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

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***Abstract*— Several recently-designed 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 Climbing Mini-Whegs™ robot cannot make a 90° transition from a vertical wall up onto a flat horizontal surface. It is known that 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 climbing robots for other environments.**

I. Previous Climbing Robots

ROBOT mobility is being improved through the intelligent application of mechanical and control principles found in biological systems. Attachment mechanisms like the adhesives pads and sharp spines found on insects have already been implemented on robots that climb steep surfaces [1–6]. Unlike end-effectors that adhere by vortex-generation [7–8], suction cups [9–10], or magnetism [11–12], the attachment properties of the biological mechanisms are highly directional. Hooks, peeled adhesives and structured adhesives can be prone to detach or lock rather than slide along the substrate. Unlike for ground-walking robots, it is important to design the leg kinematics of a climbing robot such that the feet do not slip. Directional attachment mechanisms, like hooks, may detach or break rather than translate along the substrate. Even for non-directional end-effectors, like magnets, dragging a foot is inefficient. Detachment must also be precisely timed in order to prevent the robot from falling off the surface.

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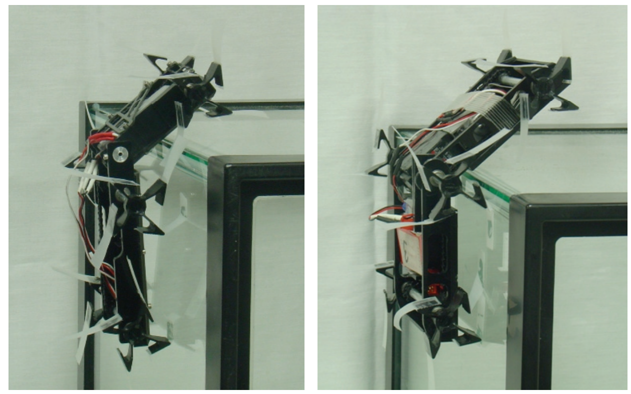

Fig. 1. Climbing Mini-Whegs™ B31 and Climbing Mini-Whegs™ B00 making an external up transition.

Because wall-climbing presents these challenges, many climbing robots are designed to operate on surfaces parallel to the body. To the best of our knowledge, even the RiSE platform with six independent two-degree-of-freedom legs cannot transition between orthogonal intersecting surfaces [2]. Climbing Mini-Whegs™ [13] and Tri-Leg Waalbot [4] are exceptional in their ability to make interior transitions (see Fig. 2). These transitions are possible because their rotating feet naturally contact the new climbing substrate. However, traversing exterior transitions is essential for overcoming large obstacles in the path of a small robot as shown in Fig. 2.

Cockroaches take advantage of a body joint[14] to make these types of transitions. Body joints have 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 [15]. Xiao et al. [8] 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 [16].

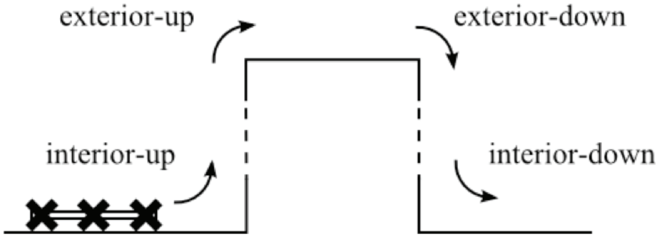

Fig. 2. A small robot can climb over a large obstacle by making an upward interior angle transition on to a vertical surface, an upward exterior transition on to the top of the obstacle, a downward exterior transition on to the farther vertical wall, and a downward interior transition on to the ground.

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 robots (Fig. 1). The result is a climbing robot that can transition around both external and internal angles.

II. Biological Inspiration

Cockroaches are extremely agile climbers on steep and uneven 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, stabilize its center of gravity, 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) and many degrees of freedom available in its six legs to perform this maneuver. 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 be struggling to maintain balance).

III. Design Principles

The fundamental challenge in climbing is for the robot, or animal, neither to slip down the surface nor pitch back from the substrate. 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 [13].

To support these forces with biological attachment mechanisms, the orientation of a foot, the direction of movement during its attachment, and the direction of movement during its detachment are critical [17][3]. Robots and animals typically climb with their bodies parallel to the substrate, attaching their feet in a consistent way at each step. 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 [16]), 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. 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 forgo as many of the sensors as possible, and we 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 and there are no leg sensors. PROLERO [18] and RHex [19]

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 abdomen with respect to the pronotum changes by approximately 35°.

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 ground-walking Whegs™, which allows it to climb taller obstacles without high-centering [15]. Mini-Whegs™ 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 [13].

When Climbing Mini-Whegs™ transitions around interior angles, their front feet are pressed against the new, orthogonal surface even when the body is rigidly straight. 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 on exterior angles.

V. Simulation Analysis

We examined the design and control required for a Whegs™ robot to make external transitions using a planar kinematic simulation. The simulation allows us to vary chassis parameters such as the location of the body joint without rebuilding a robot and allows us to systematically sample environmental variables such as the location of the edge relative to the initial stance position. Using a simple kinematic simulation eliminates the need to define a contact model, making these results applicable for any attachment mechanism, assuming that the attached feet have sufficient contact strength to support the robot and that the feet can be detached sequentially.

A. The Model

To model the behavior at the feet, we assume a few rules based on observation of previous Climbing Mini-Whegs™ robots. The foot, which is the most distal point of each leg, attaches to the surface upon contact. The attached feet are fixed and are not permitted to move either tangential or normal to the surface. The previous foot on the wheel-leg detaches when another foot on the same wheel-leg attaches. When more than two wheel-legs touch the surface, the program selects which two will be fixed to the surface. For the exterior-up condition in Fig. 2, first the middle and rear wheel-legs are attached until the front wheel-leg touches the top surface, then the middle wheel-leg detaches until the middle wheel-leg gets to the upper surface, then the rear wheel-leg detaches. This is consistent with the way the experimental robot is driven. Similarly, the simulated robot fixes two of the attached feet and drives forward until another foot touches the surface. (The one exception is that the rear foot is permitted to translate 1mm along the wall before the front foot reaches the upper horizontal surface.) Observations of the current Mini-Whegs™ show that the feet generally do not slip very much, and when slippage does occur, the foot generally detaches. If the front feet detach, the robot falls backwards catastrophically.

The angle of the body joint is determined by the simulation in order to maintain the fixed foot positions, unless the body joint is not in series between the two fixed feet. In that case, as when the rear and middle wheel-legs are attached, the body joint angular velocities relative to drive velocities must be specified. Because it is important to compare only the best-controlled runs, on the exterior-up environment we parameterized the control of the body joint to hold straight for a specified time as the robot rises above the edge, then the body joint bends quickly, bringing the body down onto the top surface. 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 simulation is halted when the robot collides with the substrate in any place other than the foot, or when a foot that should detach is instead driven into the substrate. At this

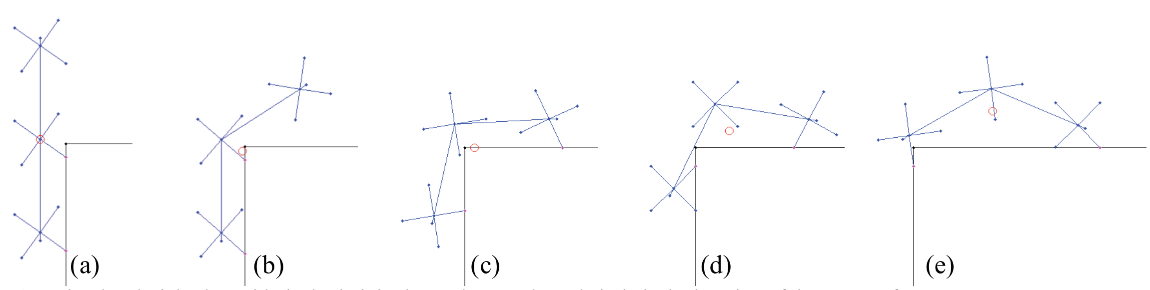

Fig. 4. A simulated trial robot with the body joint located at 0. The red circle is the location of the center of mass.

point the simulation stops. The simulation assumes that such a collision would prevent further progress or cause the feet to slip and detach. On the experimental robot, sometimes the feet slip or detach briefly without causing a fall, however the no-slip condition allows the simulation to make conservative predictions.

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 (which is sampled as described above). 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. Thus, when the joint is at 0.0, it coincides with the middle wheel-leg axle and when the body joint is at .5 it is halfway between the front and middle axle. We assume that the front wheel-leg is driven with respect to the front segment, and that middle and rear wheel-legs are in phase with the front wheel-leg but with respect to the rear segment.

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 from starting at the edge to a distance of $2\sqrt{2}$ below the edge, which represents the distance between foot falls of the four-spoked wheel-leg. 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 negative of 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. (Note that for an exterior-down transition, a similar measurement of the y-coordinate could be made.)

B. Simulation Results

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 normalized body joint location between .25 and .40 of the middle to front distance 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 body joint locations of .0625 and .125 is so severe, see Fig. 6. In this bar graph, the success rates of various milestone phases are 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. For around 90% of initial conditions and body joint positions, there is a way to get a foot onto the top surface. Group (b) shows the percentage conditions that allow the center of mass to achieve a positive x-value. This shows that if the body joint was located at .31 or .37, few initial conditions permitted the center of mass to cross the edge. This is an important phase because if the x value is positive, the robot will not tumble backwards. Group (c) shows the percentage that got the center of mass at least 1.5 over the edge. This corresponds to both the front and middle 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-value 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.

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

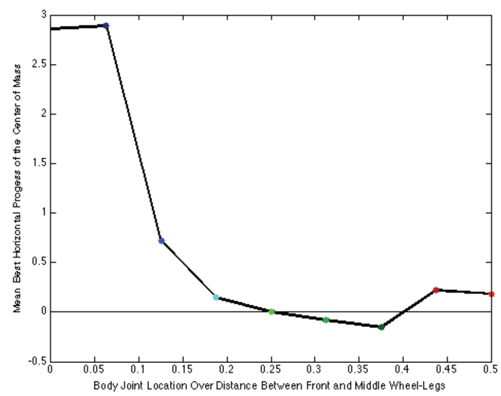

Fig. 5. The effect of the location of the body joint on the simulated progress averaged over initial conditions

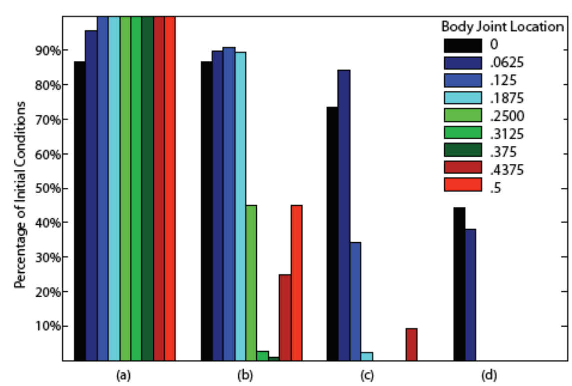

Fig. 6. The percentage of initial conditions resulting in various phases, (a) contacting the top surface, (b) having the center of mass cross 0, (c) getting the second wheel-leg past the corner, and (d) getting the center of the third wheel-leg past the corner.

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 since the body and wheel-legs may interfere with each other and servos generally have a small range of rotation.

The simulation results presented above predict that the optimal location for the body joint is close to the middle wheel-leg. In addition the types of collisions described above were observed to cause failures in the physical prototypes described in the next section.

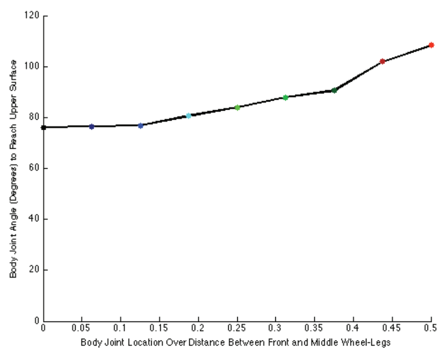

Fig. 7. The effect of body joint location on body joint angle required on average to bring the first wheel-leg down into contact with the top surface.

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. This 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 axle, 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. As in previous Whegs™ and Mini-Whegs™, a single central drive motor drives all the wheel-legs. 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 demonstrates that steering on a vertical surface is possible[13]. 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.

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*	0° (No body joint)	–45° to +45°	–180° to +45°
Successful 90° Transitions (Fig. 2)	Internal	Internal and external-down	All four types

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

Several sets of wheel-legs were tested on the robot. Three-spoke non-adhesive wheel-legs allow 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 [1]. These feet stick reliably to glass without slipping and can support the weight of the robot, so they are helpful for testing robot designs. Future versions may use novel structured adhesives[13].

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 (see Fig. 1a). 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

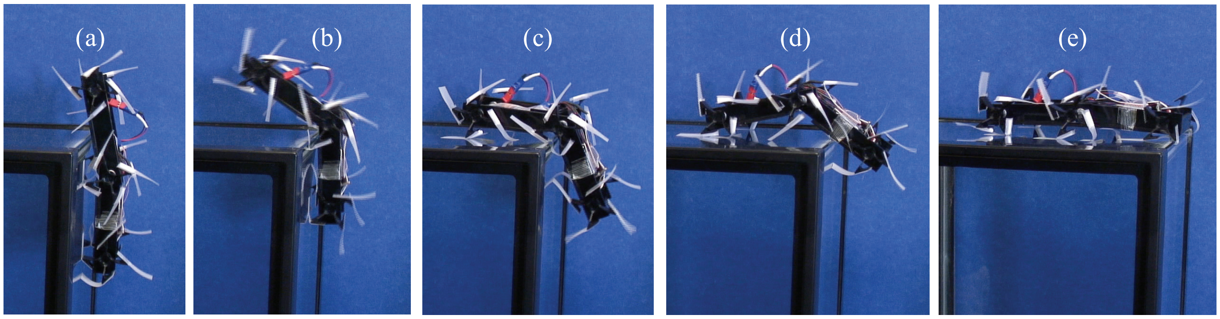

Fig. 8. Shows Climbing Mini-Whegs™ B00 making an exterior up transition.

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 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, allowing the middle legs to reach the surface when they otherwise cannot, as in Fig. 4e. See ICRA 2008 video proceedings submission: Making Orthogonal Transitions with Climbing Mini-Whegs™ for video of Climbing Mini-Whegs™.

VII. Conclusions

This two-degree-of-freedom robot makes exterior-up and exterior-down transitions with reduced-actuated gait and body joint inspired by cockroaches. Directly mimicking the location and range of a cockroach body joint, as in CMWB31, allowed the robot to traverse only some types of transitions. 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. Using a simple planar kinematic simulation, we were able to find a better body joint location for our robot type and determine the required range of the actuator. The second prototype, CMWB00, navigated orthogonal exterior transitions that, to our knowledge, no other biologically-inspired climbing robot can carry out. These methods could be used to optimize other design parameters of climbing robots for various environments.

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