increase the amount of inert surface area. Therefore, joint actuators should take up as little space as possible, to reduce the size of space occupied by joints (called "joint space").

Extensive studies of these requirements and of joint actuators potentially meeting these requirements led to the second unique design feature of the OmniTread, the use of pneumatic bellows for actuating the joints. Our research [Granosik and Borenstein, 2004a] shows 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. Because of the latter feature we call our bellows-based pneumatic system "Integrated Joint Actuator" (IJA).

2.2 OmniTread Design Details

In this section we provide details on some the most critical components of the OmniTread. Specifically, we discuss the design of our first fully functioning prototype of the OmniTread, called "OT-8," which is shown in the photographs in this paper. The OT-8 requires a tether to the off-board electric and pneumatic power sources. A smaller version of the OmniTread with onboard electric and pneumatic power sources is under development at our lab but is not discussed in this paper.

Figure 3: The OmniTread is beginning to lift two lead segments to reach the overhanging obstacle to the right. Weaker serpentine robots must lean against the obstacle to scale it; they can thus not scale overhanging obstacles as shown here.

Figure 4: The OmniTread successfully crosses a gap that is a little wider than half the robot's length. By lifting its front segments up, the center of gravity shifts slightly toward the rear.

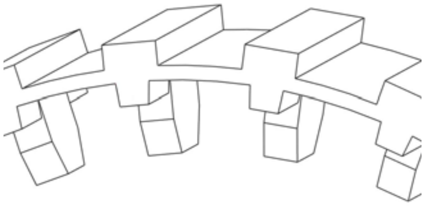
The OT-8 described in this paper has five segments and four pneumatically actuated 2-degree-of-freedom (DOF) joints. The size of each segment is 20×18.6×18.6 cm (length × width × height). Each joint space is 6.8 cm long. The entire robot is 127 cm long and weighs about 13.6 kg.

2.2.1 Tracks

The OT-8 has 40 tracks and 160 sprockets and rollers. These components make up a significant portion of the overall weight of the system. In order to minimize system weight, we sought tracks that were particularly lightweight. In addition, the tracks had to offer low drag and they had to be able to accommodate debris (especially sand) that could get trapped between the tracks and the drive sprockets.

A solution was found in the form of a slightly elastic urethane material that would stretch to accommodate debris without mechanical tensioners, yet was strong enough not to slip over the sprocket teeth under stress. After testing different tracks designs we selected the section profile shown in Figure 5. This design is an adaptation of the rubber tracks found in the *Fast Traxx* remote-controlled toy race car made by Tyco.

Figure 5: Profile of the OmniTread's urethane tracks.



The trapezoidal extrusion on the bottom of the track fits into a groove on the sprocket, ensuring that the track stays aligned on the sprocket. For further testing we rapid-prototyped tracks based on this design using 50 through 90 durometer urethanes.

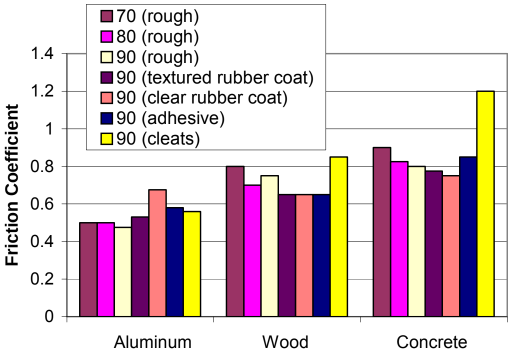
Of the test samples, the 90 durometer urethanes were found to perform the best. Lower durometer urethanes had the benefit of a higher friction coefficient and lower running drag but the 90 durometer tracks were the only ones that could successfully lift the robot over an edge with all the weight applied to only one segment as shown in Figure 6. In this test the lower durometer tracks would stretch and slip over the teeth of the sprocket too easily.

In order to compensate for the undesirably low friction coefficient of the 90 durometer urethane we tested different surfaces treatments for the grousers of the tracks. Specifically, we tested spray-on rubber coatings, rubber-like adhesives, and metal cleats. The results of these tests are summarized in Figure 7.

The various compounds applied onto the 90 durometer tracks helped mainly on the aluminum surface but otherwise showed only a marginal improvement. Of the three compounds, the adhesives showed the best wear resistance, while the spray would last only a few runs and required thorough cleaning to be useful. The metal cleats, basically stainless steel pins pushed into the grousers, showed great potential but were too aggressive toward the hands of the experimenters.

Figure 6: OmniTread climbing over an edge. At this moment almost all the weight of the robot rests on the tracks contacting the edge. Tracks of too elastic a material would slip out of the sprockets under such loads.

Figure 7: Static coefficients of friction for different tracks materials on different surfaces. The grousers of urethanes that were tested without added materials were roughened prior to the experiments.

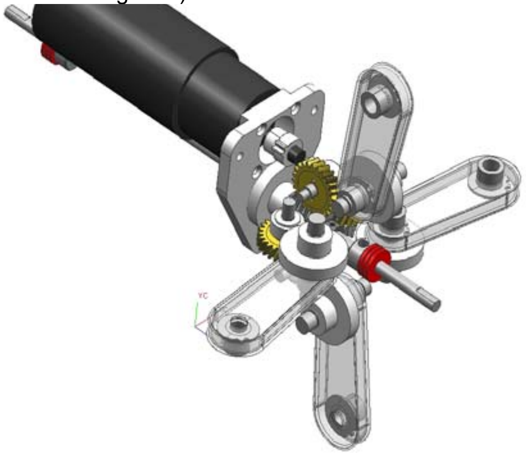


Although we have not implemented this approach for cost reasons, we believe that the ideal compromise between the different demands on the tracks would be a two-compound track made mostly of high-durometer urethane but with a very soft urethane molded into the grousers.

2.2.2 Power Train

A single 70W drive motor (the RE36 made by Maxon) located in the central segment provides torque to all tracks on all five segments via the drive shaft spine. The drive shaft spine is an axle that runs longitudinally through all segments. Universal joints let the axle transfer torque at joint angles of up to 30°. We chose a single motor design over the alternative of having a motor in each segment in order to minimize weight and maximized the available space in each segment. Within each segment there is a worm on each driveshaft that drives four worm-gears offset 90° from each other, as shown in Figure 8. Each worm gear runs two spur gears ending in chain drives to deliver power to the sprocket shafts. The purpose of the spur gears is to bring the chain back to

Figure 8: CAD view of the Gearbox (here shown for the motor segment).



center again so that the two tracks on each side can be of equal width. The chain drive is very slim and therefore minimizes the gap between the tracks. The total gear reduction from the motor to the sprockets is 448:1. The drive system and chain drive is sealed to prevent dirt from entering the mechanism.

2.2.3 Joint actuation

The joints of serpentine robots are its single most critical component. We are aware of serpentine robot designs that failed in practice because the joints were too weak to lift one or more distal segments up and over obstacles.

We researched this subject in depth and subsequently developed a powerful yet naturally compliant joint actuation system based on pneumatic bellows. This system, called "*Integrated Joint Actuator*" (IJA), is shown in Figure 9. Our paper [Granosik and Borenstein, 2004a] describes the design considerations and the implementation of the IJA and this subject is therefore not further discussed in this paper.

2.2.4 Power

In the OmniTread OT-8 prototype described in this paper, electric and pneumatic energy, as well as control signals are provided through a tether – a 1 cm thick and 10 m long cable comprising six wires and a pneumatic pipe. Compressed air is supplied from an off-board compressor and distributed to the control valves from a single pipe running through the center of the robot. In the experiments described below the compressor provided variable pressure from 85 to 95 psi but the control system limited the maximum pressure in the bellows to 80 psi.

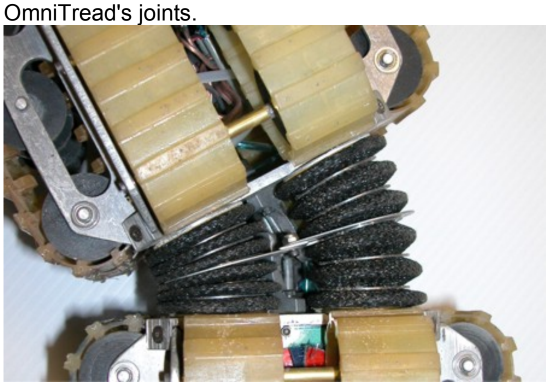
Of course, a tether is highly undesirable for most inspection and surveillance tasks, and we are currently designing a smaller version of the OmniTread that will operate entirely on onboard power systems and with only a very thin fiber optic cable for control and data communication. However, in this paper our focus is on the kinematic capabilities of the OmniTread robot, and those can be discussed regardless of the power source.

2.3 Control

The four joints of the OT-8 prototype are actuated by a total of 16 pneumatic bellows. With this design the OmniTread has 33 individually and proportionally controllable parameters, namely: 16 × position, 16 × stiffness, and 1 × speed forward/ backward.

In order to control the OmniTread we developed a microprocessor-based distributed control system consisting of five local controllers – one for each IJA and one for the motor. Each local controller is based on a 16-bit Motorola MC9S12DP256B microcontroller and all five controllers communicate with a master PC via CAN bus. A schematic diagram of the control system is shown in Figure 10.

Figure 9: These pneumatic bellows actuate the OmniTread's joints.



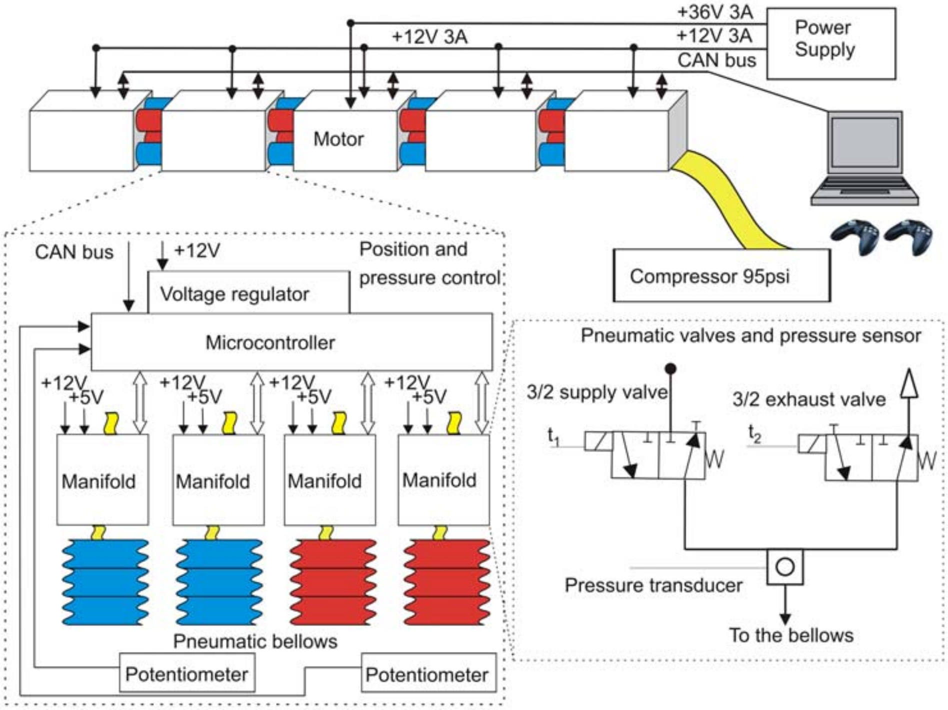
Each microcontroller manages the position and stiffness control for its adjacent 2-DOF joint. The microcontroller can receive new position and stiffness commands and return feedback data (two positions and four pressures) every 10 ms. Each microcontroller sends digital PWM signals to eight on-off pneumatic valves (two for each bellows) to implement the *Simplified Proportional Position and Stiffness* (SPPS) controller described in detail below. Each microcontroller also reads positions from two potentiometers and pressures from four pressure transducers.

The Simplified Proportional Position and Stiffness Controller

In our paper [Granosik and Borenstein, 2004] we proposed a control system called "Proportional Position and Stiffness" (PPS) controller. The PPE system is designed to do what its name implies: it allows for the simultaneous and proportional control of position and stiffness of pneumatic actuators. The PPS controller is further optimized for use in mobile robots, where on-board compressed air is a valuable resource. To this end, the PPS employs a uniquely designed system of valves that assures that compressed air is consumed only during commanded changes of pressure or stiffness, but not while an actuator is held at a constant pressure and stiffness.

However, the PPS controller as described in [Granosik and Borenstein, 2004] is based on an approximated model of cylinders and requires the real-time measurement of certain system parameters. For example, the polar moment of inertia of masses that are being moved by the joint must be known at all times, as well as the torque needed to move the joint. In complex environments where the serpentine robot may be laying on any side additional sensors would be needed to measure these parameters.

Figure 10: Schematic diagram of the OmniTread control system.



In the OmniTread described in the paper here these sensors are not yet implement. However, we were able to simplify the control system so that these sensors are not needed, while maintaining acceptable performance. In order to distinguish the simplified control system from the proper control system, we call it "*Simplified Proportional Position and Stiffness*" (SPPS) controller. The SPPS controller uses a PID position controller with a stiffness control subsystem, as shown in Figure 11.

The task of the control system is to control the position of a joint, as well as its stiffness. The controlled parameters are the pressures p_A and p_B in the bellows-pair that actuates the joint. In order to control p_A and p_B, the PID controller generates the control signal u as input for the valve control subsystem. This subsystem realizes the stiffness control and air flow minimization by activating the four pneumatic valves according to the flow chart in Figure 12. In every control cycle only one of the four valves is active, i.e. generates airflow to or from one of the bellows.

The SPPS assigns higher priority to stiffness when conflicts between position control and stiffness

Figure 11: Block diagram of Simplified Proportional Position and Stiffness (SPPS) system with zero air consumption at steady state.

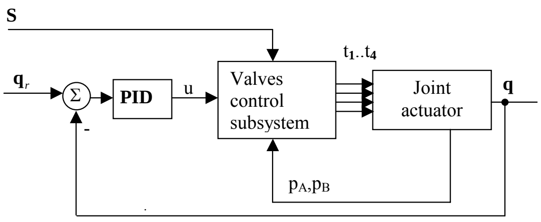
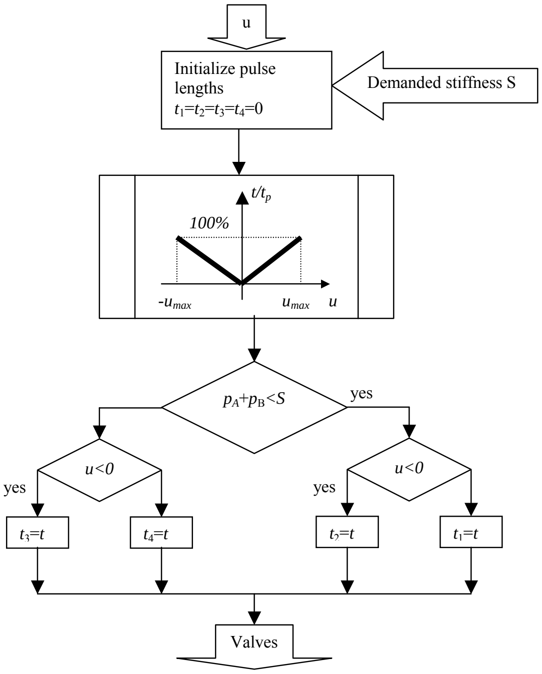


Figure 12: Flow chart for the valve control subsystem.



control arise. However, the SPPS control system cannot change the stiffness of a joint in steady state because the valve control subsystem is activated by position errors only. As our experiments showed, however, this limitation can easily be accommodated by the teleoperators or by an onboard computer, in future, more advanced, OmniTread models.

3 EXPERIMENTAL RESULTS

In order to test the performance of the OmniTread under realistic and objective conditions, we tested the robot at the Small Robotic Vehicle Test Bed at Southwest Research Institute (SwRI) in San Antonio, Texas.

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 robot's behavior at all times. The SwRI test facility is well designed and allows for the objective assessment of vastly different small robot designs. Among the tests were tasks such as climbing over high steps, ascending through the inside of pipes, traversing wide gaps, any many more. Some numeric test results are summarized in Table I. Other performance results are best conveyed through the photographs in this section.

Table I: Performance specification of the OmniTread

Maximum velocity	10 cm/s
Minimum turning radius	53 cm
Maximum sideways slope	Concrete Ramp: 25°
Maximum incline	Concrete Ramp: 30° Sand Ramp: 15°
Maximum angle of slope of PVC pipe (30 cm diameter)	22°
Maximum height of curb	45.7 cm
Maximum gap traversed	66 cm

The feature of tracks all around the body of the OmniTread was quickly validated in some of the first tests. This is documented in Figure 13a, where the robot traversed a natural (not man-made/urban) environment. Tracks on the sides of the robot provided additional propulsion, the lack of which might have stalled a vehicle without them. There were also abundant situations in which the robot rolled over sideways. Because of its almost complete coverage with propelling tracks, the robot continued operation without any difficulty.

Another unique OmniTread feature that fared well during the tests is the large amount of torque generated by the pneumatic bellows. This enables the robot to lift its two front (or rear) segments up, to reach up and over high steps. One impressive result obtained thanks to this feature was the successful climb up a 45.7-cm (18 inch) high curb, as shown in Figure 13b. This is about 2.3 times the height of the OmniTread. Such capabilities cannot be achieved by conventional tracked or wheeled mobile robots unless they are specially designed for the task.

Figure 13c shows the OmniTread entering a PVC pipe with an inside diameter of 30 cm and an inclination of 22°. Thanks to the OmniTread's powerful joint actuators, the robot is able to wedge itself between the upper and lower inside surfaces of the pipe and produce enough normal force against the inside walls of the pipe in order to climb up. Even though we do not explicitly control contact forces between OmniTread and the walls of the pipe, there is no danger of damaging the actuators due to their natural compliancy.

Figure 13d shows a sequence of photographs of the OmniTread traversing a 66 cm wide trench. This is actually over 50% of the robots length. This seemingly impossible task can be accomplished by lifting the front segment up, which moves the center of gravity slightly toward the rear. A combination of high lifting power and high stiffness is needed to perform this maneuver.

With regard to stairs, our original OmniTread prototype produced mixed results. It was only during our testing at SwRI that we discovered a possible problem. This problem may occur when the pitch of the stairs (i.e., the distance between the edges of the steps) is equal to the pitch of the robot (i.e., the combined length of one segment and one joint). In this case, there will eventually develop a situation, in which all edges of the steps that are in contact with the robot coincide with the inert areas of joint space and the robot is stuck. In practice, this problem can be avoided by designing the robot pitch to be different from the pitch of standard stairs. Alternatively, if a serpentine robot has seven or more segments, then it can perform certain maneuvers to overcome the stair pitch problem.

When we designed our OmniTread prototype, we had not yet become aware of this issue, and, upon testing at SwRI, the OmniTread promptly got stuck on a flight of standard-pitch stairs. However, the OmniTread successfully climbed up a set of non-standard pitch stairs even though the inclination was steep, about 30°, as shown in Figure 14.

4 CONCLUSIONS AND FUTURE WORK

This paper introduced a new mobile robot that belongs to the class of serpentine robots. Serpentine robots have the potential to provide hitherto unattainable capabilities, such as climbing over high steps, travel inside or outside of horizontal or even vertically pipes, or traversing wide gaps. While individual tasks of this nature have been tackled in the past by special-purpose mobile robots (e.g., pipe crawlers), it appears that only serpentine robots may be able to perform a large variety of difficult tasks.

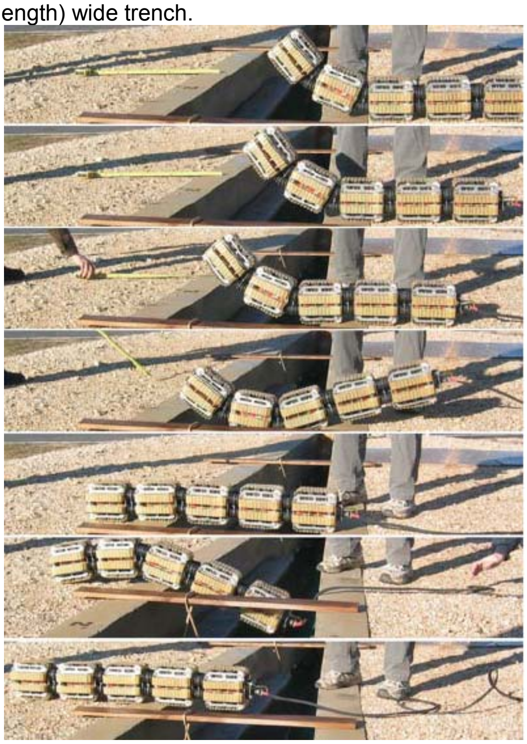
Figure 13: Situations during experiments in different test environments of the Small Robots test facility at the Southwest Research Institute (SwRI).

(a) During a traverse of the "large rocks" site, we observed several episodes of rocks pressing into the OmniTread's side. Because of the "tracks-all-around" feature, the rocks didn't impede motion. Rather, they added propulsion.

(b) OmniTread climbing up a 46-cm (18") high step.

(c) OmniTread entering and climbing up inside a PVC pipe sloped at 22°.

(d) OmniTread crossing a 66 cm (51% of robot's length) wide trench.



We believe that the OmniTread serpentine robot introduced here has a particularly high potential to become truly feasible and practical. Notable in the OmniTread are several innovative features as summarized here:

- **Pneumatically actuated 2-DOF joints** – The 2-DOF joints of the OmniTread are actuated pneumatically. Pneumatic actuation provides natural compliance with the terrain for optimal traction and shock absorption, as well as a very high force-to-weight ratio.
- **Bellows used as pneumatic actuators** – Bellows are ideal for serpentine robots because they fit naturally into the space occupied by the joints. This minimizes the need for space, especially space not covered by propulsion elements. In addition, bellows can expand to four times their compressed length. (Patent pending).
- **Proportional Position and Stiffness Control system** – The pneumatic control system, developed at our lab especially for serpentine robots, allows simultaneous, proportional control over position and stiffness of each individual bellows. In addition, the system uses compressed air only when changing the position or the stiffness of a bellows. Thus, during long stretches of straight travel no compressed air is used at all. (Patent pending).

- **Maximal coverage of robot surface with moving tracks** – In this paper we identified and formalized the need for maximizing the so-called the “Propulsion Ratio,” P_r. P_r is the ratio between propulsion area (surface area that provides propulsion when in contact with the environment) and inert surface (surface area that could come in contact with the environment but doesn’t provide propulsion). We implemented this design doctrine by covering all sides of all segments with extra-wide, moving tracks. The cost for this approach is additional complexity. The cost for not using this approach is mission failure when the robot gets stuck on troublesome terrain (US Patent #6,774,597).
- **Single drive motor for all segments and drive shaft spine** – Our analysis shows that a single drive motor is more energy, weight, and space-efficient than multiple motor configurations (i.e., one motor in each segment). Motor power is transferred to the segments via a drive shaft spine that runs the length of the robot. Within each segment the drive shaft spine is a rigid axle, connected to the axle in neighboring segments via a universal joint (not a flexible shaft). (US Patent #6,512,345).

We are currently designing the next generation of the OmniTread, which we refer to as “OT-4.” The OT-4 will have a smaller cross section but more segments, likely seven (compared to the five segments of our present prototype, OT-8). OT-4 will also have onboard power resources (electric and pneumatic) for over one hour of untethered operation. Pneumatic power will be provided by commercially available liquid CO_2 cartridges. In the OT-4 it will be possible to engage or disengage each individual track from the main drive shaft. Disengagement of tracks not in contact with the ground will result in a significant saving of electric energy. So-called floaters built into the pneumatic bellows will dramatically reduce CO_2 consumption, and a unique, so-called “roller gripper” will allow the OT-4 to latch onto thin pipes and travel along them.

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Figure 14: Sequence of photographs showing the OmniTread climbing up a flight of wooden stairs.

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