A Body Joint Improves Vertical to Horizontal Transitions of a Wall-Climbing Robot

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Abstract— **Several recent robots are able to scale steep surfaces using animal-inspired strategies for foot attachment and leg kinematics. These designs could be valuable for reaching high vantage points or for overcoming large obstacles. However, most of these robots cannot transition between intersecting surfaces. For example, our previous robot Climbing Mini-Whegs™ cannot make a 90° transition from a vertical wall up onto a flat horizontal surface. This ability will be important for practical applications. Cockroaches bend their body to accomplish such transitions. This concept has been simplified to a single-axis body joint which allows ground-walking robots to cross uneven terrain. In this work, we examine the effect of a body joint on wall-climbing vehicles using both a kinematic simulation and two prototype Climbing Mini-Whegs™ robots. The simulation accurately predicts that the better design has the body joint axle closer to the center of the robot than to the front wheel-legs for orthogonal exterior transitions for a wide range of initial conditions. In the future, the methods and principles demonstrated here could be used to improve the design of the robot for other environments.**

I. INTRODUCTION

ROBOT mobility is being improved through the intelligent application of mechanical and control principles found in biological systems. Animals such as insects and geckos are able to move up vertical walls and over high obstacles. A robot able to climb such steep surfaces could reach locations previously difficult to access by robotic systems. The ability to climb up, across and down an obstacle allows a small machine (Fig. 1) to negotiate objects much larger than it would be able to step over. Such a climbing robot may have limitless unforeseen applications and will be immediately usable for time-critical search and rescue in hazardous and variable environments and surface-based operations such as cleaning, painting, and inspection.

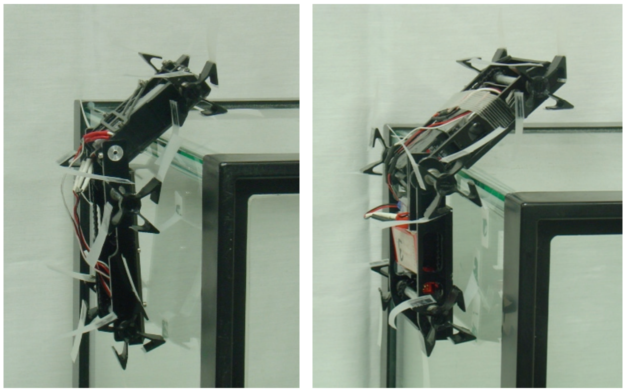

Fig. 1. Climbing Mini-Whegs B31 and Climbing Mini-Whegs B00 making an external up transition.

Insects and geckos use claws and adhesive pads to negotiate both rough and smooth surfaces [1][2][3]. Climbing robots have been designed to mimic various aspects of these and other biological systems to operate in specific vertical environments. Robots that adhere to the surface through suction cups [4][5][6], magnetic end-effectors [7][8][9], or adhesive pads [10][11][12][13] can climb featureless, flat, or smoothly curved surfaces. Vortex-generating climbers [14][15] do not require smooth surfaces. Robots have been designed with end-effectors that match specific features of the environment, such as peg-holes [16], handrails [17], climbing-wall footholds[18], and poles [19]. Robots have also been fit with insect-inspired spines [20][21] to scale rough vertical surfaces.

Several of these systems were designed to operate on both horizontal and vertical surfaces, but few can make orthogonal transitions between the two surfaces. Our previous climbing vehicle, Climbing Mini-Whegs™ [12] was able to transition from horizontal ground onto and climb a vertical glass surface. However, to complete a climb over an obstacle, the robot needs to be able to transition from the vertical surface to the top of the obstacle (Fig. 2).

However, traversing exterior transitions is essential for overcoming large obstacles in the path of a small robot as shown in Fig. 2. The path requires that the vehicle make interior (concave) and exterior (convex) transitions between orthogonal surfaces. A robot capable of walking on any surface without regard to the direction of gravity would be able to transition to and from ceilings as well.

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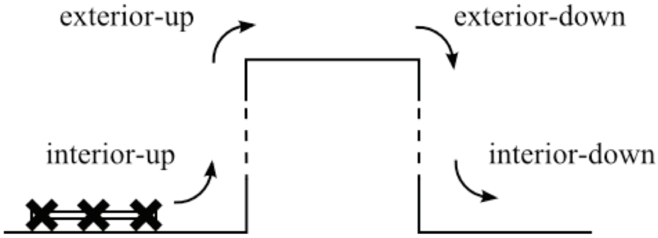

Fig. 2. A small robot can climb over a large obstacle by making an upward interior angle transition on to a vertical surface, an upward exterior transition on to the top of the obstacle, a downward exterior transition on to the farther vertical wall, and a downward interior transition on to the ground.

The external transitions are more difficult because the front feet do not encounter the orthogonal surface in their normal swing phase. Climbing robots designed for operation with their bodies' parallel and close to the substrate are likely to have this problem during exterior transitions.

Cockroaches take advantage of a body joint to make these types of transitions [22] and a body joint has already proved valuable on ground-walking robots. Whegs™ II uses its body joint to conform its body to the terrain, lower its center of mass, and avoid high-centering when climbing obstacles [23]. Xiao et al. [15] have a prototype design for a vortex machine with a body joint that will make exterior transitions, but to our knowledge they have not shown successful results as of yet. Analysis of biped wall-climbers demonstrated the usefulness of large body (hip) joint angles to initiate fore-foot contacts with a wide range of plane angles through both interior and exterior transitions [24].

This paper investigates the cockroach-inspired concept of adding a body joint to a wall-climbing vehicle to make these types of transitions. The fore-aft location of the body joint and the timing of its movement were studied in cockroaches, in a robot simulation and in two physical prototype robots (Fig. 1). The result is a climbing robot that can transition around both external and internal angles. This work provides a set of principles and methods applicable for the design of other types of legged climbing robots.

II. BIOLOGICAL INSPIRATION

Cockroaches are extremely agile climbers on a wide variety of surfaces. When an interior transition is encountered, a cockroach uses its middle legs to pitch its body upward to place its feet onto the new surface. When a cockroach encounters an external transition it will bend its body to stay close to the substrate, avoid high centering, and more easily reach the substrate with its front legs.

The cockroach shown in Fig. 3 makes an upward exterior angle transition on a Styrofoam block by first placing its front feet along the top edge. A middle leg is placed on the wall just under the edge. The animal then simultaneously raises its body and extends one of its front legs. After the animal moves its body up, it bends downward and extends the front legs to reach far along the top surface. The middle legs are swung onto the top, and finally the rear legs detach and are pulled up.

The cockroach has many sensors (such as eyes, tactile antennae and strain sensors on the legs) that help it perform this complex maneuver. In addition, each leg has many joints that allow the feet to move in three dimensions. During transitions, there is generally only one foot in swing at any time. The legs are so agile that even without the body joint the animal can succeed in making this transition from vertical to horizontal, (although the animal appears to struggle more to maintain balance due to of high-centering).

III. DESIGN PRINCIPLES

The fundamental challenge in climbing is for the robot neither to slip down the surface nor pitch away from it while moving along the surface. To avoid slipping down a wall, a robot's feet (or wheels or treads) must provide traction tangent to the wall. To avoid pitching away from the wall, a robot's front feet must provide tensile normal force and its rear feet must provide compressive normal force [27].

The orientation of a foot, the direction of movement during its attachment, and the direction of movement during its detachment are critical for a climbing robot or animal, especially if directional adhesives are used [3][11]. Robots and animals typically climb with their bodies parallel to the substrate. When a surface of a different orientation is encountered they must adapt their movements or their feet will not attach properly. One way they can do this is by altering the orientation of their body locally using a body joint(s), so that legs designed for substrates parallel to the body can function on surfaces at different orientations.

If two feet must be in contact with the substrate to avoid slipping or pitching, then a robot must have at least three feet so that one foot can be in swing while the other two are attached. If the feet cannot change their order (as in flipping type robots [24]), this means that to accomplish an upward exterior angle transition, first the front feet, then the middle, and finally the rear feet should be moved from the lower surface to the upper surface, as observed for cockroach leg pairs.

Each phase of the transition has unique requirements. After a front foot is detached, the first challenge is to reattach the front foot on the surface of the new substrate.

Fig. 3. Still image captures from high speed video of a cockroach climbing around a block of foam. During this transition the angle of the body lower with respect to the pronotum changes by about 35°.

This requires that the foot reach the substrate without interfering with the legs or body on the way. The next challenge is to maintain the fixed attachment points of the rear and front legs without causing the middle feet to collide with the substrate while they are being placed on top of the obstacle. Finally the rear feet have to be moved to the upper surface.

IV. APPLICATION FOR WHEGS

In designing a climbing robot, we hope to forgo as many of the sensors as possible and couple and simplify the legs to reduce weight and size. Thus we are investigating through software and hardware models, lightweight robots in which each leg has been abstracted to a single segment. PROLERO [25] and RHex [26] demonstrate the feasibility of walking with simple rotating spoke-like legs and RHex runs in a cockroach-like alternating tripod gait. Whegs™ robots have six wheel-legs, each with multiple spokes, that can step over obstacles like legs but drive continuously like wheels which allows them to be coupled together and driven by a central motor. A body joint was implemented on a 50cm long Whegs™, which allows it to climb taller obstacles without high-centering [23]. Mini-Whegs™ have four wheel-legs and are small (8cm) and lightweight (100-200g). Their high power to weight ratio and cyclic symmetry make them good platforms for wall climbing. Climbing Mini-Whegs uses compliant feet attached to the end of its wheel-leg spokes to scale vertical surfaces and ceilings. Different materials on the feet such as Velcro, tape, and spines allow climbing on different substrates [27].

When Climbing Mini-Whegs transitions around interior angles, their front feet are pressed against the new, orthogonal surface using their normal gait. When the front feet attach, the body is pulled up the substrate and the rear feet slip – either the feet detach and slide or there is observable compliance of the foot. When the robot encounters an external transition, the front feet do not attach to the new surface, and when the end of the original surface is reached the robot tumbles backwards. The foot of the first spoke beyond the corner of an external transition can not make contact with the substrate because it is at the wrong angle to form an attachment. Even if the foot was able to attach to the substrate at any angle, the spoke of the wheel-leg is most likely to collide with the corner before the foot reaches the substrate. In fact, if the spokes as well as the feet were covered with an adhesive material, it would still be difficult to develop enough contact area along the sharp edge of the transition corner to make a successful attachment. This work shows how a single revolute joint in the body, a body joint, can improve a robot's climbing ability.

V. SIMULATION ANALYSIS

To further examine the design and control required for a robot to make external transitions using wheel-legs, we simulated a simplified planar version of a robot using Matlab, see Fig. 4. All segments are assumed to be lines, all components are assumed to be rigid, and all feet are points that can attach on contact with the surface. The previous foot on the wheel-leg detaches when the next foot on the same wheel-leg attaches, and when more than two wheel-legs touch the surface, two feet are chosen to be attached. Thus, the simulated robot fixes two attached feet and drives forward until another foot touches the surface. The attached feet are fixed and are not permitted to move either tangential or normal to the surface. The one exception is that the rear foot is permitted to slip 1mm before the front foot reaches the upper horizontal surface. The simulation is kinematic because forces are not needed to determine interference. We will assume that two feet (or two pairs of feet) have sufficient attachment strength to support the robot, and that the feet are not permitted to slip with the exception noted above. In the current Mini-Whegs™, robots the feet have been observed to slip, although in general if a foot slips, the risk of detachment is greater. The angular velocity of the body joint relative to the drive motor is specified when the middle and rear wheel-legs are attached. When the body joint is between the front and middle wheel-legs, the angle of the body joint is adjusted so that the attached feet remain attached.

The results of the simulation are dependent on the geometry of the robot and the environment, on the initial conditions and on the control of the body joint. The following results were obtained for a 90° exterior transition. The legs of the robot were 2cm long and the distance between the front and middle and middle and rear wheel-legs was 6cm. To understand how placement of the body joint affected the transition, we varied the location of the body joint from 0% to 50% of the distance between the front and middle wheel-legs. When the joint is at 0%, it coincides with the middle wheel-leg axle.

A few representative test trials confirmed the assumption in Section III that the best method to climb over the obstacle

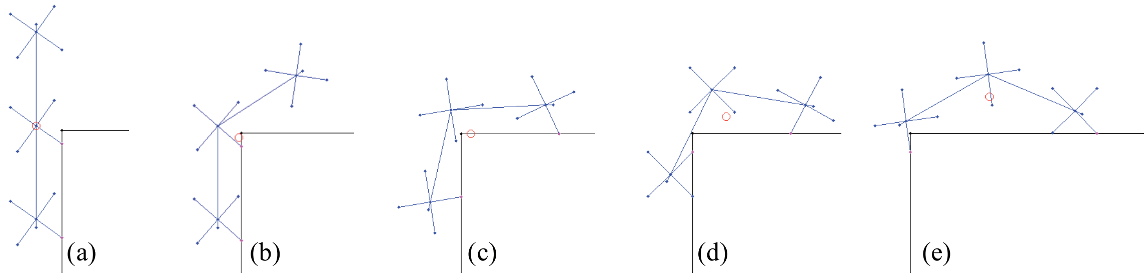

Fig. 4. A simulated trial robot with the body joint located at 0%. The red circle shows the location of the center of mass.

is to first drive the front wheel-leg off the edge, then use the body joint to place the front wheel-leg on the top. Then the first and last wheel-legs are fixed and the position of the body joint is determined. In many trials, it is during this phase that the frame or the middle wheel-leg collides with the ground. The simulation assumes that such a collision would prevent further progress or cause the feet to slip and detach. On the real robot, sometimes the feet slip or detach briefly without causing a fall, however the no-slip condition allows a conservative prediction.

Because it is important to compare only the best-controlled runs, we parameterized the control of the body joint to hold straight, then a fast descent. This parameterization will not capture the control method that is best for stability, because it would be better to keep the center of mass close to the substrate by lowering the front gradually. However, sampling the possible hold times does represent the space of possible combinations of upper and lower attachment points.

The possible initial conditions were accounted for by running the simulation with different starting points along the vertical wall. For the data presented here, 113 starting points were chosen ranging over the distance between foot falls of the wheel-leg, in this case $2\sqrt{2}$. For each initial condition, 71 control efforts were compared and the control that resulted in moving the center of mass the farthest horizontally was identified as the best. The progress of the robot is defined as the motion of the center of mass in the x direction, where -2 (the leg length) is the starting position of the center of mass and 0 corresponds to when the center of mass is in line with the vertical wall. Note that the center of mass is calculated assuming the chassis has mass proportional to length and the wheel-legs are massless. Because the center of mass is not a point fixed to the body, the center of mass can cross the y-axis before the middle wheel-legs do. As the x coordinate increases toward zero the required adhesion decreases making a fall less likely. Once the center of mass crosses zero, adhesion tensile to the wall is no longer required to prevent pitch-back.

The results show the sensitivity of the system to body joint location. Fig. 5 shows the average final progress of the center of mass over all of the tested initial conditions. This figure shows that a body joint location between 25% and 40% will not on average allow the geometric center of mass to cross the centerline. This means that when a collision with the wall induces slip, the robot will tend to fall backwards rather than onto the upper surface. According to Fig. 5, a body joint located very near the middle wheel-leg axle is optimal.

To understand why the decrease in performance between 6.25% and 12.5% is so severe, see Fig. 6. In this bar graph, the success rate of various phases is shown. Group (a) shows the percentage of initial conditions for each body joint configuration that resulted in the front wheel-leg touching the top surface. Group (b) shows the percentage that could result in a positive x-coordinate of the center of mass. Group (c) shows the percentage that got the center of mass at least 1.5 over the edge. This corresponds to both the front two wheel-legs crossing the corner. Often they are prevented from continuing further by a collision with the chassis as is close to occurring in Fig.4d. Group (d) shows the percentage of runs that almost made it all the way over with final center of mass past x = 5 (only a collision with the back leg prevented the x from being arbitrarily large). The series of images in Fig. 4 is an example of such a trial. This can be observed on the robot, but instead of stopping, the rear foot just slides along the corner of the obstacle, allowing the robot to continue.

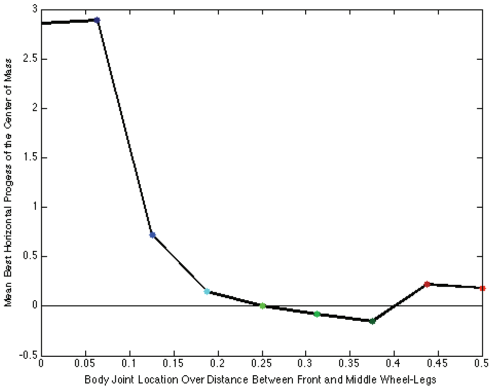

Fig. 5. The effect of the location of the body joint on the simulated mean progress before slipping over initial conditions.

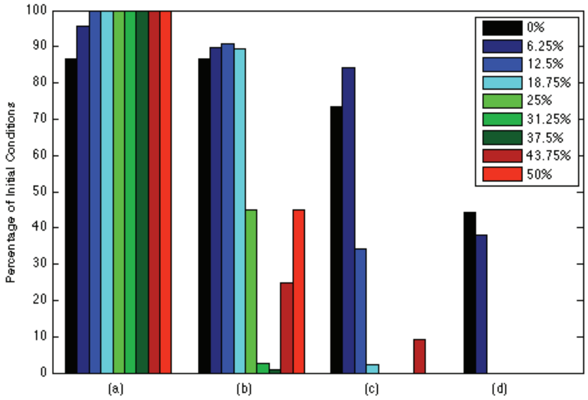

Fig. 6. The percentage of initial conditions resulting in various phases, (a) contacting the top surface, (b) having the center of mass cross 0, (c) getting the second wheel-leg over the stop, and (d) getting the center of the third wheel-leg past the corner.

Finally another important parameter is the magnitude of the required body joint deflection, which is shown in Fig. 7. The closer the body joint is to the middle wheel-legs the less the body joint needs to bend on average to place the front wheel-legs on the upper surface in the best possible control. This is significant because large bending angles are difficult to implement because the body and wheel-legs may interfere with each other and servos generally have a small range of rotation.

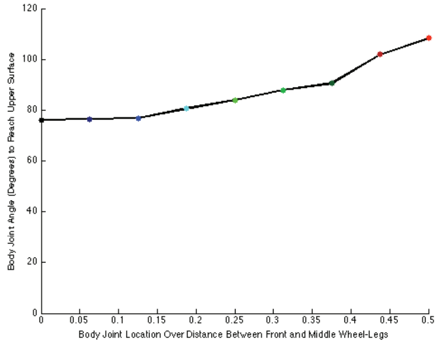

Fig. 7. The effect of body joint location on body joint angle required on average to bring the first wheel-leg down into contact with the top surface.

VI. CLIMBING MINI-WHEGS™ WITH BODY JOINT

Two prototype robots were built and tested with body joints, see Table I. The first robot, Climbing Mini-Whegs B31 (CMWB31), see Fig. 1 (left), has a body joint located between the front and middle wheel-legs, located such that the distance between the body joint axis and middle wheel-leg axis is 31% of the distance from the middle wheel-legs to the front wheel-legs. The robot was built before we did the simulation so the ratio was chosen because it appeared to mimic that of the cockroach when bending around external angles (see Fig. 3) and because it was convenient for mechanical design. The second robot, Climbing Mini-Whegs B00 (CMWB00), has a body joint that is co-axial with the middle wheel-legs, see Fig. 1(right).

A. Climbing Mini-Whegs™ B31

CMWB31 is the first iteration of a small wheel-legged robot with a body joint for steep-surface climbing. Like previous Whegs™ and Mini-Whegs™, all the wheel-legs are driven by a single central drive motor. While CMW has only 4 wheel-legs, CMWB31 has 6, three on each side of the chassis. The front wheel-legs are mounted on one segment of the body and the middle and rear wheel-legs are mounted on a second segment. A servo-motor adjusts the relative angle between the two segments, which is called the body joint angle. For simplicity, this robot was not designed to steer, although our previous work with CMW suggest that steering on a vertical surface is possible[27]. The center of mass is in the rear of the vehicle so that when the robot is on the ground the body joint can raise the front segment before approaching an obstacle or wall.

Several sets of wheel-legs can be used on the robot. Three-spoke non-adhesive wheel-legs can be used for stepping onto obstacles twice as high as the leg length on the ground. Wheel-legs with passive-ankles and metal spines allow climbing on steep (50°) foam. The tests on the transition environment were performed with four-spoke wheel-legs with flexible feet made of office tape as described in [12]. These feet stick reliably to glass without slipping and can support the weight of the robot, so they are helpful for testing robot designs.

TABLE I
COMPARISON OF CLIMBING MINI-WHEGS™

	Climbing Mini-Whegs	Climbing Mini-Whegs B31	Climbing Mini-Whegs B00
Mass of chassis	90g	104.6g	166.4g
From front to middle wheel-legs	7.0 cm	6.5 cm	6.5 cm
From middle to rear wheel-legs	No rear wheel-legs	6.5 cm	6.5 cm
Middle wheel-legs to body joint	No body joint	2 cm forward	0 cm
Leg length	2 cm	2 cm	2 cm
Body Joint Range of motion*	No body joint	–45° to +45°	–180° to +45°
90° Transition Types (Fig. 2)	Internal	Internal and external-down	All four types

*Where (+) is bending the front up and (–) is bending the front down

CMWB31 was able to make upward interior transition climbs from a horizontal surface to vertical on glass. On both Styrofoam and glass the vehicle was able to make transitions up to ±45°. Interior angles could be traversed, but for exterior angles, the limitations of the body joint prevented the front wheel-legs from contacting the top surface in exterior angle transitions. The body joint flexed about 45°, and continued the vertical climb, but then the middle wheel-legs lost contact on the vertical surface. CMWB31 subsequently fell backwards instead of forwards. External-down transitions often resulted in a fall, but in one trial the transition was accomplished.

B. Climbing Mini-Whegs™ B00

The next robot was built to incorporate two design changes. First a body joint-servo, a Hitec HS-85MG, with a larger range of motion was chosen. Secondly the location of the body joint was moved to coincide with the middle wheel-leg axle. These changes increased the weight of the robot as shown in Table I and increased the width of the chassis from 5.1cm to 7.6cm. Both CMWB31 and CMWB00 have both drive and body joint motors in the front and the batteries in the back, with center of mass very close to the middle axis when the body joint is straight.

CMWB00 is able to make upward internal transitions from horizontal glass to vertical glass and upward external transitions from vertical glass to horizontal. This external transition was impossible even after many tries with CMW and CMWB31. To accomplish this, the operator drives the vehicle up the glass slowly, keeping the body joint straight until the upper wheel-legs are free of the wall. Then the body joint is adjusted gradually so that the front wheel-legs reach down and contact the upper horizontal surface. In some cases, the robot slipped before the front feet made contact, falling unto the surface. According to Fig. 6a this happens about 15% of the time even with the best control, however because the center of mass will usually be over the obstacle, the robot will fall in the right direction. The middle feet then are attached onto the horizontal surface, followed by the rear wheel-legs. Like in the simulation results, the body is initially bent at the top, but because the

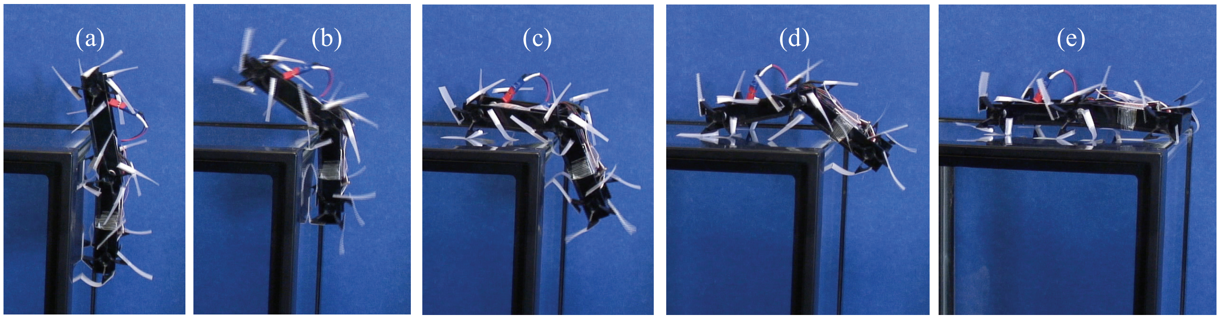

Fig. 8. Shows Climbing Mini-Whegs™ B00 making an exterior upward transition.

wheel-legs slip, the body joint flattens with applied torque from the servo.

The robot could make an exterior-down transition without falling if the feet on the middle wheel-leg were adjusted to be collinear with the spoke rather than nearly parallel to the substrate. Feet in this orientation act like compliant extensions to the legs. See ICRA 2008 video proceedings submission: Making Orthogonal Transitions with Climbing Mini-Whegs™ for video of Climbing Mini-Whegs™.

VII. CONCLUSIONS

The simulation predicted an improved location of the body joint axle. The cockroach has the advantage that it can reach with its front legs to grasp the substrate, so it is not surprising that the optimal location of a body joint on Mini-Whegs™ is not the same as on the cockroach. The resulting vehicle progressed farther than predicted. The no-slip assumption is conservative and useful, but the real robot works better because there is compliance in the attached feet. These methods could be used to optimize other design parameters of climbing robots for various environments.

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