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Design of a Wall-Climbing Hexapod for Advanced Maneuvers

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***Abstract*— A hexapod designed for wall climbing with a body joint and six 3-DOF legs can perform complex maneuvers such as sharp turns, making both interior and exterior transitions between vertical and horizontal surfaces, and traversing obstacles on both surfaces. This paper presents work toward the design and construction of the hexapod DIGbot, named for its utilization of Distributed Inward Gripping (DIG) to generate adhesive forces. The biologically-inspired DIG approach allows robots to climb on surfaces of any orientation with respect gravity, including ceilings, or in zero gravity environments.**

I. INTRODUCTION

There are very few natural terrains that cannot be traversed by legged animals. The ability to use obstacles as stepping stones is a valuable locomotion tool that few wheeled and tracked vehicles can match [1], [2]. Mobility is multiplied further if the animal can scale or climb up obstacles too large to step onto. A legged robot that climbs unstructured obstacles or vertical surfaces, combined with the ability to work in remote and hazardous environments, would be valuable for planetary exploration, military reconnaissance, and most immediately, time-critical search and rescue missions. This paper presents work toward the development of DIGbot, a wall-climbing hexapod designed to perform complex maneuvers. Figure 1 shows the SolidWorks CAD model of DIGbot.

Magnets [3], tape [4], suction [5] and microfiber pads [6] have been used on robots to generate the normal adhesive and shear tangential forces necessary to climb, but biologically-inspired directional attachment strategies have recently yielded promising results on a variety of rough surfaces [7], [8], [9], [10]. Directional attachment is performed by animals and robots using multiple foot styles with the common working principles that adhesion is 1) activated when the foot is pulled tangentially in a single direction along the surface, and 2) deactivated when the foot is pushed tangentially in the opposite direction [11], [12]. When hooks or spines are used (cockroach [13], SpinybotII [7]), an initial tangential force positions the hook into place such that large normal adhesive forces can be generated while the hook is held in place by a nominal tangential force. In the case of directional adhesive pads (gecko [12], Stickybot [8]), the normal adhesive force is a function of the tangential pulling force, so a significant pulling force must be maintained throughout the stride. In either case, the detachment force is not a function of the magnitude of the adhesion forces developed during the leg stride. This helps the animal or robot to detach its foot quickly, and without having to exhaust energy overcoming significant attachment forces. Clark et al. [14] rely on rapid and low-energy directional attachment on a robot designed to execute dynamic climbing.

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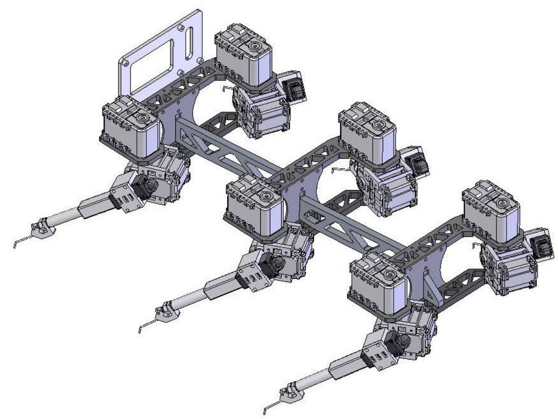
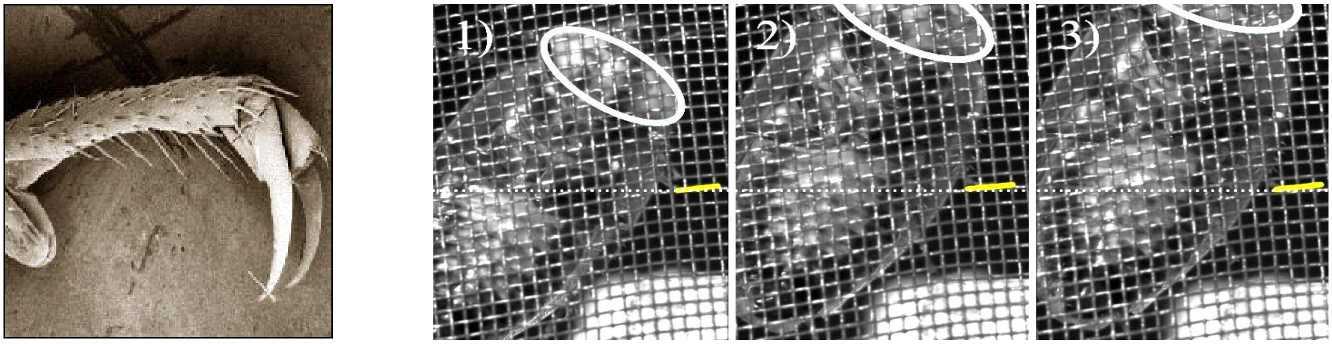


Fig. 1. DIGbot design. This hexapod is designed to perform complex maneuvers on a vertical surface using the DIG attachment strategy.

Robots SpinybotII [7] and Stickybot [8] use directional attachment to climb up vertical surfaces. SpinybotII has its micro array of spines arranged to oppose gravity and Stickybot has its structured adhesive pads arranged in the same manner. In both robots, the tangential force working to engage the attachment mechanism when climbing is the robot's own weight. This restricts the tangential shear force and hence the motion of the robot to only the vertical direction. Both robots benefit from the directional nature of each adhesive strategy by not requiring significant energy to detach the feet, and the success of these robots substantiates the viability of directional adhesion for robotic wall climbing.

Distributed Inward Gripping (DIG) advances the concept of directional attachment by directing legs on opposite sides of the body to pull tangentially inward toward the body. The shear forces oppose each other rather than the pull of gravity, allowing the robot to climb on surfaces of any orientation with respect to gravity, including ceilings. The authors of this work previously presented Screenbot [15] to verify the effectiveness of this strategy and now present



(a) (b)

Fig. 2. Subplot (a) shows the foot of a cockroach which includes spines and a claw [13]. Subplot (b) shows the movement of the cockroach body and middle leg when the claw is engaged. The head area of the cockroach is circled to highlight the direction of motion. The other highlighted area is the distal leg linkage of a middle leg, whose orientation remains unchanged throughout the motion of the body, suggesting that the direction of force also remains constant.

DIGbot, which is designed to further investigate DIG as a long-term attachment strategy for robust climbing. The RISE project [9], [10] also directs leg forces toward the body, and is able to climb vertically on trees, brick, and stone surfaces. The RISE project yields its most promising results in the study of foot design and its interaction with complex surfaces, while the DIGbot project predominantly aims to investigate maneuverability and transitions while climbing. Distributed Inward Gripping and the success of Screenbot are discussed below, followed by a description of DIGbot and its goals.

A. Distributed Inward Gripping

DIG is the biologically-inspired attachment strategy for climbing by which opposing legs pulling inward toward the body create increased shear at the foot and result in normal adhesion forces. This strategy was developed after observing the directional nature of the adhesive material on the feet of small climbing animals such as the beetle, cockroach and gecko. When the gecko leg applies a shear force in one direction, its adhesive feet also create the normal attachment forces needed to overcome the tipping moment caused by the mass at some distance from the wall [16]. This is true in only one direction of shear, as no normal forces are developed during motion in other directions. This helps the animal to detach its foot without having to overcome attachment forces. Cockroaches also use directionally-functional spines for attachment. Figure 2a shows the cockroach claw and spines.

Figure 2b shows the movement of the cockroach body and middle leg when using its claw. The head area of the cockroach is circled to highlight the direction of motion. The other highlighted area is the distal leg linkage of a middle leg. Note that the orientation of this linkage is unchanged throughout the motion of the body, suggesting that the direction of force also remains constant. The middle leg in Fig. 2b works in unison with the unpictured front and hind legs on the opposite side of the body as this cockroach employs the tripod gait.

Screenbot [15] was designed to test the effectiveness of DIG by using hooks to climb up and down vertically, walk inverted on a screen ceiling and cling passively in each orientation. Throughout the stride, sufficient tangential forces are directed toward the center of the body to continuously engage the hooks with the screen. These inward gripping forces are created by passive springs in each leg being pulled through an open-loop trajectory. The motor and mechanical linkages essentially form a pattern generator for the desired motion of the leg. Screenbot was only designed to move in a straight line, so all six legs have the same desired motion during their respective support periods. To operate effectively on multiple substrates, the open-loop trajectory required offline tuning.

B. DIGbot

DIGbot is made primarily from Delrin and 6061 aluminum. The body length measures 30 cm between the fore and hind hip locations and 12 cm between the right-side and left-side hips. Each of the six legs is made out of an L12 linear actuator from Firgelli Technologies, Inc. which can supply 40 N of linear force at 1.2 cm/sec. The L12 has a 5 cm stroke range and is mounted such that the leg length can vary between 6 and 11 cm. The total mass of DIGbot is approximately 2 kg. The top view of DIGbot is shown in Fig. 3.

Two rotational servo motors on each leg control protraction and retraction in the fore-aft direction, and vertical levation and depression. The protraction/retraction swing servos have a sweep limit of approximately 130 deg and the legs can depress completely underneath the body, which will be necessary for orthogonal transitions. The motors are AX-12 servos from Robotis Inc, and can deliver 118 $N-cm$ of torque from a 55 g package. The servomotors are interfaced using half-duplex serial communication to access multiple built-in advanced feedback capabilities such as position,

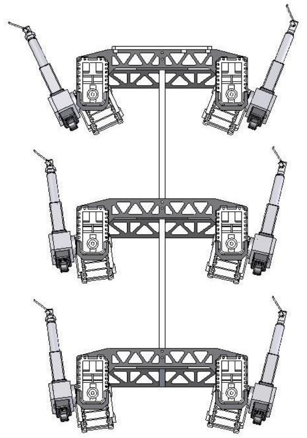


Fig. 3. Top view of the DIGbot design.

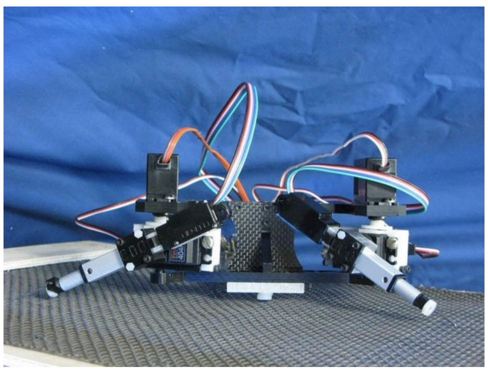


Fig. 4. Working prototype. The two-legged system shown produces inward gripping forces while turning the body on a flat screen surface, and has resulted in an improved foot design and servo interface strategy.

temperature, load and input voltage feedback in real time, and the ability to enforce a user-input torque limit.

Control of DIGbot is implemented onboard with the Servopod-USB microcontroller from NewMicros Inc. The controller board weighs $54\ g$ and is programmed using IsoMaxTM, a derivative of the Forth programming language. The board has outputs for to 26 PWM-controlled servomotors as well as 8 ADC converters.

Presently, preliminary tests are being performed on the 2-legged system shown in Fig. 4. The biped produces inward gripping forces while turning the body on a flat screen surface, and has resulted in an improved foot design and servo interface strategy. The control strategy for hexapod turns and transitions, and the description of the biologically-inspired foot design follows.

II. Advanced Maneuvers

DIGbot is being designed with the capability to perform climbing maneuvers more advanced than what other climbing robots are reportedly capable of doing. Initially, turns and transitions are investigated, and analysis done in preparation for these maneuvers follows.

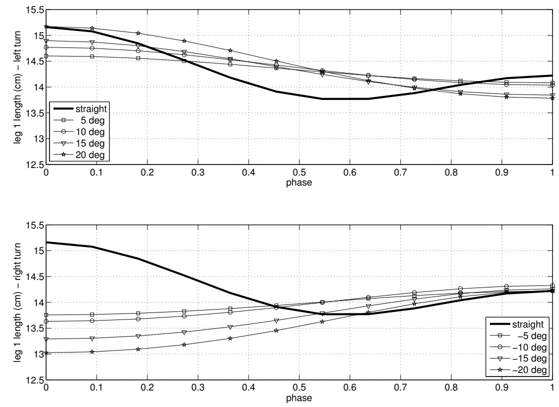


Fig. 5. Leg lengths during turning. A genetic search algorithm computed the front left leg lengths offline that turn the body to a choice of angles during one step. The function for the leg lengths is approximated online with a neural net.

A. Turns

Control of DIG requires that opposing legs maintain sufficient inward forces throughout the entire support period. Screenbot walked in multiple orientations with respect to gravity, but only in a straight line. This simple motion only required that a single leg trajectory be executed, and these trajectories were achieved through open loop position control of the leg length and the leg angle. No electronic feedback was required to maintain sufficient inward gripping.

Turning requires multiple trajectories and a more comprehensive strategy for computing these trajectories. Figure 5 displays the computed length trajectories of the left front leg for the body to turn in place. The top subplot shows the leg lengths needed to generate straight forward walking and turns to the left of 5, 10, 15, and 20 deg. A 20 deg turn means that the body's orientation turns 20 deg during one step, which is the motion produced by one tripod support period. The bottom subplot shows the leg lengths needed to generate the same body turns to the right. A genetic search algorithm generated these trajectories with the limitation that the leg length has a finite available stroke. Available stoke is determined by the kinematic limits of the servo system. The Firgelli linear servos used in this work have an available stroke length of $5\ cm$. From Fig. 5, the front left leg needs an available stroke of approximately $2.5\ cm$, measured from the minimum length in either turn direction to the maximum length in either turn direction, to execute turns from $-20\ deg$ to $20\ deg$.

The search is computed offline and the equations for the trajectories are approximated online by a neural net. A separate neural net is trained for each leg because the leg motions during turning are not similar. The two inputs for each neural net are the desired turn angle per step and the normalized phase of the support period. The normalized phase is a timer-generated counter from zero to one during the support period of each step. Once the neural net is trained for the 9 turn angles between $-20\ deg$ and $20\ deg$ shown in Fig. 5, the leg

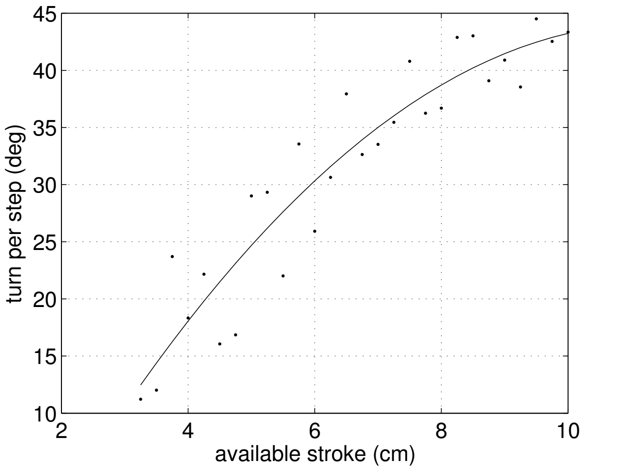
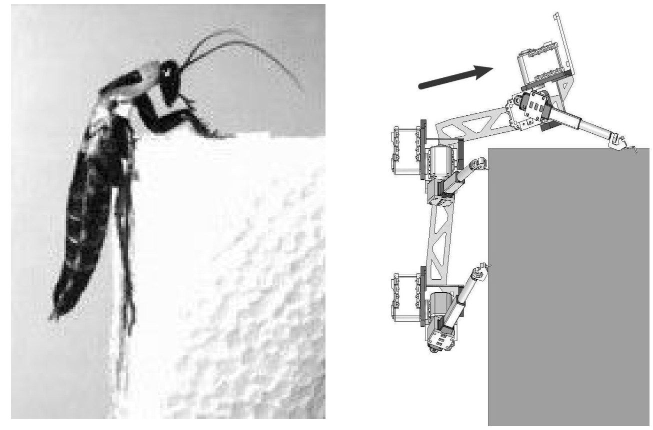


Fig. 6. Body turn achievable from available leg strokes. The available stroke of the leg length primarily dictates how much turn the body can undergo in a single step. DIGbot uses Firgelli actuators with 5 cm of stroke, for which trajectories can be computed to turn the body 25 deg is one step.



(a) (b)

Fig. 7. Using a body joint during exterior transitions. The DIGbot design takes inspiration from a cockroach which flexes the body joint forward during an external transition to lower the front legs toward the body.

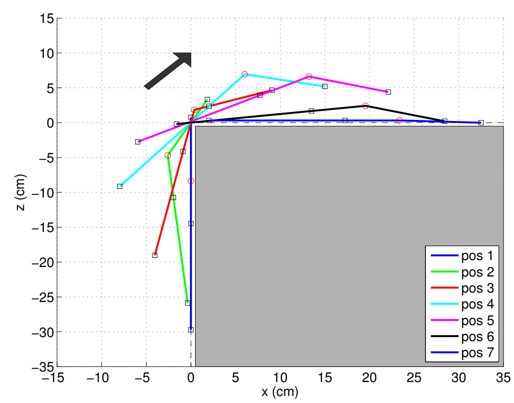


Fig. 8. Hexapod transition. Seven of the computed body positions between the initial vertical position (pos 1) and the final horizontal position (pos 7).

trajectory for any turn angle in that range can be calculated. Trajectories are similarly computed and emplemented for the protraction/retraction and levation/depression actuator of each leg.

The search algorithm was expanded to compute the maximum angle of turn the body could achieve for a given available leg stroke. Figure 6 shows this data for strokes between 2.25 cm and 10 cm, fitted with a quadratic trend line. The Firgelli linear servos can be purchased with a maximum stroke of 2, 3, 5, or 10 cm. The 5 cm actuators on DIGbot allow for turns up to approximately 25 deg per step, which is comparable to cockroach turns which were measured to peak at approximately 20 $deg/step$ [17].

B. Transitions

DIGbot is also designed to make interior and exterior transitions between orthogonal surfaces. Taking inspiration from biology, as shown in Fig. 7a, the cockroach flexes its body joint forward during external transitions to lower the front legs toward the surface. During interior transitions, the body joint is flexed backward to bring the middle legs closer to the surface. Lowering the head during exterior transitions also moves much of the body mass closer to the surface, reducing the normal forces needed at the feet.

The strategy to compute the desired body motion for an orthogonal transition attempts to reduce the leg lengths necessary for the maneuver. As stated previously, available stroke is limited, so keeping the body hip locations close to the wall decreases the leg length needed to maintain contact with the surface. Figure 8 shows the saggital plane view of the body as it ascends over an exterior transition. The legs are not shown because the goal of this analysis is only to compute the hip locations – leg trajectories can be generated after the body motion has been optimized.

An iterative brute-force search algorithm computed the trajectory of Fig. 8 given the body length, location of the body joint and the maximum joint angle. The angle of the body joint is 0 deg when the system is flat, and the maximum joint angle is a design parameter based upon kinematic constraints. For clarity, only a fraction of the computed positions are shown. In Fig. 8, DIGbot's 30 cm length is used, 60 deg is the maximum joint angle, and the body joint is located at a distance 30$\%$ of the way from the head to the rear of the system. The maximum hip-to-wall separation, or hip height, for this transition is approximately 8 cm and occurs in position 4.

Figure 9 shows the maximum hip height during an exterior transition for a range of maximum joint angles (60, 90, 120, and 150 deg) and body joint locations. The location of the body joint is moved from the head (no joint) at 0% to the body's fore-aft bisector line at 50%, where the middle legs are mounted, and the resulting maximum hip height is shown as a percentage of the body length. It is clear that for any maximum joint angle, placing the body joint toward

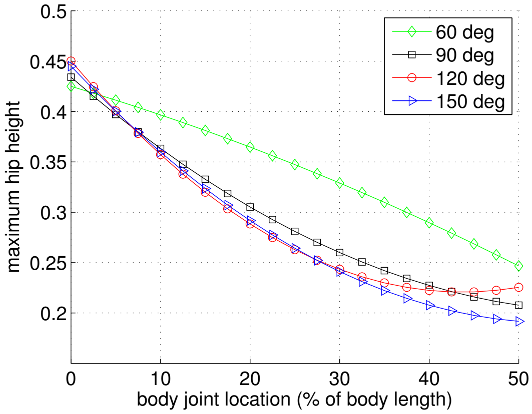


Fig. 9. Maximum hip height during an exterior transition. Each line represents the maximum hip heights that results for one of the maximum joint angles 60, 90, 120, or 150 *deg*. For each maximum joint angle, the resulting hip height is decreased when the body joint location is moved toward the center of the body.

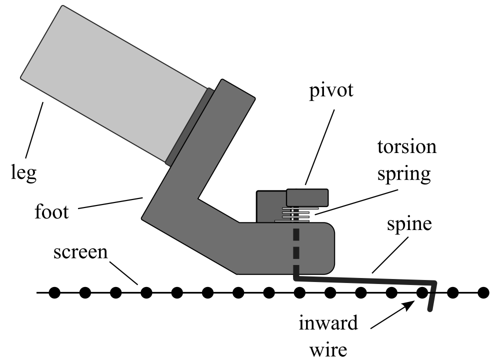


Fig. 10. Model of the foot mechanism. The leg is pulled left during the stance phase, causing the spine to seek the inward wire and develop a gripping force. When the spine is removed from the screen, the torsion spring returns the spine to its original angle.

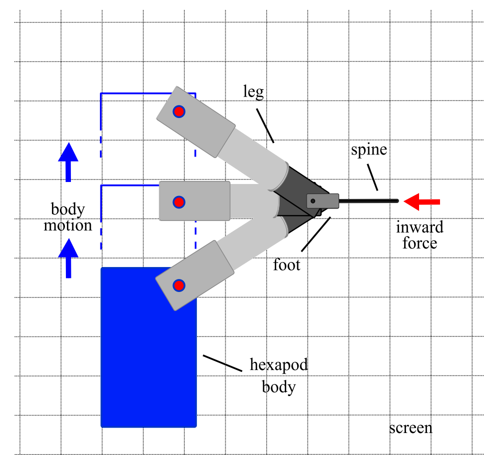


Fig. 11. Leg motion through the support period. As the body moves through a step, the angle of the leg changes with respect to the desired inward force and the spine rotates about its pivot to maintain the desired orientation.

the center of the body reduces the maximum hip height during the transition. This matches the results from another wall-climbing vehicle, Climbing Mini-Whegs [18], that was able to maneuver over exterior transitions with a body joint. Figure 7b shows the projected location of the body joint on DIGbot.

III. Foot Mechanism

Directional attachment stipulates that the foot should only produce a gripping force when pulled from a single direction, and DIG further stipulates that the direction of pull be in opposition to the contralateral legs. Figure 10 shows the foot assembly utilized by DIGbot. The leg is pulled left during the stance phase, causing the spine to seek the inward wire and develop a gripping force. As the body moves through a step, illustrated in Fig. 11, the angle of the leg changes with respect to the desired inward force and the spine rotates about its pivot to maintain the desired orientation. When the spine is removed from the screen, the torsion spring returns the spine to its original angle. The pivot acts as a passive wrist as the DIGbot foot successfully mimics the distal link motion displayed in Fig 2b.

The constant angle of the spine with respect to the screen will allow each foot to have multiple rigid spines in an array or forked arrangement over which the load can be spread. Each spine can be simultaneously engaged with the screen because no rotation with respect to the screen occurs during the support period. A foot with multiply-engaged spines reduces the load on each spine, allowing the spines to individually become smaller so that smaller asperities on a vertical surface can be exploited as footholds. This drives the success of the previously-mentioned SpinybotII [7] and the RISE vehicle [9], which climb vertically up stucco and brick surfaces.

IV. Summary

This paper presented design features of DIGbot and analysis toward the control of DIGbot making sharp turns and maneuvering over exterior transitions. DIGbot is named for its use of Directional Inward Gripping (DIG) to generate the normal adhesive forces and tangential shear forces required for wall climbing. DIG incorporates the principles of directional attachment, which produces attachment forces only when the foot is pulled tangentially in a single direction. Presently, robots incorporate directional attachment by using the weight of the body to produce the tangential forces necessary to activate the feet. This restricts body motion to only the vertical direction. Distributed Inward Gripping (DIG) advances the concept of directional attachment by directing legs on opposite sides of the body to pull tangentially inward toward the body. The shear forces are opposed by the contralateral legs rather than the pull of gravity, which will allow DIGbot to climb on surfaces of any orientation with respect to gravity, including ceilings.

DIGbot is designed for robust climbing on vertical terrains. A robot with its range of leg motion and attachment strategy

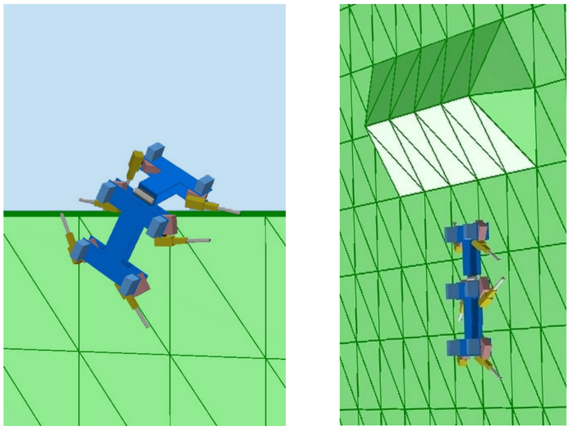


Fig. 12. Complex climbing maneuvers to be investigated in the future. On the left, DIGbot approaches the transition with its body not squarely aligned to the transition. On the right, DIGbot is faced with an obstacle to navigate over. Both of these maneuvers are presently unsolved by robotics researchers but readily accomplished by climbing animals using DIG.

should be able to ascend over orthogonal transitions when the body is not squarely aligned with the transition and over obstacles on the vertical surface. These maneuvers, shown in Fig. 12, are just two of the many maneuvers unachievable by previous climbing robots. These images of DIGbot are taken in RobotBuilder [19], a robot simulation environment built upon the DynaMechs [20] dynamics engine for general robotic systems.

V. ACKNOWLEDGMENTS

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