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The Kinematic Design of the OmniPede: A New Approach to Obstacle Traversion

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ABSTRACT

This paper introduces the kinematic design of a novel vehicle capable of traversing extremely rugged terrain, such as the rubble of a collapsed building. The vehicle, called "*OmniPede*," is currently being developed at the University of Michigan's Mobile Robotics Laboratory.

The foremost innovation in the OmniPede is its kinematic design: the OmniPede can be thought of as an elongated, round, flexible body that has a large number of small "hands" or "feet" all over its hull ("skin"). Ideally these hands all perform a coordinated shoveling motion that provides forward propulsion wherever a hand is in contact with any feature in the environment, regardless of how many of the hands make contact and which ones do.

1. INTRODUCTION

Since ancient times wheeled vehicles have been successfully used for travel over relatively smooth terrain. However, most of the natural terrain on earth is not smooth enough for traversal with wheeled vehicles. Even in man-made environments wheeled robots can easily come across terrain that is impossible for them to overcome (e.g., stairs or curbs). One particularly great challenge is the traversal of *failed* man-made terrains, such as the rubble of a collapsed structure. One way to overcome this limitation is to increase the diameter of the wheels, but this necessarily increases the overall size of the vehicle and thus introduces many more limitations. For example, an off-road truck can traverse many obstacles that a human can traverse, but it will not fit through a standard door.

In order to overcome this limitation tracked vehicles were invented. Earth moving equipment and military tanks are the best known examples for tracked vehicles. Additional improvements have been made in the form of *auxiliary tracks* (see Figure 1), which further improve the ability of tracked vehicles to overcome large height differences.

The idea of adding an auxiliary track can be extended by adding more auxiliary tracks, one onto the next in a serial fashion. And this idea can be further extended by controlling two degrees of freedom between each segment of tracks instead of one. This is similar to the approach that the German National Research Center for Information Technology (GMD) took with its *Snake2 v*ehicle, except that GMD uses an array of wheels instead of tracks (see Figure 2.)

Snake2 is an example of a robot that is inspired by the physiological structure of snakes. The unique shape and movement of snakes allows them to move effectively in very complex and rough terrain, and has inspired many other robots attempting to accomplish this task. Researchers at PRI automation in Billerica, MA, studied the motion of a 20 degree of freedom snake robot and developed unique gaits for forward propulsion with the hope that these can be incorporated in a snake-like mobile robot [Dowling, 1999].

Significant insight can be gained by studying nature and how living creatures traverse obstacles. For example, legged creatures can traverse obstacles that even the best man-made vehicles of similar size could not overcome. However, trying to copy nature's designs is not trivial at all. For example, the mechanical design poses substantial problems, and the associated control problems can be daunting as may be evident in Figure 3. Several researchers have addressed the complex dynamics of multi-articulated robots and their subsequent control problems. Researchers at the Tokyo Institute of Technology proposed two different methods for modeling and controlling hyper-redundant mechanical systems. Their bottom-up and top-down approach to modeling provides sets of equations describing the dynamics of multi-articulated mechanisms such as snake-like robots [Matsuno and Hara, 1999]. Researchers at the National Technical University of Athens proposed a multi-articulated robot and used forward kinematics to model the mechanism. The design of this snake-like robot consist of seven links connected by six revolute joints and propelled forward by small wheels [Migadis and Kyriakopoulos, 1997].

The University of Michigan's Mobile Robotics Laboratory is currently developing a new type of vehicle, called "*OmniPede,*" promises to offer unprecedented motion capabilities on extremely rugged terrain, such as the rubble from a collapsed building. In the remainder of this paper we will refer to travel over such rugged terrain as "obstacle *traversion.*"

Although we conceived of the idea for the OmniPede independently, we later found that nature had produced a similar design: the millipede (see Figure 4).

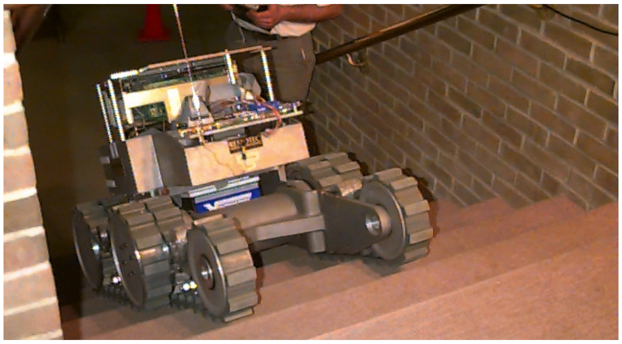

Figure 1: (a) A [Remotec] Andros tracked vehicle with auxiliary tracks in front and in the rear.

Figure 2: *Snake2* is a fairly recent development from [Klaassen and Paap, 1999]. Snake2 combines the advantages of a wheeled robot with the advantages of a snake-like robot.

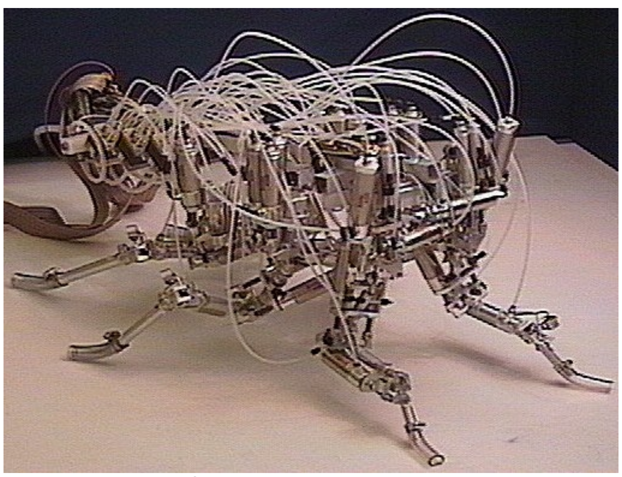

Figure 3: Much of the legged robot research is presently being done on configurations with a relatively small number of legs. *Robot III* is a hexapod built at Case Western Reserve University that has a total of 24 DOF [Nelson et al., 1997].

Figure 4: Millipedes have exceptional maneuverability and flexibility. Here: Two millipedes entangled

A millipede can traverse terrain that is very rough compared to its size. It also moves very slowly and with many "legs" (we use the term "leg" in conjunction with a millipede in a rather abstract way) in contact with the ground at once, thus dynamic stability is not an issue. The OmniPede, like the millipede, will move rather slowly with multiple legs on the ground at once to provide static stability. When the OmniPede needs to overcome an obstacle that is taller than its step height, it will lift the first few segments much like a millipede (or a snake, or a worm).

One significant difference between the OmniPede and a millipede is the scale. Millipedes are only a few centimeters long and about a centimeter in diameter, but the OmniPede will be about one meter long and about 10 centimeters in diameter.

The key innovation in the OmniPede is the concept of an elongated, segmented body that is entirely surrounded by feet, all of which are continuously performing a "shoveling" motion designed to propel the structure forward. This paper focuses on this central aspect, the kinematic design, in Section 2. Section 3 briefly discusses power options, and Section 4 present preliminary experimental results aimed at demonstration the feasibility of the kinematic design. Other aspects, such as the gait and the control and actuation of the joints between the segments will be addressed in future publications.

2. Kinematic Design of the OmniPede

In order to present the rather complex mechanical design of the OmniPede this section is divided into three subsections, which describe the legs, the segments and joints, and the drive train, in that order.

2.1 Legs

One of the key features in the design of the OmniPede is that each leg has only one degree of freedom (DOF). A "leg" and its associated "foot" look like the cross section of an umbrella. The trajectory of the foot and the orientation of the leg are determined by a simple mechanism as shown in Figure 5.

The geared 5-bar mechanism moves the leg so that the foot makes contact with the terrain while performing the backward portion of its motion (which is the portion that propels the vehicle forward). Then the foot disengages from the terrain while it performs the forward portion of its motion (as shown in Figure 5b). As a result the OmniPede moves forward.

By having only one DOF per leg instead of the two or three DOF that most other legged vehicles have, the number of required actuators is reduced (compare the complexity of leg actuation in Figure 5 with that of Figure 3). The price that is paid for the reduced complexity, weight, and cost is having less control over the position and orien-

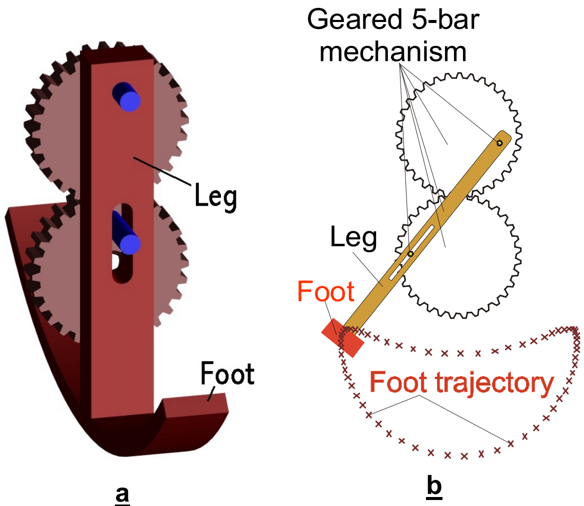

Figure 5: The OmniPede leg design. (a) A geared five-bar mechanism is used to transfer power to the leg and to define the foot's trajectory. (b) Each foot follows a crescent-shaped path indicated by the x-marks when the gears are turned.

tation of the legs. However, we consider this to be a small sacrifice because with the OmniPede precise leg positioning is unimportant. Also, the reduced complexity of the legs offers further advantages, as described below.

2.2 Segments

The OmniPede consists of several segments, the exact number of which remains to be determined. Figure 6 shows a version of the OmniPede comprising nine segments. All segments are identical with the exception of the "head" segment that will house sensors and the on-board computer, and the tail segment, which will house the motor. Each segment has four of the legs shown in Figure 5 arranged circularly on its circumference and evenly spaced at 90-degree intervals. The legs are arranged this way so that no matter which part of the OmniPede is in physical contact with the environment, contact is always made through some of the feet.

The segments are connected through articulated joints, which allow two DOF between the segments. These two DOF are each independently controlled with a pneumatic piston by means of a four-bar mechanism as shown in Figure 7 (more specifically, it is a crank-slider: the floater is the crank, and the piston rod is the slider). This feature provides the OmniPede with the versatility that was lost by linking the legs kinematically. The joint actuators enable the OmniPede to lift its front end on top of obstacles much the same way a millipede (or a worm or a snake) do. This allows the OmniPede to adjust to the contour of the terrain and overcome obstacles that are orders of magnitude larger than its step height.

Another key feature of the OmniPede design is that the motion of each leg is kinematically linked to a common drive shaft, called the *drive shaft spine*, that runs through the center of the vehicle (see Figure 6). This allows all of the legs to be driven by just one actuator, which supplies torque to the common drive shaft. Also, because the legs are all kinematically linked by the common drive shaft, the phase differences between all of the legs are fixed.

The use of a single actuator for supplying power to all of the legs has numerous advantages:

- Multiple actuators weigh more than a single actuator that converts the same amount of power, thus the overall weight of the OmniPede is reduced by using one actuator for all the legs [Hirose '93].
- The use of high energy density power sources, such as a small gasoline engine, is feasible. The energy density of a small gasoline engine with tank is about one order of magnitude greater than that of a comparable electric motor with a lithium-ion battery.
- If necessary (see discussion in Section 3), a miniature pneumatic compressor could be powered from the same engine.

2.3 Drive train

The OmniPede can be composed of anywhere between six and more identical units connected to each other in a serial fashion. The number of units that a particular OmniPede model will have will depend on the terrain that

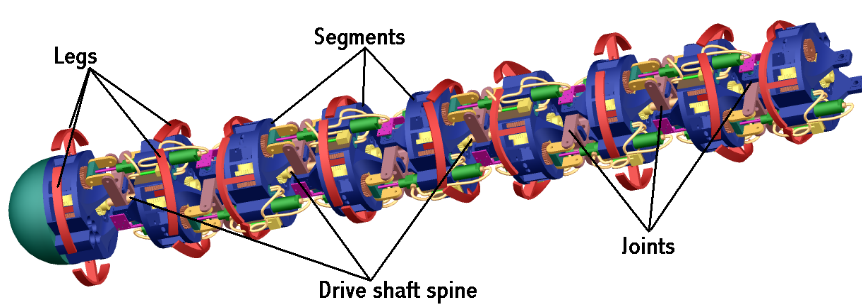

Figure 6: The OmniPede consists of several segments. A flexible drive shaft that runs through the whole vehicle like a spine (and is thus called "spine") drives all of the legs.

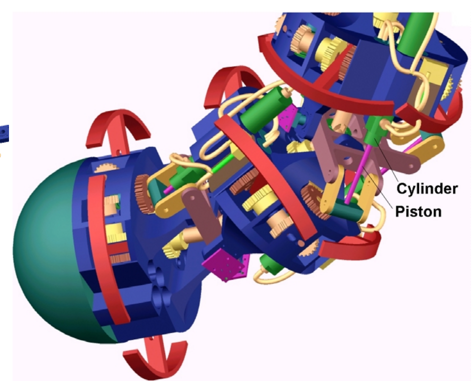

Figure 7: Two pneumatic pistons control the two DOF of a joint.

must be covered. Each unit includes a rigid part called a "segment" that provides a framework for the unit.

At the centerline of each segment is the drive shaft spine, which is constrained to rotate about the centerline of the segment. The drive shafts of any two adjacent segments are connected by a universal coupling, thus allowing one drive shaft to transmit torque to the next. The intersection point of each universal coupling coincides with the intersection point of the articulated joint that joins the two segments. Within each segment the four legs of the segment receive power from the drive shaft spine through a transmission system comprising gears and chains.

An analysis using Gruebler's criterion[1] will give the misleading result that the mechanism is over-constrained. However, this is not the case due to the constraint that the drive shafts are joined by universal couplings that have the same intersection point as the articulated joints that join the respective segments. Because of this, the mechanism actually has one degree of freedom that allows the drive shafts to rotate freely with respect to the segments independent of the configuration of the joints.

3. Power Considerations

In principle three different power sources are required for the OmniPede:

1. **The electric power system** requires an electric source of energy, such as a lithium-ion battery. The electric system powers the onboard computer, the sensors, and the control components.
2. **The kinematic power system** requires a motor, predominantly to power the motion of the legs. This system will be by far the largest power consumer in the OmniPede. Our proof-of-concept prototype uses an electric motor, but we are considering the use of a gasoline-powered engine (like the ones used in model cars). This approach would be made possible by the kinematic design of the OmniPede that requires just one single kinematic power source for driving all of the legs.
3. **The pneumatic power system** (used to actuate the joints) requires a source of pressurized gas. Pressurized gas is normally stored in tanks that are filled with an electric or gas powered compressor. A compressor, however, would take use up precious space, power, and payload resources. A potentially more elegant solution is based on the use of liquid carbon dioxide stored at its vapor pressure at room temperature (~830 psi). Controlled, local heating would turn small amounts of CO_2 into gas. The gas then passes through a pressure regulator that brings the pressure down to 70 psi, which is below the triple point for CO_2. Such a device would have many advantages over the compressed air tanks, which store air at around 9000 psi, and which are used on some other mobile robots. The power density of the proposed carbon dioxide device (which is completely passive and has very few moving parts) is higher than that of NiCd batteries.

[1] Gruebler developed a way to analytically determine the DOF of a mechanism. There are however pathological cases in which the analysis gives misleading results [Burton, 1979].

4. Prototype Manufacture

The kinematic design of the OmniPede requires some complex parts, and manufacturability must be considered in an overall feasibility analysis. The single most complex part in the OmniPede is the so-called "*segment shell*," shown in Figure 8. In order to assess the manufacturability of this part we manufactured segment shells with three different processes.

1. **Machining**. We manufactured one complete prototype segment of the OmniPede by machining the ~50 individual sub-parts from a plastic material called Delrin. However, it was clear that this was not a viable solution for manufacturing all of the segments because of their mechanical complexity.
2. **Fused Deposition Manufacturing (FDM)**. The FDM process produces three-dimensional parts of complex geometry in a single run from a plastic-like material. FDM offers the possibility to combine the manufacture of numerous individual sub-parts into one, and it allows the manufacture of more complicated, lighter, and stiffer parts. One disadvantage of FDM is that the designer has no choice in materials and that the surfaces of the produced parts are rough. Another disadvantage

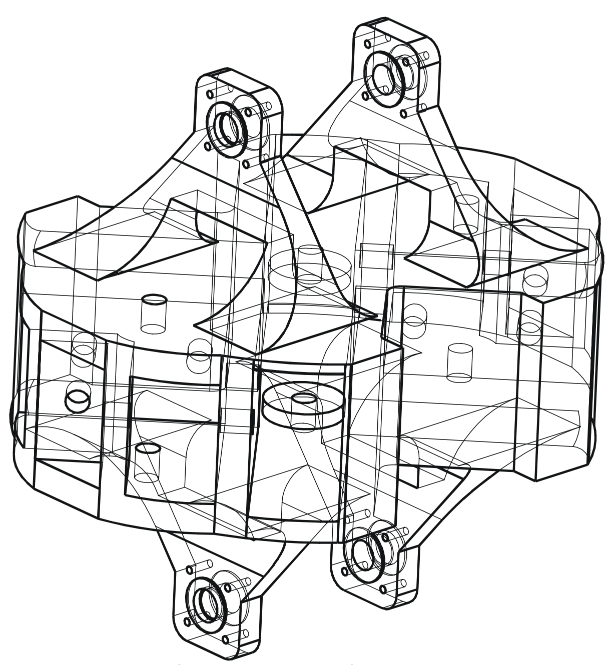

Figure 8: Wire frame drawing of a single segment shell.

is the need for so-called "support structures." A support structure is material that needs to be added underneath overhanging features in order to support them during the manufacturing process. Because of the need for support structures the segment shells had to be designed as two parts. Prior to assembling the segment we had to remove the support structures, which is tedious. The strength of the FDM parts was adequate.

3. **Selective Laser Sintering (SLS)**. This process has all of the advantages of the FDM process, but doesn't require support structures (and their manual removal prior to assembly). Since no support structures were needed we could manufacture each segment shell as one part. The disadvantage of the SLS process (as well as that of the FDM process) is that the dimensional tolerances of the SLS process, ±0.015" (0.38 mm), are not sufficient for the proper meshing of the many gears and moving parts in the OmniPede. It was therefore necessary to locate, drill, and ream the holes for bearings using conventional machining techniques with tolerances of ±.001" (±.025 mm). This was a tedious process since each segment requires 24 bearings, but we think that the effort is still feasible.

After having manufactured segment shells in all three of these methods, our preference is clearly with the Selective Laser Sintering (SLS) process. The three segment shells in our current proof-of-concept prototype were manufactured using this method, and we will manufacture all additional segment shells with the same process. The material used was "*Duraform*," which has mechanical properties similar to those of Nylon 6-6.

5. Experimental Results

We built a preliminary proof-of-concept prototype with three segments and two connecting joints, as shown in Figure 9. On the "rear" of the vehicle we mounted a 24-volt motor that was powered at the time of the experiments by an off-board power supply. Pneumatic cylinders are installed in the joints and are working, but were not actuated for the experiments reported here. This is because we have not yet developed the strategies and algorithms that would govern the behavior of the joints. The joints were thus limp and compliant and allowed the three segments to conform to the floor. The bottoms of the feet were covered with a high-friction rubber-like material to provide better traction when walking on smooth floors.

The purpose of the preliminary proof-of-concept experiments was to observe the motion of the legs and verify their effectiveness as a means for propulsion. We also wanted to assure that the friction along the single drive shaft and the numerous gears would not consume an intolerably large amount of power.

We conducted the proof-of concept experiments on a level and smooth concrete floor. The motion of the legs matched our expectations, without perceivable jerkiness. We measured a speed of 22 mm/sec (80 m/hr) on a flat and smooth surface, and the power consumption at this pace was 6 watts. Additional tests were performed on smooth but inclined surfaces and on gravel. The OmniPede's ability to climb up smooth inclines (plywood) was limited only by the traction of the feet on the plywood, allowing motion on inclines of up to 35°. On gravel (as shown in Figure 9), the speed was slightly slower

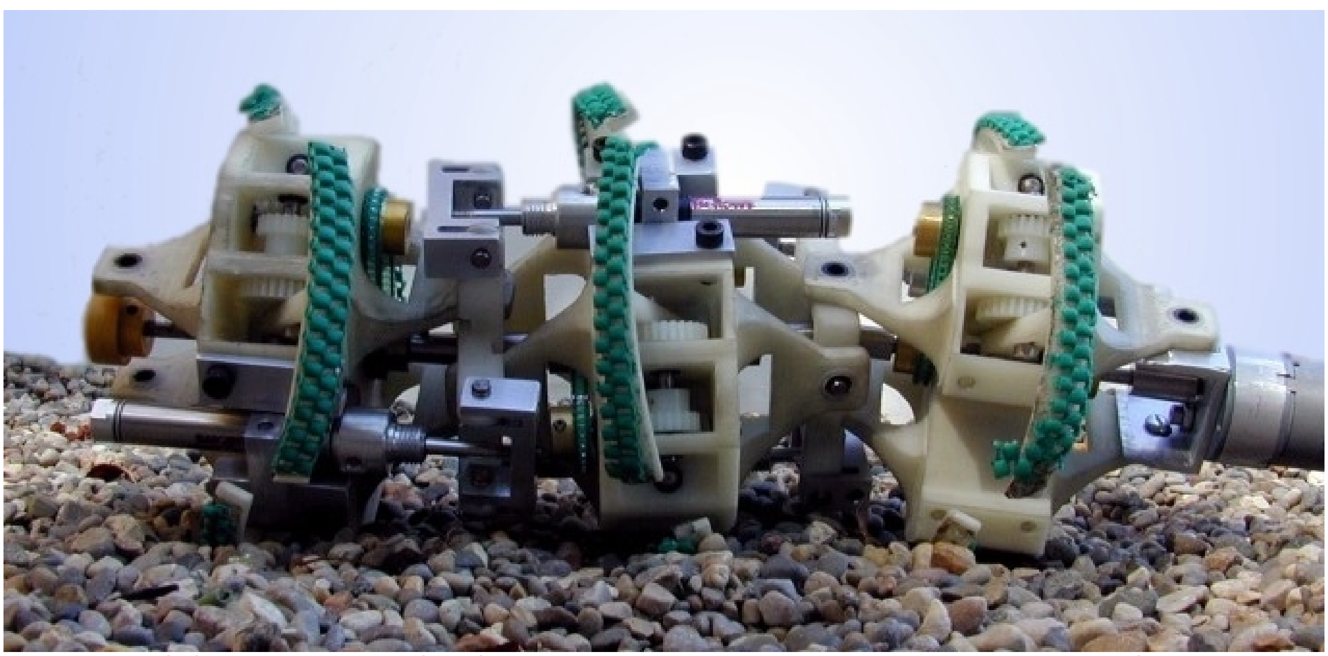

Figure 9: Proof-of-concept prototype of the OmniPede. This prototype has only three segments, instead of the nine segments we envisage for the final model. A video clip is at http://www.engin.umich.edu/research/mrl/video/14omnipede.mov

(20 mm/sec) because some pebbles would roll backward under the propelling motion of the feet.

In another test we confirmed that the current design allow the OmniPede to lift its first three segments up (and thus overcome high obstacles) with a pressure of 70-100 psi in a 7/16”-bore pneumatic actuators

6. Ongoing and Future Work

Based on the preliminary results we are strongly encouraged to move ahead and add functionality beyond the current proof-of-concept level. To do so we will initially add three more segments, to allow the study of a greater variety of gaits. This is important because at the moment the OmniPede uses a three-legged gait (the only feasible gait with the three-segment prototype). With this gait the synchronization of the legs is extremely important: if the legs are out-of-sync the OmniPede will take one step forward and one step back essentially walking in place.

One other observation is that the four feet of a segment are currently too closely approximating a circular circumference – this makes the OmniPede slightly unstable, allowing it to roll sideways. Giving each foot a smaller radius combined with a center closer to the foot will help to keep the OmniPede from rolling sideways. Ultimately, however, when there are six or more segments, this problem will be avoided by the control algorithm that should never allow all the segments to be concentrically aligned.

Another aspect that will be addressed in future work is that of a suitable skin. For some applications a sealed skin that protects all internal parts from moisture or dirt is essential, for other application a vehicle without skin might work.

The most important future focus will be on the control strategies and algorithms for the joints. The challenges here are with the provision of appropriate levels of compliance to assure good adherence to terrain features.

7. Conclusions

Wheeled locomotion has been understood since ancient times. Legged locomotion with six or eight legs is currently being studied, but rough terrain can only be traversed with these robots if dynamic stability is maintained. It is interesting that the most ancient form of legged locomotion, *multi*-legged locomotion, has not been investigated until very recently. This is probably because the mechanical design challenges look daunting. We believe that with the innovative kinematic design of the OmniPede, as described here, we have moved closer to the realization of a fully functional multi-legged vehicle.

Some possible applications for the OmniPede are:

- Fully autonomous search for survivors of earthquakes and other disasters underneath the rubble of collapsed buildings.
- Military applications in very rugged terrain.
- Mining and autonomous search for other natural resources in terrain that is not accessible to humans (i.e., jungles, mountains, etc.).
- Nuclear disaster cleanup (e.g., Chernobyl) and sample retrieval.
- Research platform for studying multi-legged motion.

The OmniPede design is also suitable in principle to crawling through pipes or burrowing through soft soil.

Acknowledgements

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