Centipede-inspired locomotion for climbing stairs

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Abstract

This paper explores the ability of centipede-inspired robotic locomotion to climb stairs. Rather than focusing on complex controls, the effects of different mechanical parameters are simulated and examined in order to determine how best to construct such a robot. The results of existing research on such myriapods and robots they have inspired are examined and expanded.

1. Introduction

It is often a challenge for walking robots to maintain stability on uneven or unfamiliar terrain. In order to remain upright amidst such environmental factors as rocks, gravel, stairs, or large rubble, a great deal of sensor and control complexity is required. This is further exacerbated by traction-compromising factors such as ice, leaves, or oil.

Looking to nature for inspiration, it can be seen that reducing the number of legs generally comes with a corresponding increase in control structures; for example, the human walking gait is essentially a sequence of controlled falls, as the brain calculates highly complex dynamics to maintain stability on a single foot. Cockroaches or other hexapods, by contrast, are able to keep 3 legs on the ground at any given time, forming a highly stable plane of contact without the need for more advanced brain work.

Further increasing the amount of legs, as found in myriapods such as centipedes, brings a high degree of robustness to various environments, as well as increased traction and maneuverability in such environments.

1.1. Existing Research

Roboticists have studied centipedes for decades.

An early example of this study is the multi-legged robot developed at Seikei University. Importantly, the group notes that hexapods generally walk with one half-cycle between subsequent legs whereas centipede legs move in a wave motion, propagating down the body with less than one half-cycle between each segment. The group then constructed a segmented robot with a high degree of actuation; each leg uses two motors to step, lift, and reset similar to a rowing oar. Each segment contained a cpu and sensor suite to determine leg positioning. A control law was implemented to keep each leg a fraction of a cycle behind the previous leg, effectively propagating a

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wave similar to those studied in the actual animals. These fractions are not discussed or optimized. Note that with one brain, 5 sensors, and 2 motors per segment, the system requires a great deal of computation and actuation. (Torige et al., 1993)

Control algorithms utilizing this many degrees of freedom have been studied in order to determine optimal walk cycles, during both forward and turning movement. One such study, performed at the Harvard School of Engineering and Applied Sciences, notes that the optimal forward gait is achieved when the phase angle between segments is $2\pi/(n-1)$, where n is the number of segments. Note that this effectively distributes an entire sinusoidal cycle across all the segments. Furthermore, this is in contrast with rigid-bodied hexapods, which have an optimal angle of π radians between sets of legs; in fact, the study showed that using this angle between legs resulted in sub-optimal performance due to interference between segments. Given that there is a compliance between segments, these optimal phase angles induce undulation along the entire body (that is, the body is wiggling independent of the legs) whereas the non-optimal angles counteract these beneficial undulations. Note that the same undulations are observed in real centipedes. (Hoffman and Wood, 2012)

In another paper, the same researchers found that actuating a centipede robot with so many degrees of freedom allows a highly adjustable gait. Since the walk cycles can be manipulated on a per-segment basis, the delay between legs (ie, the walk cycle fractions relative to preceding segments) in such systems can be optimized to exhibit a high degree of robustness to missing or damaged legs.

The researchers determined a critical number of missing legs, under which the gait can remain unchanged (phase angle $2\pi/(n-1)$) and above which the gait can be adjusted to maintain a different angle between existing legs (phase angle adjusted relative to how many consecutive segments are missing). Their results indicate that performing such gait adjustments allows movement speed, turning radius, and stability to remain relatively unchanged. (Hoffman and Wood, 2013)

The adaptability and robustness demonstrated by such systems is highly desirable for robotics. Moving beyond turning in a single plane, researchers at Hosei University were able to design a centipede robot with the intention of climbing rubble by adding an additional degree of actuation. A wire running along the body of the centipede pulls the body upward, much like the tendons which curl fingers inwards. By lifting the body in this manner, the front legs are able to catch the elevated surface, while the rear legs are still providing a propulsive force from the ground surface. (Ishigaki and Ito, 2014)

Though there are clear advantages to actuating every degree of the robot like this, the control complexity and overhead required in coordinating so much movement results in a very complicated mechanical design.

Researchers affiliated with the Korea Advanced Institute of Science and Technology took a simpler approach while conducting further research into rough terrain traversal. Their robot consists of a single DC motor at the end, with a universally-jointed driveshaft connecting the segments. At each segment, a worm gear translates some torque to the legs, which do not use the stepping motion seen in other robots, but rather a rotational motion akin to car wheels. Since the speed of each leg is the same, the phase angle is locked and determined by the mechanical placement of the mechanism. The group notes the tradeoff between varying angles, with some angles working better for contact area, and others working better for avoiding collisions between legs. The robot was found to traverse various types of terrain successfully, without provisions for turning or control. The motor spins, and the centipede goes. (Koh et al., 2010)

2. Formulation of the problem

The goal of this research is to simulate a robot which will climb up a specified staircase while carrying an egg. In the following formulations, we will restrict our analysis to two dimensions (the X-Y plane) for simplification and ease of simulation.

2.1. The Staircase

The staircase to be climbed is that of the E2 staircase in the Baskin Courtyard at UCSC, which was measured by colleagues to have stairs approx. 127 cm tall and 381 cm deep and counted to be 30 steps in total. Figure 1 shows the staircase, restricted to 2 dimensions and drawn to scale.

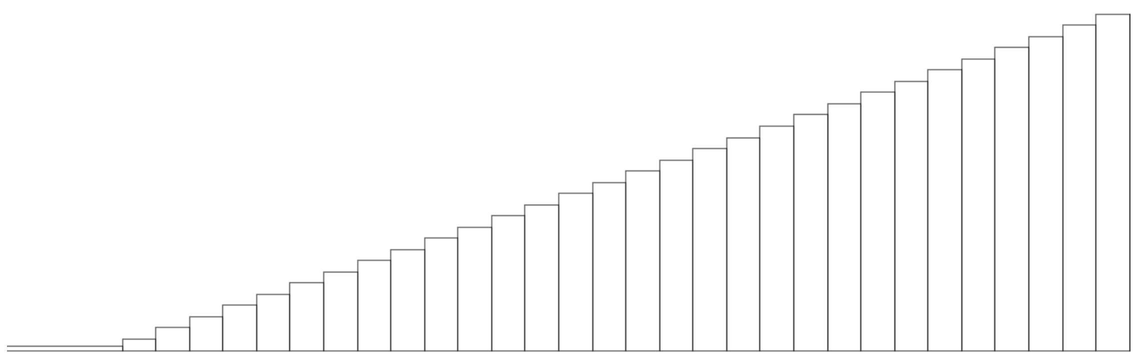

Figure 1: The Stairs

2.2. The Robot

Similar to the work of Koh et al. discussed above, I propose a robot which consists of multiple segments joined by a spring-loaded pivot and a single actuator driving each of the segments. Each segment will contain a pair of motorized wheels and be free to move up or down along a revolute joint as per the 2D restriction, along with the dynamics of a torsional spring. In reality, this may be accomplished with a series of universal joints.

A high-level overview of the stair climbing strategy is to push the leading wheel against the stair in order to generate a normal force which will in turn work with friction to drive the wheel up the stair as per rolling wheel dynamics. Hypothetically, the amount of force the robot can generate at the front end will depend on the traction and force contributions of each segment. Figure 2 shows the nature of this operation as well as different segments in different stages of the climbing process. This figure, taken from the simulations discussed below, clearly illustrates the benefits of this redundancy, as the robot maintains multiple segments in contact with the ground even as the terrain varies.

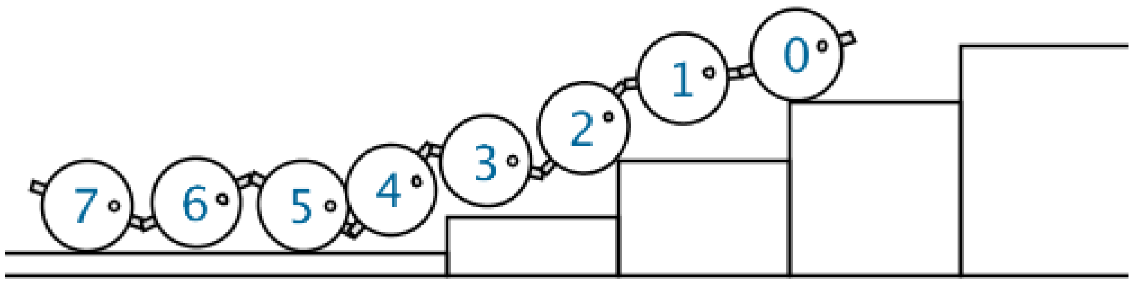

Figure 2: Climbing

2.3. *Free Body Diagram*

The following free body diagram illustrates a rudimentary view of the forces and torques present on any given segment in the middle of the robot. Note that the 2D representation can be though of as the combination of both wheels in the segment. These forces and torques work together with friction to generate rolling forward motion. We note that solving the dynamics of this system is not necessary for simulation, as discussed below; calculations for these multi-body equations of motion are complex and beyond the scope of this paper.
The following nomenclature is used:

ϕ = Segment angle relative to the ground	r = Wheel radius
θ_{left} = Joint angle to lefthand segment	l = Segment length
θ_{right} = Joint angle to righthand segment	m = Segment mass
τ = Motor torque	
κ = Torsional spring constant	

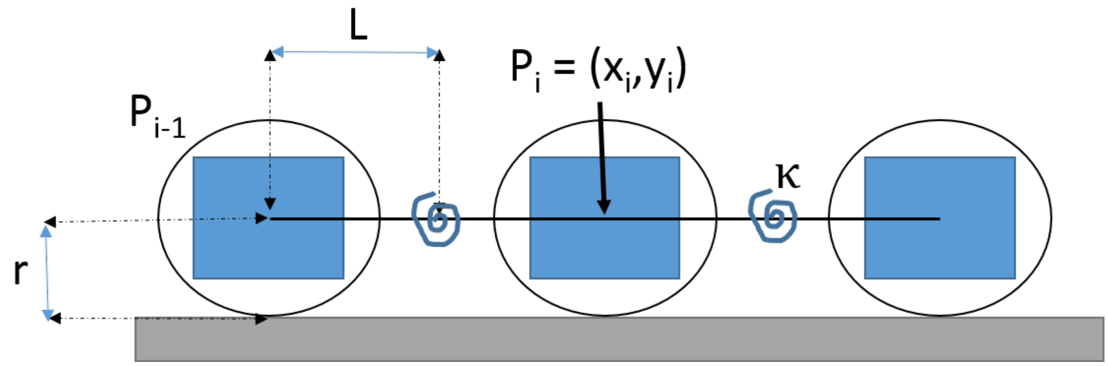

Figure 3: Segments

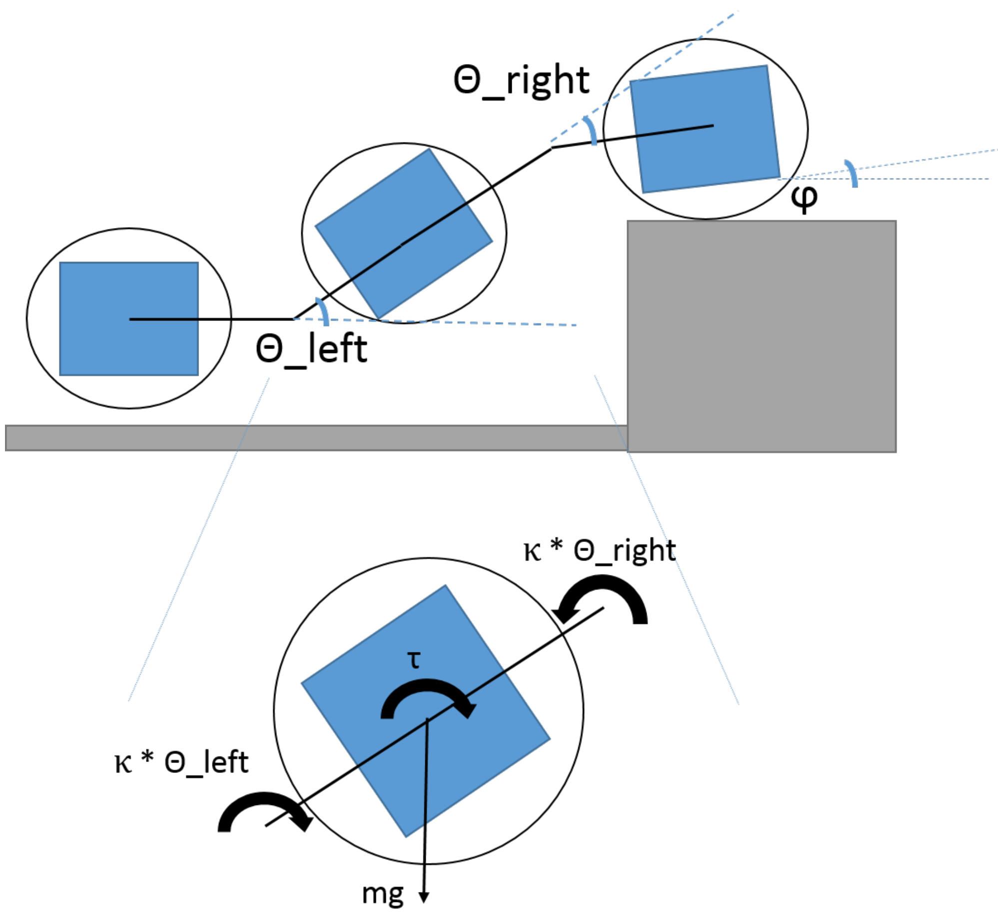

Figure 4: Forces and Moments

With the assumption that segment position is known,θ_{left} and θ_{right} can be derived using the law of cosines. The normal force exerted on the ground will be projected along the ϕ direction and, driven mostly by the motor torque, determines how much force friction is able to exert to move the body.

m, n, r, τ,and κ are design parameters to be determined during simulation.

3. Implementation

3.1. Method of solution

Rather than solve and implement the above free body diagram, far more accurate results can be achieved by using a so-called physics engine. This refers to a type of software used to simulate the movement of dynamic systems. Since physics engines can do the heavy lifting of calculating all forces (including such factors as mass, gravity, and moment of inertia), they are well suited to a simulation.

The Box2D physics engine for java was used to simulate the centipede. This set of libraries was chosen for its precise 2D calculations done in standard units (kg, m, s). Box2D uses an iterative solver to determine the positions and velocities of objects in its world. The world it calculates consists of bodies (which have associated mass, shape, and other physical properties) and their constraints (which consist of physical collisions and various types of joints.)

3.2. Simulation

The simulated centipede was constructed using the Box2D system of bodies (segment mass, wheel) and constraints (axles, joints) in order to accurately simulate its behavior. A rectangular bar was attached to a wheel using an axle-type joint, which was actuated using Box2D's motor functionality (which applies a specified torque to the joint).

The staircase was implemented as a sequence of rectangular objects sized according to the staircase measurements, which interact with the centipede in the Box2D environment. The simulation was run at 1/60 seconds per step, with 20 iterations of both solvers per step.

To begin with, some parameters were chosen to "lock down" in order to easily observe the effects of other parameters. We note that the simulation was coded to easily allow adjustment of these parameters for future optimization. These were chosen roughly as follows:

- Wheel radius: 100mm based on rugged wagon- or electric wheelchair-type wheels
- Segment length: 130mm to allow hinges to protrude enough out from the wheel to connect to the neighboring segments
- Spring constant: Automatically adjusted in Box2D to achieve critical damping dependent on system; the code only allows the simulation to specify damping ratio
- Segment mass: 750g based roughly on measured weight of two similar-sized wheels

With these parameters in place, simulations were run and iteratively adjusted until good stair-climbing performance was achieved. Results are discussed below.

Figure 5 shows a sample simulation window; refer to figure 2 for view of the centipede.

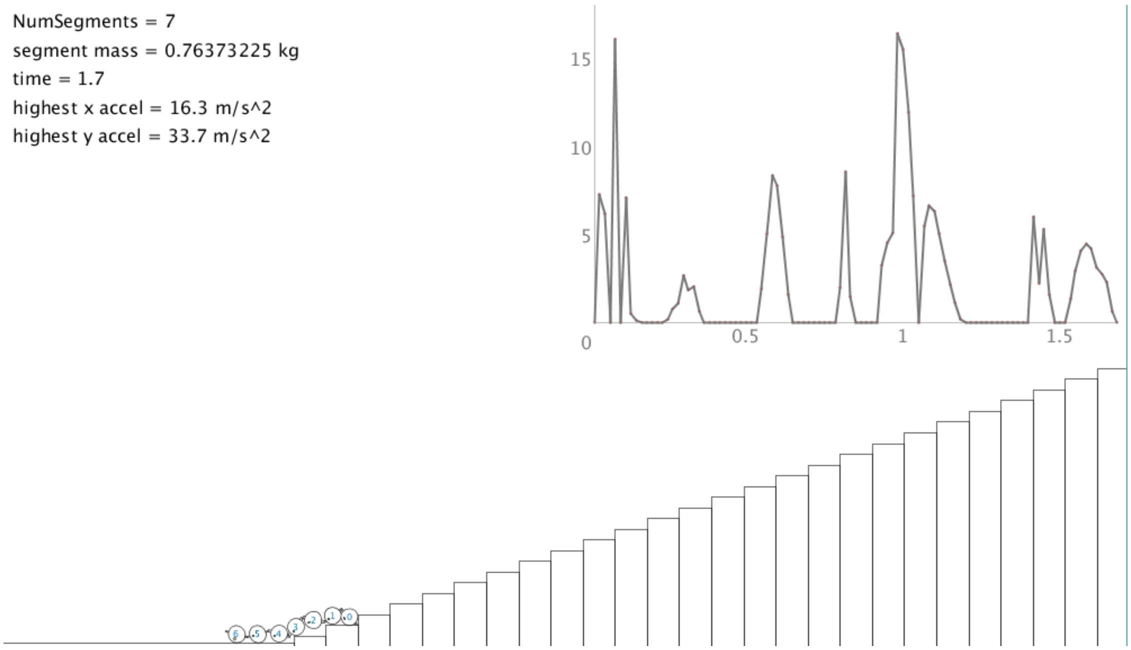

Figure 5: Simulation showing acceleration and other data

3.3. Addition of Legs

It is relatively simple during simulation to replace the wheels with rotating legs. In theory, this allows the legs to get a tighter grip on the next step when climbing, as well as adapt to more irregularly shaped obstacles. A version of the simulation was created to use thin legs, sized the same as the wheel diameter. The results for both types of segment are discussed below.

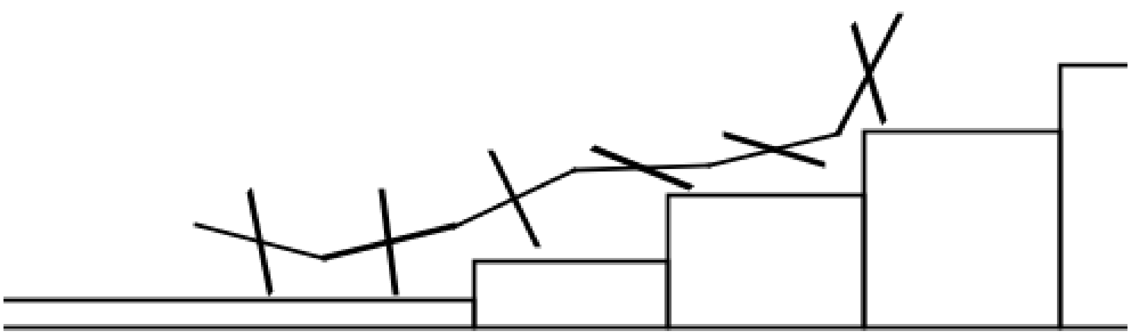

Figure 6: Legged segments

4. Numerical results and discussions

4.1. Number of Segments

The following table illustrates the effect of added segments upon climbing speed. Simulation showed that the centipede fails to climb the stairs with 3 or fewer segments. Noting the diminishing returns, we conclude that the optimal number of segments is 6. Fewer segments results in visibly reduced traction, while more segments added sluggishness and physical size. The addition of legs seems to bypass the traction problems and shows similar times across all numbers tested, but does not outperform the wheels with 6 segments. The remainder of simulation was performed with 6 segments for both wheeled and legged robots.

number of segments	wheel time to climb (s)	leg time to climb (s)
4	56.2	35.2
5	40.5	37.3
6	34.4	37
7	36.3	36.2
8	36.8	38
9	36.8	37.7

4.2. X- and Y-accelerations

The following graphs show the acceleration of the center of mass for the 3rd segment during the first 20 seconds of simulation. During normal travel, we can see that the acceleration stays largely within 10 m/s^2, or normal g-force. The periodic impulses naturally appear when the segment rams into the next stair; these spikes generally do not exceed 40 m/s^2 apart from the occasional outlier, though we note that the legged version occasionally produces spikes up to 60 m/s^2. The egg could be sheltered from these impacts by implementing some sort of shock absorption between joints, at the axles, or in the carrying method.

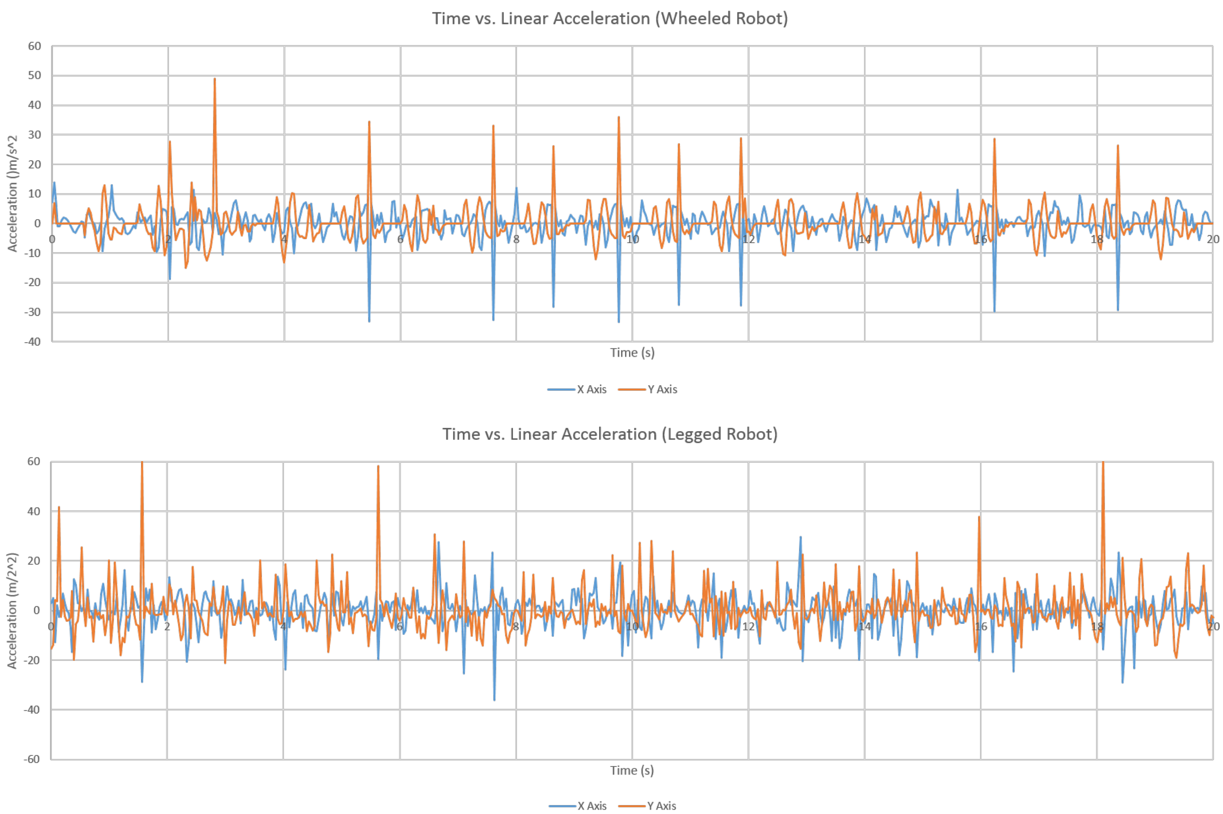

Figure 7: Simulation Results for segment C.O.M Acceleration

We can conclude from the above results that it is quite feasible for a myriapod-inspired robot to climb staircases. With so many different segments able to move and find grip in the environment, this style of locomotion is sure to be useful in traversing all kinds of terrain.

5. Future Work

Future work for this project includes:

- A wider exploration of other variables; for example, varying the spring constant or wheel radius
- Optimization of parameters for different sized stairs, and analysis of wheels vs. legs for performance on taller or more generalized stairs
- Exploration of different body types; for example, a version with a circular body which skids along the ground while the rotating legs propel it

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