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OmniTread OT-4 Serpentine Robot – new Features and Experiments

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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, military intelligence gathering, and for surveillance and inspection tasks in hazardous and hard-to-reach environments. One such serpentine robot, developed 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. The OT-4 can 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. These bellows allow 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 with driven tracks. This design makes the robot indifferent to roll-overs, which are happen frequently when the slender bodies of serpentine robots travel over rugged terrain.

This paper describes the OmniTread concept as well as its latest technical features, and an extensive Experiment Results Section documents the abilities of the OT-4.

Keywords: OmniTread, Serpentine Robot, Snake Robot, Snakebot, Mobile Robot, Hyper-redundant, Multi-segmented, Hypermobility, Tracks.

1 INTRODUCTION

Urban Search and Rescue, military intelligence gathering, and certain industrial inspection 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).

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

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.

In the interest of brevity and since the focus of this paper is on serpentine robots, we omit a review of snake robots. 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. More recently, 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 the vehicle’s orientation (i.e., its roll angle). Segments are connected 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]. MOIRA[a] 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, which was 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 to our earlier-developed[9] 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[9] describes the OT-8 in detail.

Figure 2: Our earlier-developed and larger OmniTread OT-8 can fit through an 8-inch diameter hole. Here it is driving up an inclined sand pit.

2 THE OMNITREAD CONCEPT

The OmniTread OT-4 comprises seven segments and six 2-DOF joints, as shown in Figure 3. The segment in the 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 joint actuators. Segments #1 and #7 can hold some payload such as cameras, microphones, and speakers, or they can be equipped with flipper tracks,

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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.

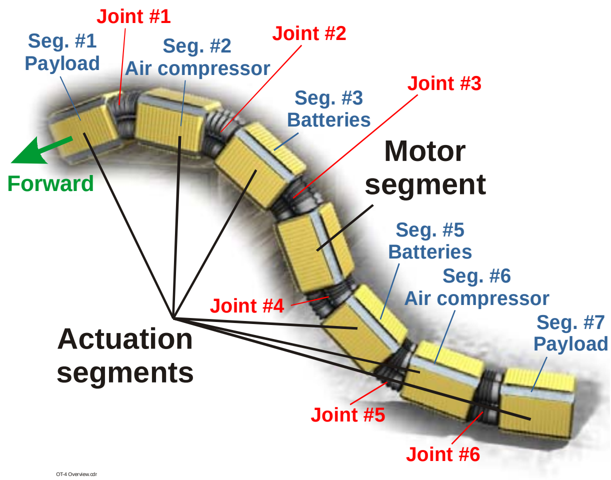

Figure 3: The OmniTread Model OT-4: Nomenclature for segments and joints.

as discussed in Section 3.1.5. Segments #2 and #6 hold micro air-compressors for pneumatic power, and Segments #3 and #5 hold Li-Polymer batteries. Table I lists some of the OT-4's key specifications.

Table I: Specifications for the OmniTread OT-4.

Structure:	7 segments, six 2-DOF rotary joints
Dimensions: L×WxH: Weight: Motor Seg. length: Actuator Seg. length: Joint length:	 94 cm (37") x 8.2 cm (3.2") x 8.2 cm (3.2") 4.0 Kg (9.0 lbs) 10.9 cm (4.3") 10.3 cm (4.0") 3.6 cm (1.4")
Performance: Diameter: Lifting power: Flexibility: Turning radius Speed:	 Can pass through a 10-cm (4.0") dia. hole When stretched out horizontally, OT-4 can lift three segments off the ground. Joints bend at least ±33° in any direction but ±41° in principal directions. Outside: 22.9 (9") Inside: 15.2 cm (6") 15 cm/sec (6 in/sec)
Control:	Off-board PC, connected through wireless data link. Full proportional control over angular position of joints, stiffness, and forward/backward drive speed. 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 two onboard compressors.
Electric power:	Obtained from onboard batteries. Sufficient for up to 75 minutes of operation.
Micro-clutches:	Any track can be individually engaged or disengaged under computer control, resulting in significant power savings.
Wireless control:	Wireless system for sending commands and receiving sensor and telemetry data.

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

1. All four outward surfaced of each segment are covered by driven 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 importantly, pneumatic bellows provide natural compliance with the terrain. This assures good 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 some inefficiency when articulating the joints.

   In the remainder of this section we discuss these features in more detail.

2.1 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

$$P_r = A_p/(A_p + A_i) \tag{1}$$

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. In our paper[13] we compute the propulsion ratio for the OT-4, where $P_r = 0.51$ and for the OT-8 we found $P_r = 0.4$.

2.2 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 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. On the other hand, the joints of a serpentine robot must be very strong to lift distal segments up and over high obstacles. The OT-4 can easily lift three distal segments, as shown in Figure 4.

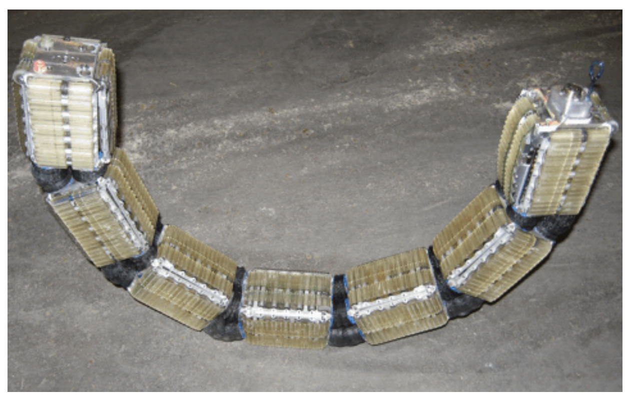

Figure 4: OmniTread OT-4 flexing its pneumatic muscles.

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 pneumatic joint controller[11]. 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[11]. When we tested the air consumption of conventional pneumatic position-control circuits with our optimized control system[12], we found that our system reduced air consumption by a factor of 30.

Three types of pneumatic actuators exist: Cylinders, bellows, and McKibben "muscles." In the OmniTread line of serpentine robots, we chose pneumatic bellows as the joint actuators, since they fit entirely into the space of the joint, without taking up any of the very limited space inside the segments.

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

2.3 Drive system

One key design feature of our OmniTread robots is the placement of a single drive motor in the center segment (see Figure 5). With the motor taking up space only in on segment, all other segments have space for a manifold, valves, and electronic control boards.,

The single electric motor in the motor segment powers a 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 together. On each shaft segment is a worm. Four worm gears feed off that worm on the drive shaft. Each worm gear drives a chain that drives the track sprocket that drives the tracks. 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.

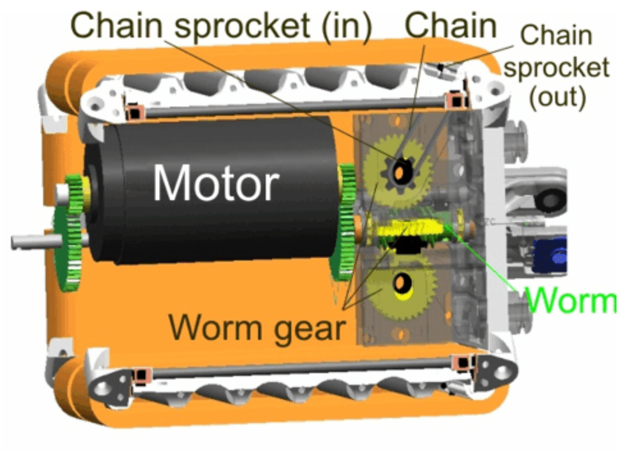


Figure 5: CAD drawing of the single drive motor in the center segment, along with its reduction gearing and gear box.

A detailed discussion of all aspects of the OT-4 design is presented in our forthcoming paper[13].

3 SUPPORT FOR UNTETHERED OPERATION

The design concepts explained in the proceeding section are common to our older OT-8 and to the earlier versions of the OT-4. A common limitation of those robots was the need for a tether, to supply external electric and pneumatic power. Our newer and more advanced OT-4 can operate without a tether. To enable this functionality we implemented various new features, as discussed in this section.

3.1 Completely tetherless operation

The OT-8 and our earlier OT-4 required three resources to be supplied to the robot through a tether: Electric power, compressed air (at 80 psi for the OT-8 and at 30 psi for the OT-4), and control signals. In order to make the OT-4 entirely tetherless, these resources have to be supplied onboard. We discuss here how these onboard supplies were implemented.

3.1.1 Electric power

The OT-4 has two electric power circuits: a motor power circuit and a control power circuit.

a. The motor power circuit powers the drive motor and the two onboard compressors. This power is supplied by two 7.4 V, 2,000 mAh Lithium-Polymer (Li-Pol) batteries, one each stored in Segments #3 and #5. The two batteries are connected in series to provide 14.8 V and their total energy storage capacity is 29.6 Whr. These batteries take up a volume of 84 cm^3 and weigh a total of 160 gr.

b. The control power circuit powers the electronics control boards and pneumatic valves, as well as the wireless communication system. This power is supplied by two 7.4 V, 730 mAh Li-Pol batteries, one in Segments #3 and one in Segment #5. The two batteries are connected in parallel to provide 1,460 mAh at 7.4 V and their total energy storage capacity is 10.8 Whr. These batteries take up a volume of 34 cm^3 and weigh a total of 76 gr.

In total, all four onboard batteries store 40.4 Whr of electric energy, occupy a volume of 118 cm^3, and weigh 236 gr. Figure 8 shows one of the two battery segments with its 730 mAh and 2,000 mAh batteries.

In an endurance test under optimal conditions (see details in Section 4.1) the motor power and the control power batteries lasted for roughly 75 minutes. On extremely difficult obstacles, where joints are actuated a lot and all tracks are engaged, the motor battery can be depleted in as little as 25 minutes.

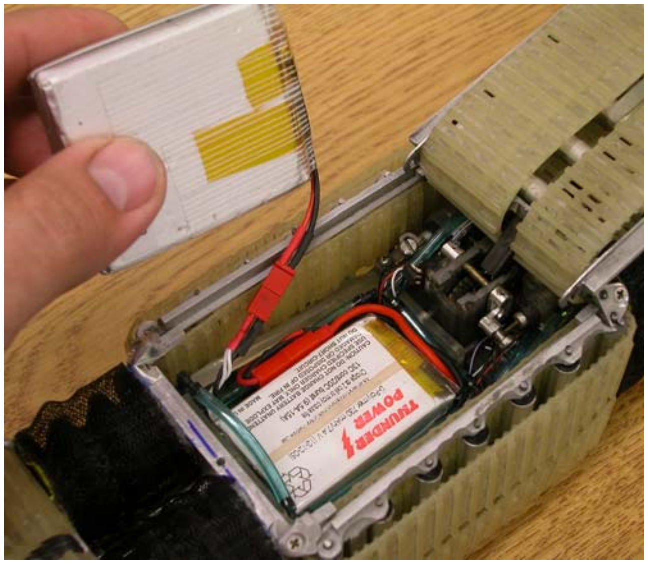


Figure 8: The 730 mAh Li-Pol battery is in its place in Segment #3. The remaining space will be completely filled by the 2,000 mAh Li-Pol battery in the engineer's hand. An identical set of batteries is located in Segment #5.

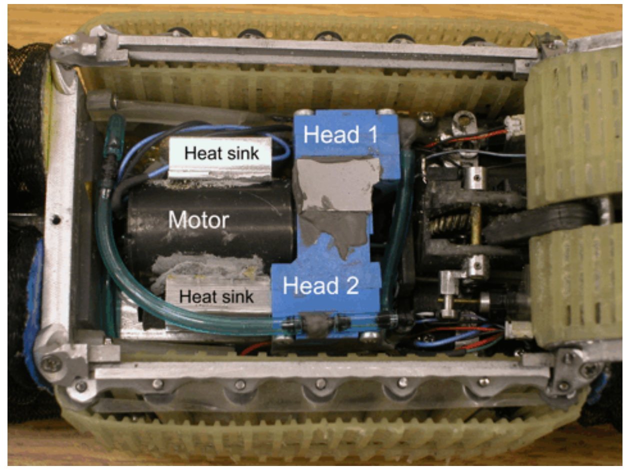


Figure 6: Modified dual-head air compressor installed in Segments #2 and #6.

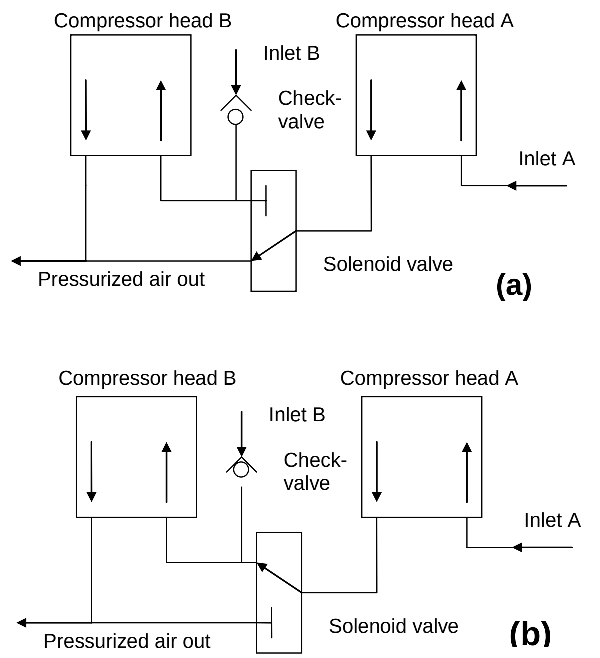


Figure 7: The dual-pressure compressor system. The compressor heads can be switched between (a) Parallel Mode and (b) Series Mode by switching the state of the solenoid valve.

3.1.2 Pneumatic power

Pneumatic power is supplied by two off-the-shelf Hargraves CTS mini-compressors. In order to increase the flow rate we added another compressor head to the motor so that in one revolution of the crankshaft two pistons go through a compression cycle, thereby increasing flow rate significantly. We then further modified these compressors by replacing the stock motor by a more powerful one, the Faulhaber Model 2232 012 SR. The Faulhaber motor is coreless, slightly larger (22 mm as opposed to 20 mm) and has a higher power rating. Because of that higher rating, it draws only 1/3 the current of the stock motor, which was somewhat overloaded when running two heads.

In this configuration, the compressor provides about 25 psi (less when flow rates are high). This maximal pressure is sufficient for most ordinary tasks with the OT-4, since its bellows were specifically designed for a much lower operating pressure than that of the OT-8. However, for extreme task, such as the vertical climb in large-diameter pipes and other tasks with vertical motion requirements, a higher pressure would is desirable. That's because higher pressures translate into proportionally greater joint actuation torques. To achieve this higher pressure we connected the two heads in series, increasing the effective output pressure of one compressor up to 50 psi. Implementing the pneumatic diagram of Figure 7, it is possible to switch the two compressor heads between series and parallel mode, by means of a single solenoid valve and a check-valve. In principal, switching can be done anytime during operation without stopping the compressors, but at the time of writing this paper we have not yet found a small enough solenoid valve with high enough flow rate to make the design beneficial.

We measured the output (pressure and flow rate) of both compressor modes by connecting the outlet of one of the two compressors to a 2.1-liter container and timing how quickly it built pressure. The results are shown in Figure 9. As can be seen, low pressures up to 15 psi can be built faster in Parallel Mode. Pressures above ~15 psi build up faster in Series Mode.

3.1.3 Wireless control communication system

In the OT-8 control signals from the joysticks (via an off-board laptop) to the robot and sensor signals from the robot to the off-board laptop were sent through a tether. In the OT-4, we implemented a wireless communication system, as shown in Figure 10.

Our solution involved removal of the housing and other components from a Lawicel CAN-to-RS-232 converter to reduce it's volume, and wiring it to a Maxstream Xbee transceiver. Despite the complexity of the multiple-conversions system, we managed to integrate the components into the OT-4's tail segment such that most of the payload space in that segment remained available.

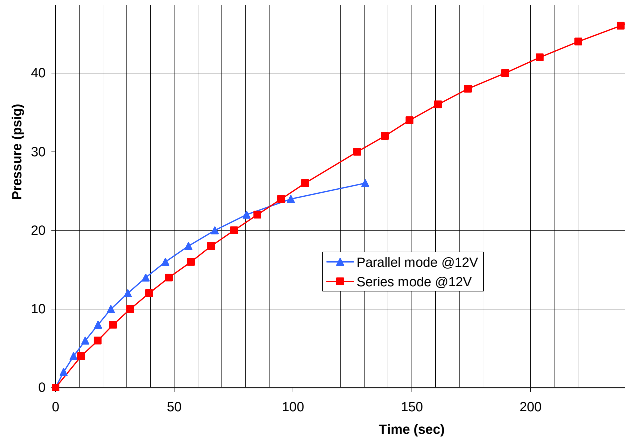


Figure 9: Plot of pressure versus time required to fill a fixed test volume (2.1 liter) with air at different pressures. Comparison of dual-pressure compressor working in series (blue) and parallel (red) mode. This chart is for one compressor, although the OT-4 uses two compressors.

The range of the system is approximately 20 m through two walls with no apparent problems. The CAN message throughput of the wireless system is slightly lower than that of the OT-8's tethered system despite similar transmission baud rates (115.2K vs 125K). This is because the messages are transmitted in the wireless system as ASCII strings rather than as binary ones.

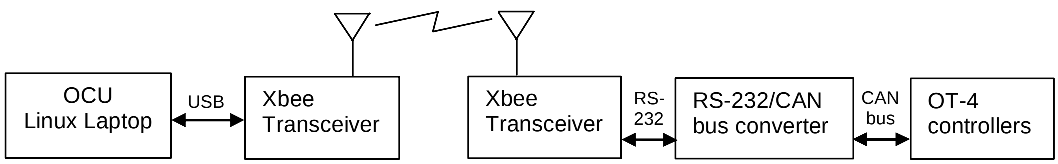
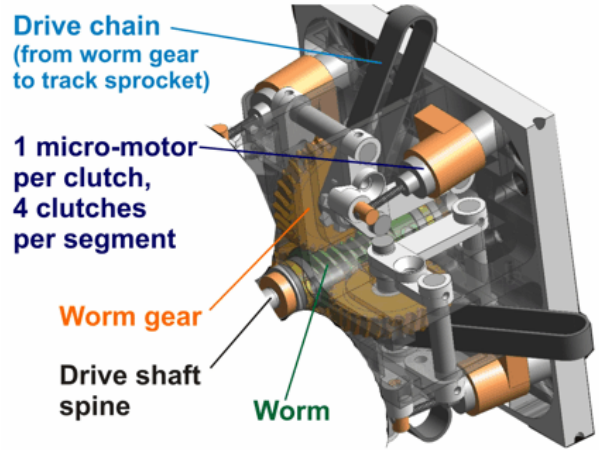


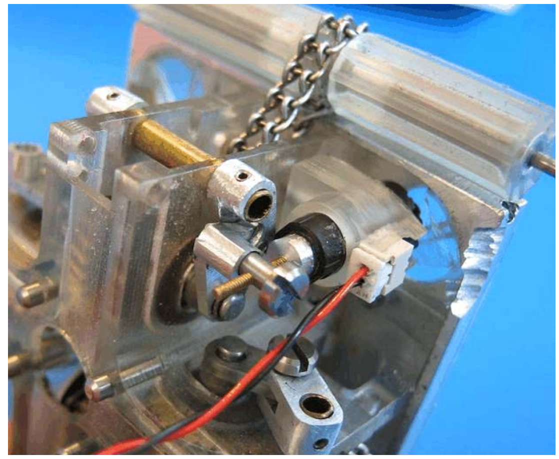
Figure 10: Wireless control communication system components for the OT-4.

3.1.4 Electrically actuated micro-clutches

One reason for then OT-4's impressive motor battery run time (75 minutes on benign terrain) is a unique feature in the OT-4: all 28 of its tracks can be engaged or disengaged from the drive train individually and under computer control. To motivate the utility of the clutches, let us consider the following measurements. A torque of T_f = 0.10 Nm is needed to drive a freely spinning track, that is, a track that is not engaged with any environmental feature. At the other extreme, the largest possible legitimate torque that a track may have to transfer is needed during vertical pipe climbs. During such climbs, one track of the center segment is pressed against the inside wall of the pipe and has to support half the robot's weight. Under this condition the torque required to turn that track is T_m = 0.42 Nm. Comparing these two extreme torque requirements shows a ratio of $q = T_m/T_f = 4.2$. The significance of this ratio is that driving ~4 tracks at the lightest possible load (i.e., spinning freely) requires the same amount of torque as driving one track under the largest possible load condition. Since torque is roughly proportional to power consumption, we conclude that idly turning four tracks consumes as much power as driving half the robot's weight vertically. It is thus obvious that *not* driving an idle track will save a substantial amount of onboard electric power.

In practice we implemented the micro-clutches as shown in Figure 11. To disengage a track, a micro motor moves one link of a four-bar mechanism so that the worm gear is lifted off the worm. Micro-switches (not shown here) stop the micro-motor in two stable, self-locking positions. These positions correspond to the worm gear being fully engaged or disengaged from the worm.





(a) **(b)**

Figure 11: Gear box and micro-clutches. a. CAD drawing; b. photograph

3.1.5 Flipper tracks

We equipped the OT-4 with two so-called "flipper tracks." These tracks, located in the lead and tail segments, can be "flipped out" or "flipped in" to extend the reach of the OT-4. The extended reach is useful in two maneuvers: (a) to cross gaps and (b) to reach up and over high obstacles. The flipper track uses a small servo embedded in the track tray to extend the flipper 180° or to retract it. An additional locking actuator locks the track in either position. The servo is slightly wider than the height of the track, resulting in the outward bulge of the track, apparent in Figure 12. Yet, the bulge does not interfere with the robot's ability to pass through a 10-cm hole. The new design functioned very well when we used it to overcome the knife-edge hole obstacle (see Experimental results, in Section 4.4), as well as in other tests, not documented here.

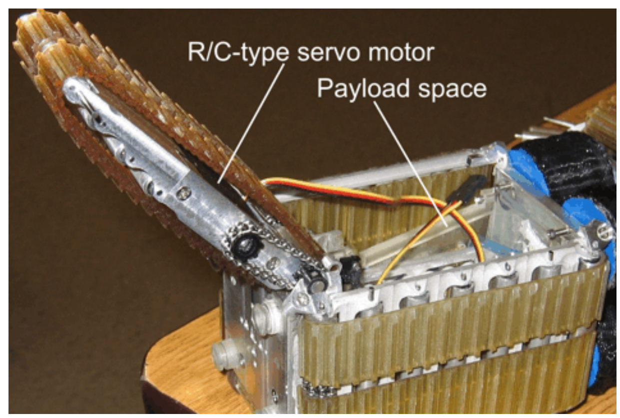


Figure 12: Flipper track during deployment to its fully extended position.

4 EXPERIMENTAL RESULTS

In August 2006, the OmniTread OT-4 was tested for four days by an independent and objective third party: the Southwest Research Institute (SwRI). SwRI has developed a variety of test environments for small mobile robots. Each test environment at SwRI has numerous obstacles or other difficulties (collectively called "Challenges") that are designed to test the limits of different types of robots. Many of the photographs shown in this section were taken during testing at SwRI, while others are from testing at our lab at the University of Michigan. All photographs in the remainder of this section were taken during successful traverses of the Challenges shown. In addition to the photos and text of this section, we refer readers to our library of high-resolution video clips and photographs of the OT-4 in different environments at http://www.engin.umich.edu/research/mrl/00MoRob_6.html.

While the maximum speed of the OT-4 is 15 cm/sec, the average speed during obstacle traverses is much slower. That is because most of the challenges require a great deal of coordination among the three joystick operators (each operator controls the deflection and stiffness of two OT-4 joints – see Figure 13). An additional difficulty is that for many situations the operators had to figure out a motion sequence that would allow the robot to traverse the Challenge. This "learn-as-you-go" operation and the required coordination among three operators resulted in many ineffective moves including many unnecessary roll-overs as the OT-4 center of gravity was raised to an unstable level. Limited coordination, ineffective moves, and roll-overs didn't result in failures to traverse the Challenges, but they did result in a substantially lower average speed in most Challenges. Clearly, computer assistance for coordinating the motion and applying smart motion sequences would be of great help in reducing the number of operators and streamlining the motion. However, this paper focuses only on the OmniTread's electro-mechanical system, and not on the very complex control problem. In the remainder of this section, we discuss the OT-4's performance on some of the Challenges.

4.1 Endurance Challenge

The goal of the endurance test was to establish the maximal drive time on a single set of batteries, under optimal conditions. During the test the robot drove along a square shaped path that required only minimal joint actuation for steering. At the onset of the test, the OT-4 assumed a specific pose with which it touched the smooth concrete floor with only three segments, while the other segments were slightly raised off the ground. Using the micro-clutches, we disengaged all tracks except for the bottom tracks of the segments that touched the floor. In this configuration we could still steer the robot around the corners of the square-shaped path, but losses from driving tracks idly were minimized. In the test, the OT-4 managed to drive for 75 minutes at an average speed of ~12 cm/sec, resulting in a covered distance of 533 meters.

Figure 13: Three operators are needed to control the OT-4's six 2-DOF joints.

4.2 Gap Challenge

With its flippers extended, the OT-4 traversed a gap 49 cm (19.25") wide, as shown in Figure 14. This is 52% of its nominal length. On closer inspection of Figure 14, and based on geometry and center of mass (c.g.) considerations alone, one might conclude that the robot could span an even wider gap. However, in several attempts the raised front segments lifted the c.g. up so much that the robot rolled over and the attempt failed. Figure 14 shows the widest gap the robot traversed without rolling over.

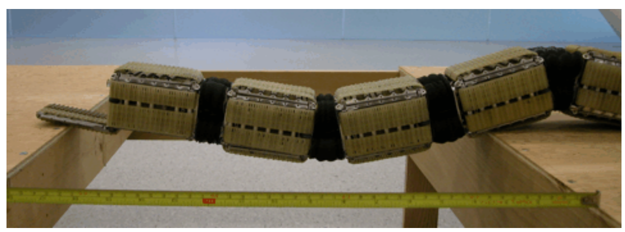


Figure 14: OT-4 traversing a gap 49 cm (19.25") wide. This is 52% of its nominal length.

4.3 Rockbed Challenge

Figure 15 shows the OT-4 during a traverse of the Rockbed Challenge. The OmniTread's "tracks-all-around" design shines in the Rockbed test. In the course of a traverse of the ~5-meter Rockbed, the OT-4 rolled over frequently and oftentimes two or even three sides of the robot were in contact with rocks simultaneously. The OT-4 successfully traversed the Rockbed on every attempt, with the fastest time being 3:56 min:sec.

Figure 15: The OmniTread's "tracks on all sides" design shines in the Rockbed test. In a rockbed traverse, the robot inevitably rolls over frequently, and many times two or even three sides are in contact with rocks simultaneously.

4.4 Hole-in-wall and Knife-edge Hole Challenges

There were two related Challenges involving traversal of a hole in a vertical wall. In the Hole-in-wall Challenge, the robot had to enter into a short, horizontal pipe as shown in Figure 16. Once tracks were in the pipe, the pipe would support some of the robot's weight. The highest hole the OT-4 could enter and traverse had its center 42 cm above ground. This test was performed at an earlier time, when the flipper tracks discussed in Section 3.1.5 were not yet implemented.

The Knife-edge Hole Challenge, depicted in Figure 17, was significantly harder to traverse. This Challenge consists of a vertical, 6-millimeter thin plywood wall with a 4-inch hole in it (they wooded frame holding wall obscures the side-view of the thin wall in Figure 17). When a joint is in the hole, the hole's edge presses against the bellows, which provide no propulsion (recall discussion on inert surfaces in Section 2); the robot is thus stuck. To avoid getting stuck, the robot has to support all of its weight on its distal segments, so as to straddle the hole and lift its inert parts entirely off the edge of the hole. The utility of the flipper tracks is obvious in Figure 17, as they extend the reach of the distal segments to the floor. Thanks to the flipper tracks, the highest knife-edge hole the OT-4 could successfully pass through was one that had its center 30 cm above ground.

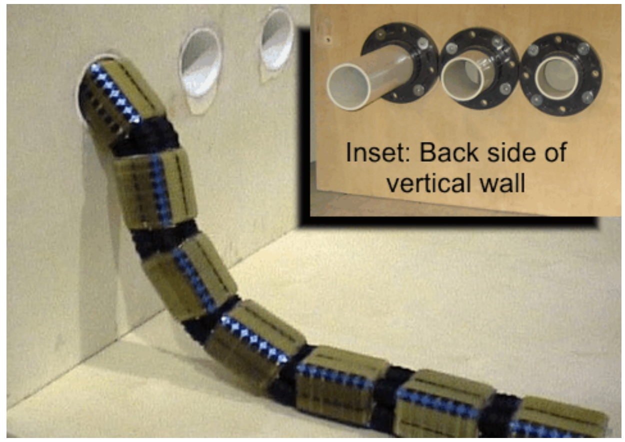


Figure 16: The Hole-in-wall Challenge at SwRI consists of a vertical wall and a short horizontal PVC pipe, four inches in diameter.

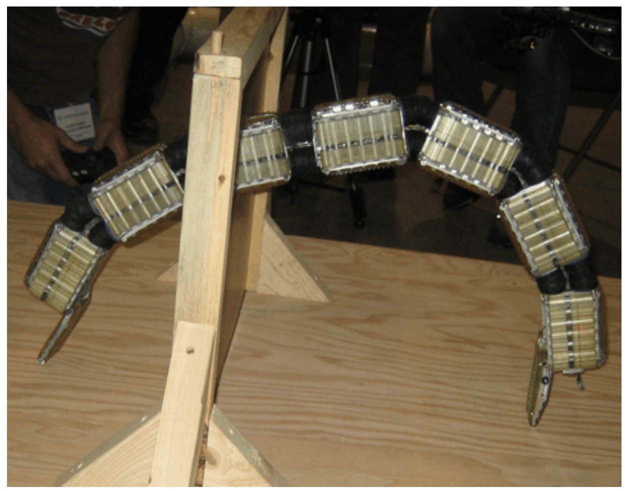


Figure 17: The Knife-edge Hole Challenge consists of a 6 mm thin plywood wall with a 4-inch hole in it. When a joint is in the hole, the hole's edge presses against the bellows, which provide no propulsion and the robot is stuck. To avoid getting stuck, the robot has to support its entire weight one its distal segments, so as to lift its inert parts off the edge of the hole.

4.5 Stair climbing

The OT-4 performed very well on stairs. It managed consistently to climb up stairs with different combinations of rise/tread, up to an angle of 40° with a rise of 21 cm (8 ¼") and a tread of 25.4 cm (10")as shown in Figure 18.

4.6 Vertical pipe climbing

One particularly strenuous Challenge is the vertical pipe climb. It requires a great deal of strength in the joints as well as a very powerful drive train. In a vertical pipe climb, the joints have to press the appropriate segments against the inside wall of the pipe with great torque so as to generated large normal forces, *N*, at the points of contact between the segment and the pipe wall. Similarly, the drive train has to produce enough torque to support the full weight of the robot, whereas under most other drive conditions on horizontal or sloped terrain the required drive torque is much smaller. Figure 19 shows the OT-4 climbing up in a 4-inch and in an 8-inch insider diameter PVC pipe. The average speeds in those climbs were 8 cm/s and 6 cm/s, respectively. In other test, the OT-4 also climbed up successfully in a vertical 6-inch diameter pipe.

4.7 Other Challenges

The OT-4 was tested at SwRI and at our own lab in numerous other Challenges. The OT-4 was successful in some of these tests, and had limited success in others. Tests in which the OT-4 performed poorly were driving in deep sand and through underbrush. In both environments the OT-4 *almost* finished the prescribed course, but suffered part breakages that couldn't be overcome without ending the experiment. The cause of these failures is that sand, twigs, or other small debris is ingested into the tracks and all of the drive system. It is interesting to note, though, that the larger and heavier OT-8 performed *exceptionally well* on those exact same terrains, completing each of multiple runs successfully. We conclude from this performance comparison that in tracked drive systems, there is a minimal ratio between the drive sprocket diameter and the diameter of environmental particles that needs to be exceeded in order to traverse the terrain

Figure 18: OT-4 climbing up a steep variable-pitch staircase set to an inclination of 40°.

successfully. In the OT-4 it may be possible to harden components further, and thereby avoid the breakages, but it was clear in both environments that large stresses acted on the drive system due to the ingested debris.

5 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 two miniature air compressors) for up to one 75 minutes of untethered operation.

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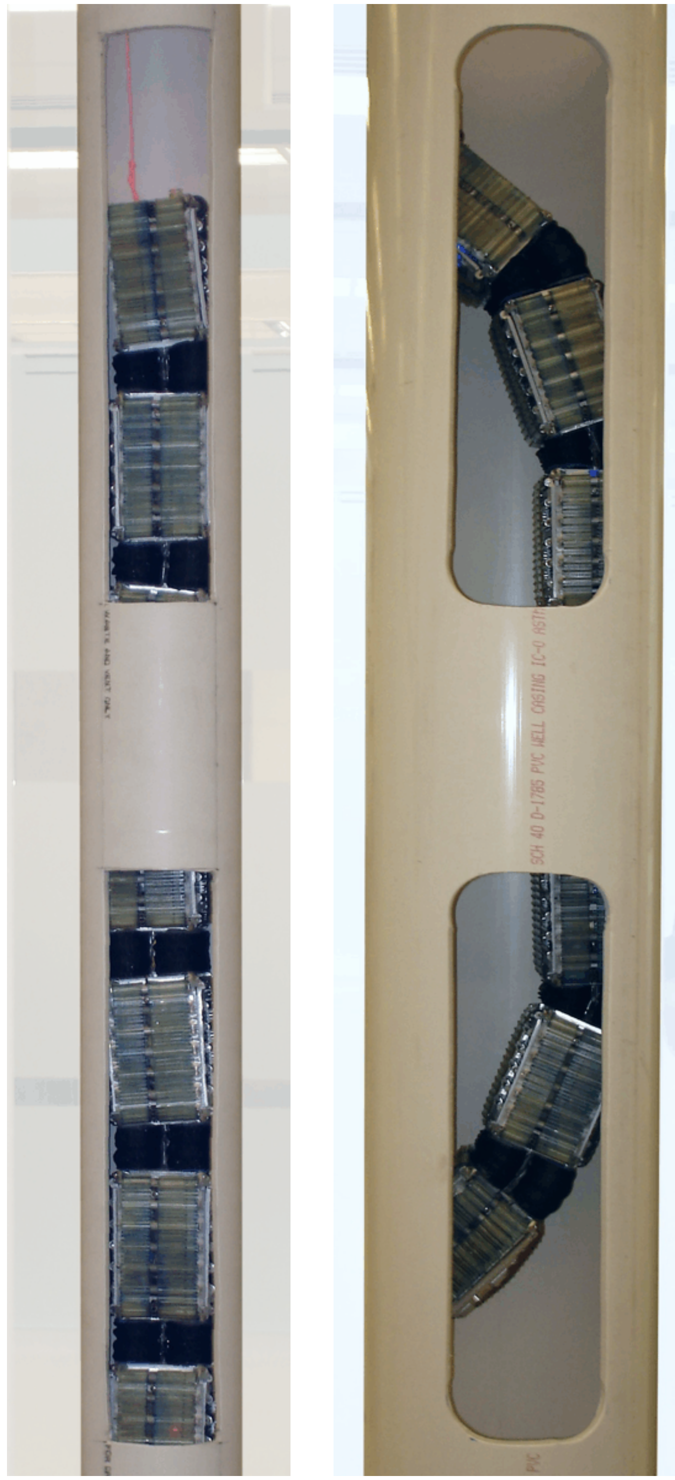

Figure 19: OT-4 climbing up vertically inside a 4-inch (left) and an 8-inch (right) diameter PVC pipe. The red cord visible in the left picture is a safety line (belay), to protect the robot in case of fall. The belay was not used to pull the robot. The "windows" in the opaque PVC pipe reveal the pose and the progress of the robot during these tests, but they did not interfere with the runs.

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