

EXTENDED ABSTRACT ROTOPOD: A NOVEL APPROACH TO EFFICIENT LEGGED LOCOMOTION*

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A number of attempts have been made to integrate the efficiency of wheeled locomotion with the terrain versatility of legged locomotion, e.g., Univ. Michigan's Rhex platform and Case Western's Whegs. Those platforms cast legs as rotating spokes placed traditionally at the corners of a rectangular platform. In this paper, we present an alternate approach, with three legs radiating down from a central hub. The energy to move the platform is generated by a rotating reaction mass mounted at the hub and, at rest, rotating parallel to the ground plane.

Our approach is to construct a platform whose *natural, uncontrolled* motion is energy efficient and useful, and which requires only a small amount of control to produce effective locomotion. We describe the platform and analyze the characteristics of its uncontrolled motion. Several strategies to produce directed motion will be presented and evaluated. Simulation models and a prototype platform have been built and will be discussed.

1. Introduction

Our objective is to develop a legged robot platform that can perform ground surveillance and reconnaissance activities in an effective and energy-efficient manner. Legged platforms have a mobility advantage over wheeled and tracked vehicles on rough terrain: They can step into depressions, onto rises or over obstacles that could defeat a wheeled vehicle. However, conventional legged platforms offer mobility at a high cost in energy use: Unlike a wheel or track, a leg must *lift* as well as *propel* the robot platform and hence will use more energy. Wheels, therefore, have an advantage of energy-efficiency over legs. Researchers have attempted to combine legs and wheels within a single platform, resulting in many different platform designs. Halme et al.'s WorkPartner [4] has wheels at the end of its legs. Birch et al.'s cricket-inspired robot [1] has wheels in the front and legs in the back. Saranli et al.'s RHex [9] has four legs that are single-spokes – legs – mounted on axles, and Quinn et al.'s Whegs robots [7] have six legs that are each 3 spokes on axles. There is evidence from insect and associated robotic studies that the reason animals exploit legged locomotion in an energy efficient manner has as much to do with the use of a tuned physical mechanism as with control or intelligent planning [8, 10]. Our design goal is therefore, to design a mechanism that *naturally* produces

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- (1) an energy efficient style of locomotion, and
- (2) a motion pattern appropriate for ground reconnaissance and surveillance applications.

In section 2 we introduce a mechanism designed according to this strategy, the *rotopod*, a three-legged mechanism that walks by rotating its body around its leg endpoints and its natural motion is captured as a hypertrochoid. In section 3 we describe how the natural motion can be controlled. In section 4 we look at the energy efficiency of the mechanism in terms of its specific resistance. We conclude in section 5.

2. The Rotopod mechanism

Our approach is inspired by the observation that the RHex and Whegs leg designs are essentially one or more wheel spokes (Fig. 1(a)). An alternate design in which legs can be considered analogous to wheels is shown in Fig. 1(b). In this case, the legs are spokes rigidly mounted to the frame, as opposed to

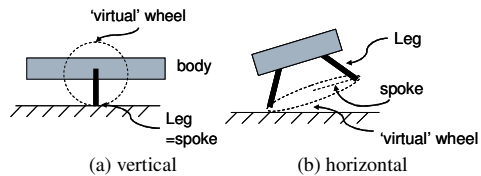


Figure 1: Legs as Analogs of Wheels

mounted on an axle as in Fig. 1(a); however, if the platform itself can be made to tilt and rotate, then the legs will raise and fall to follow the circumference of a ‘virtual’ wheel as shown. This mechanism design has the potential to fulfill our design goal because:

- (1) it exploits the spoke/leg approach already shown to be successful, and
- (2) the natural ‘rolling’ motion of this kind of mechanism can produce convoluted paths that exhibit a high-degree of area coverage.

Leg motion is effected in Fig. 1(a) by rotating the leg axles. However, in Fig. 1(b) the legs are rigidly attached, and the body must be rotated. If the mechanism is extended to include a rotating reaction mass mounted on the body, then as the mass rotates it can be used to produce the desired body motions.

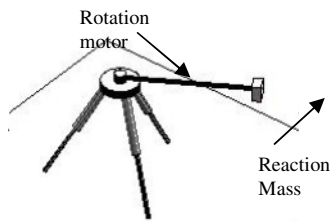


Figure 2: Rotopod Mechanism.

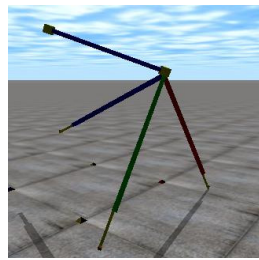


Figure 3: Mechanism Stepping

Our approach is to investigate whether the natural motion of a tripedal structure surmounted by a rotating reaction mass (Fig. 2.) can be harnessed to provide a basis for energy-efficient locomotion for surveillance and reconnaissance activities. We call such a mechanism a *rotopod*.

The natural motion of such a platform is to rotate an amount around each of its legs in turn. The raised legs can be used to *step over* obstacles that might center-ground a wheeled vehicle (Fig. 3) giving this platform the mobility to work on a wide range of terrains. When two legs are raised from the ground, the platform rotates around the third, moving and rotating its center. The amount of rotation and height of the leg stepping is a function of the leg lengths and masses and the rotational velocity of the reaction mass.

The resultant epicycloid-like path for the platform has advantages over straight line motion when the platform must cover an area for search or reconnaissance purposes. The rotating reaction mass is the principal consumer of energy of in the system; if effective search locomotion behavior can be obtained with simple control of the natural motion, a highly energy efficient system will result.

2.1. Description of the Mechanism

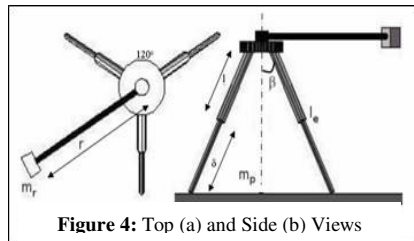


Figure 4: Top (a) and Side (b) Views



Figure 5: Prototype mechanism

The mechanism concept introduced above raises a number of design parameters. For study purposes we select the following values for these (see Fig. 4):

- (1) Number of Legs: 3. **Rational:** the minimum number for static stability.
- (2) Position of legs on body: evenly distributed around central axis (120° separation) subtending $\beta=45^\circ$ with vertical midline. **Rational:** each leg should behave interchangeably. The value of β is chosen to enhance static stability.
- (3) Degrees of freedom per leg: 1 translational degree. **Rational:** This is the minimum and most direct configuration to change leg length.
- (4) Location of reaction mass joint: At apex of legs. **Rational:** maximize the lever arm that can be applied by the reaction mass.
- (5) Platform lengths and masses: Reaction mass arm limited to about 1 meter max, and total platform weight limited to less than 20 Kg. **Rational:** safety and internal testing

purposes, though in fact a small reconnaissance drone might be of a roughly similar size.

An Open Dynamics Engine (ODE) simulation of the 3D kinematics and dynamics of the full mechanism has been build and used to evaluate motion strategies as well as energy use. This simulation takes reaction mass motor velocity and saturation torque and leg linear actuator forces and velocities as input and produces a 3D simulation (e.g., Fig. 3) and various kinematic and dynamic measurements as output.

A small prototype (~10cm height) was constructed in [5] that used an alternative rotational, instead of translational, leg degree of freedom. This ultimately proved limiting. A larger prototype (~0.45m, Fig. 5) has now been build and is being evaluated. This prototype and the ODE simulation have the same degrees of freedom, and similar lengths and masses.

2.2. Natural Motion of the Mechanism

If the mechanism is placed on a level surface, legs fully extended, and the reaction mass is rotated slowly ($\omega < 0.2 rps$ for our model) the mechanism remains stationary. If the rotational velocity is slowly increased, then a small chattering motion of the leg endpoints first results. Chattering may result in a small rotation of the platform around its center point *in the same direction* as the reaction mass rotation. As the

velocity is further increased ($\omega \sim 1 rps$) the platform tilts in the direction of the reaction mass, and the chattering turns into the rotation of the platform around each leg endpoint *in the opposite direction* to the reaction mass, as the reaction mass passes over that leg. It is this final mode of motion that we are interested in, and we refer to as the natural motion of the platform, though the chattering motion may be of some value for small ‘backwards’ motions.

Fig. 6 shows a plot of the (x,y) or plan view of the motion of the center of the platform during natural motion. Note that it is a series of ‘loops’ which are caused by the tilting of the platform and the effect of the reaction mass approaching and then leaving the position of the leg endpoint. This pattern of motion belongs to the family of curves called *hypertrochoids* generated by rotating a circle along the inside of the perimeter of a second larger circle. The standard equations for a hypertrochoid are:

$$y = (\alpha - b) \sin t - h \sin\left(\frac{\alpha - b}{b} t\right), \quad x = (\alpha - b) \cos t + h \cos\left(\frac{\alpha - b}{b} t\right) \quad (1)$$

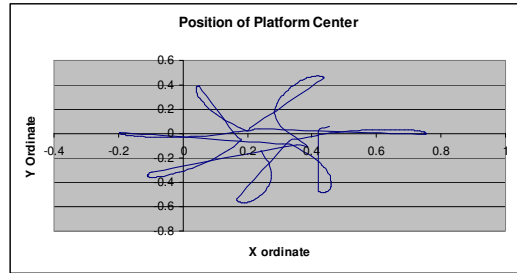


Figure 6: Plot of platform center during natural motion

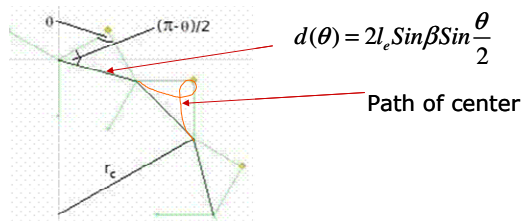


Figure 7: Kinematic simulation of mechanism rotating same angle around three successive endpoints.

We can relate the rotopod motion to these equations. Let l_e be the length of the leg projection onto the xy plane, let β be the leg/midline angle, and let α be the max angle that the platform tilts when the reaction mass passes over a leg. Fig. 7 shows the plan view of the mechanism rotating an amount θ around each of the three leg endpoints in turn. As it rotates,

the mechanism center follows a curve with radius r_c . The distance moved on each rotation can be calculated as $d(\theta)$ as shown, and the relationship with the hypertrochoid curve established as:

$$\begin{aligned} r_c &= a - (b + h) & 2\pi b &= d(\theta) = 2l_e \sin \beta \sin \frac{\theta}{2} \\ a - (b - h) &= l_e \sin \beta - l_e \sin(\beta + \alpha) \end{aligned} \quad (2)$$

3. Control of Motion

The epicyloid-like path has good ground coverage properties. However, to be useful, the motion must be controlled to cover a desired area. The natural motion of the platform is fixed

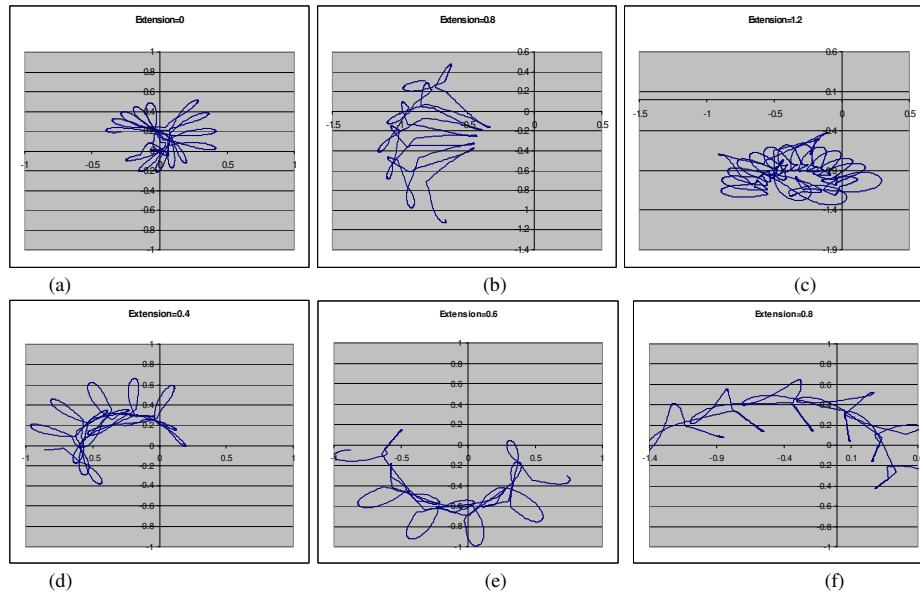


Figure 8: Changing Leg Lengths, (a-c) 2 Leg Extensions; (d-f) 1 Leg Extensions.

by the leg lengths, masses and rotational velocity, and is, simplifying somewhat, a closed circle on the ground plain. There are several choices of control parameters include the rotational velocity, moving the reaction mass along the reaction arm (with a linear actuator) or changing the leg lengths. We selected changing the leg length because of its energy-efficiency:

- (1) leg lengths can be changed while a leg is in the air, and hence require a minimal injection of energy into the system.
- (2) Once a leg length has changed, the linear actuator model requires no injection of energy to maintain that length

Fig. 8 shows the effect of modifying leg length, while leaving all other parameters the same: the radius of the circle of rotation increases in direction proportion. Extending two legs allows for smaller circles, while extending just one leg generates bigger circles. These graphs were generated from the ODE simulation. These results mean that the rotopod can be driven along a curve; however, a practical limitation is that the radius of curvature must always have the same sign.

The closed circular paths in Fig 8. can be used to build compound motions. There are three compound motions we have studied, spiral search, epicycloids and area fill. Fig. 9 shows examples of each of these. Each has the advantage that it has strong area coverage properties, and is hence a useful mode of locomotion for searching, reconnaissance and surveillance. The spiral [2] and area fill patterns are appropriate when looking at a limited geographical area, while the epicycloid is a traveling pattern and useful for traversing large areas.

These patterns of motion are *very different* from the standard approaches to legged or wheeled

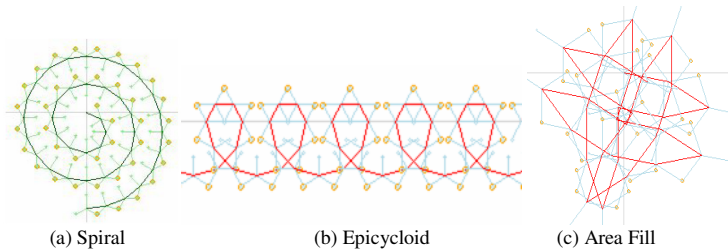


Figure 9: Compound Motion Strategies.
Path of center is shown as dark line. The small circles are leg rotation points. The ground projections of the three legs are shown in light color.

vehicles [6, 13], and its worth recalling how we got here: The rotopod is designed to have legged capabilities but high energy efficiency. The patterns shown in Fig. 9 are therefore energy-efficient search patterns.

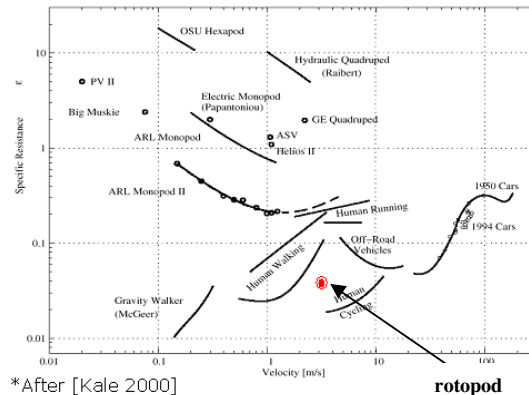
4. Energy efficiency

The specific resistance is a common measure of energy efficiency for wheeled and legged vehicles (though by no means the only one [12]). It is defined as

$$\varepsilon = \frac{\text{power}}{\text{weight} \times \text{velocity}}$$

The most efficient legged locomotion (passive-dynamic walking [3]) has ε between 0.05 and 0.08 and the less efficient legged approaches (e.g., Asimo biped) can be as great as 1.8.

We used ODE to measure the mechanical power expended by the rotopod in natural motion (e.g., Fig 6). Typical speed for the robot was about 1.29 m/s or 2.8 mph – about walking speed, and the specific resistance measured 0.03. Note this *impressively low figure* should be taken with some caution: It's the result of ODE measurements, it's the only the physical cost of motion, and it includes motion along the entire perimeter of the hypertrochoid (e.g. 8m in Fig. 6. for a curve of average radius 0.2m). We have not make measurements on the physical prototypes on the electrical cost of motion, which is what will determine longevity given current battery technology. However, this low number, which should be regarded as a best case, does indicate that the basic idea of the rotopod as energy efficient legged locomotion is a strong one as shown by the comparisons in Fig. 10.



* After [Kale 2000]

Figure 10: Potential Efficiency of Rotopod with respect to other locomotion

5. Conclusions

We have described a robot mechanism, the rotopod, that exploits a novel model of legged locomotion. The natural, uncontrolled motion of the platform has good area coverage properties and promising energy efficiency. By varying the lengths of the legs of the mechanism, this natural motion can be controlled and compound motion patterns such as a spiral (for search), epicycloid (for directed motion) or area fill produced. These results were obtained using an ODE simulation.

A physical prototype has been constructed that stands approx. 0.45m high and uses one Firgelli model CYCJ linear actuator per leg and a Korebot/Koremotor embedded computer running Linux is used as a controller, with wireless 802.11B connection. Preliminary results

duplicating those in Fig. 8 have been produced. Compound motions and energy efficiency are now being evaluated.

Beyond this, the next steps involve adding visual sensing to the prototype by mounting a camera on one or more legs. The rotating camera can in theory be used to produce a stereo from motion depth map to aid in foot placement.

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