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DESIGN ASPECTS OF A CLIMBING HEXAPOD

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The movement capabilities of a climbing animal or robot largely depend on its attachment/detachment strategy and the workspace of its legs. Design aspects of the 18 degree-of-freedom hexapod DIGbot are presented in this work. DIGbot is named for its usage of the biologically-inspired Distributed Inward Gripping (DIG) attachment strategy to walk on mesh screen in any orientation with respect to gravity. DIG utilizes contralateral legs pulling inward toward the body to activate directional attachment mechanisms, and allows DIGbot to climb vertically.

1. Introduction

The ability to scale vertical surfaces and walk on inverted ceilings greatly extends the mobility of insects and many other small animals [1]. Robots that could achieve similarly rapid and robust locomotion in any orientation with respect to gravity have uses such as military reconnaissance and time-critical search and rescue. This work seeks to further investigate the biologically-inspired Distributed Inward Gripping (DIG) attachment strategy through its application on DIGbot, shown in Fig. 1.

DIG was previously shown viable for straight walking on vertical and inverted mesh screens [2], and is now applied to an 18 degree-of-freedom hexapod designed for complex maneuvers such as sharp turns and transitions between orthogonal surfaces. DIG utilizes contralateral legs pulling inward toward the body to activate directional attachment mechanisms. When climbing vertically, fore legs must provide tensile normal force and hind legs must provide compressive normal force to prevent an animal, or robot, from pitching

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back from the wall. Directional attachment provides these normal forces when pulled tangentially to the surface in a single direction. To detach these mechanisms, the system must only push in the opposite tangential direction. This attachment strategy has been observed in cockroaches [3], geckos [4] and beetles [5]. Figure 2a shows a cockroach claw and spines, and 2b shows the DIGbot spine. When the claw is pulled inward toward the center of the body, it engages with the surface and allows for normal attachment forces during climbing. DIG can be energetically inexpensive and very rapid because the directional attachment mechanisms can support a large amount of normal force during a step without needing to overcome this force to detach the foot.

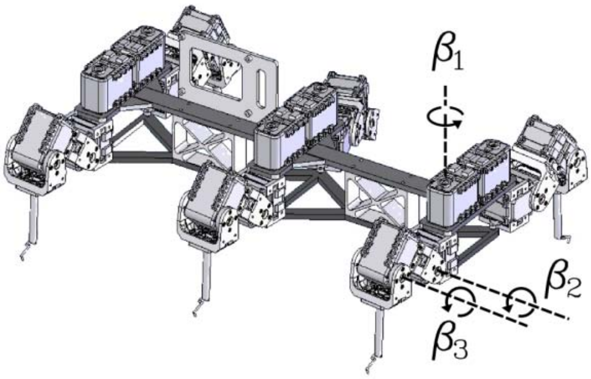
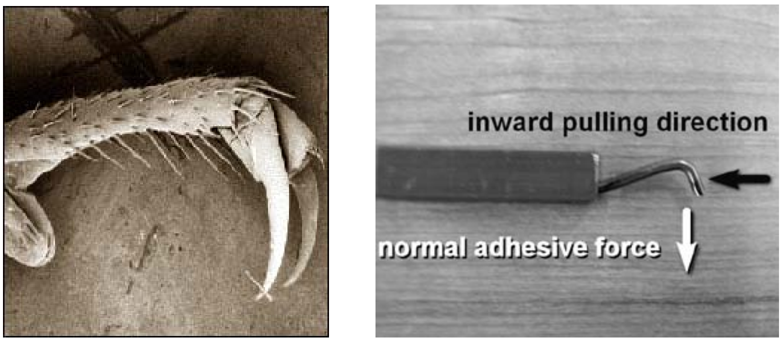


Figure 1. SolidWorks CAD model of DIGbot. Each of its legs has 3 actuated degrees of freedom to position the foot through rotations about β_1, β_1, and β_3.



(a) (b)

Figure 2. a) Cockroach claw used to grip tangentially inward toward the body during climbing. b) DIGbot mimics this attachment strategy using a spine.

Robots SpinybotII [6] and Stickybot [7] use directional spines and dry adhesives respectively to climb vertically. The RISE robot [8] also uses spines pulling inward to climb vertically up trees, brick and stone surfaces. These robots show promising work in the area of control architecture, leg mechanisms, and attachment processes. The objective of the work presented here is to perform complex motions such as sharp turns on vertical and inverted surfaces, and transitions between these surfaces. These and other advanced climbing maneuvers require an attachment strategy that does not rely on a particular robot orientation with respect to gravity, and DIG is such a strategy.

2. DIGbot

DIGbot measures 36 *cm* long between the fore and hind hip locations and 8 *cm* between the right and left-side hips. The mass of DIGbot without onboard power is 1.5 *kg*. Onboard processing is supplied by a 200 MHz ARM single board computer. Each of the six legs has three independent degrees of freedom, each controlled by a Dynamixel AX-12 (Robotis Inc.) servomotor interfaced using half-duplex serial communication to access real time feedback capabilities such as position, speed and load. One servo controls fore-aft leg protraction and retraction through motion β_1 in Fig. 1, while the two remaining servos control levation and depression of the foot through motions β_2 and β_3.

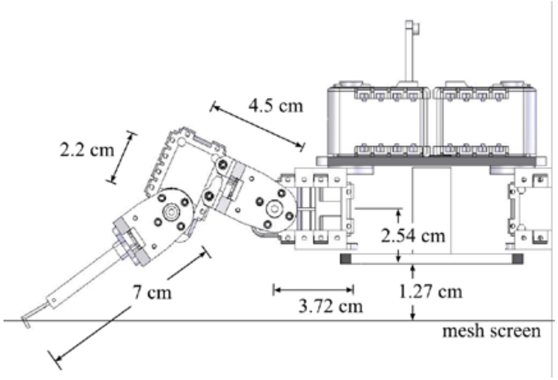


Figure 3. Front plane view of a DIGbot leg.

Figure 3 shows the measurements of DIGbot leg segments. Given the undercarriage clearance of 1.27 cm, the leg can reach the screen at distances between 6 *cm* and 15 *cm* from the hip. This reach allows the robot to move forward up to 19 cm per step or turn in place up to 37 *degrees* per step.

DIGbot walks using the alternating tripod gait, which is the fastest hexapod gait. In this gait, the middle leg on one side of the body remains in phase with the fore and hind legs on the opposing side of the body. During stance, the inward attachment force created by the middle leg is opposed by the inward forces of the contralateral fore and hind legs such that the net force on the body due to gripping does not cause lateral motion.

3. Distributed Inward Gripping (DIG)

DIGbot climbs on a mesh screen, which mimics rough natural terrains, by searching for an adequate foothold around the initial touchdown position of the foot. After lowering the spine into a screen spacing, DIGbot pulls each foot tangentially inward toward the body in search of the screen wire. Each foot is commanded to pull inward a distance of 2 *cm*. The mesh screen being used has a lateral spacing of 1 *cm* between columns, so the spines are guaranteed to engage the screen regardless of where the foot is initially placed.

Figure 4 shows a model of the top view of the body and leg positions before (solid) and after (dashed) a stationary turn. The shaded arcs represent the workspace for the DIGbot spines at the screen depth. The outer space of each arc is reserved for the inward lateral motion required to seek the screen and engage the spines. Offline planning is used to compute leg motions for maneuvers while constraining the feet to remain within the inner space. The size and shape of this inner area dictate the body motion achievable in one step. The leg trajectories are programmed into the control system using neural networks.

Forces f_1, f_2 and f_3 in Fig. 4 represent the inward foot forces created by DIG during stance. These forces may change direction with respect to the body during stance, but do not change direction with respect to the surface. This is desirable on natural terrain where footholds may only support significant forces in limited directions.

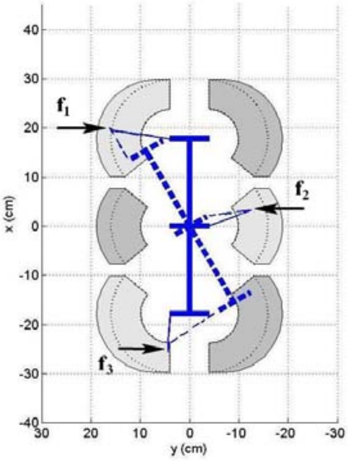


Figure 4. Top view of the initial (solid) and final (dashed) body and leg positions to execute a 30 degree stationary turn in one tripod step. Shaded areas represent the range of motion for each leg.

Figure 5 shows DIGbot climbing vertically and clinging inverted on a screen, with a close-up of the interaction between a spine and the surface.

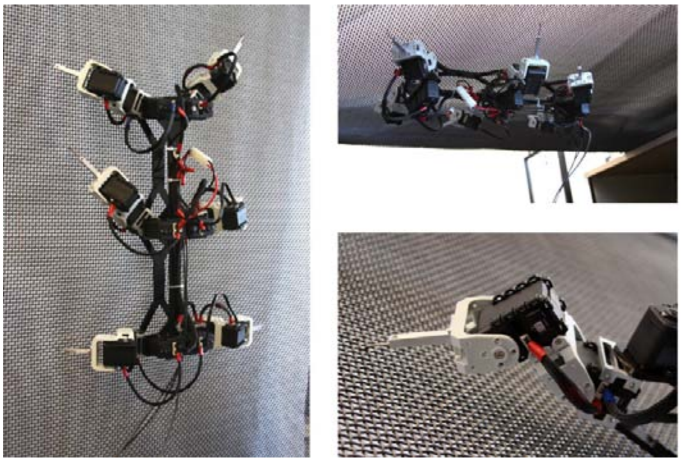
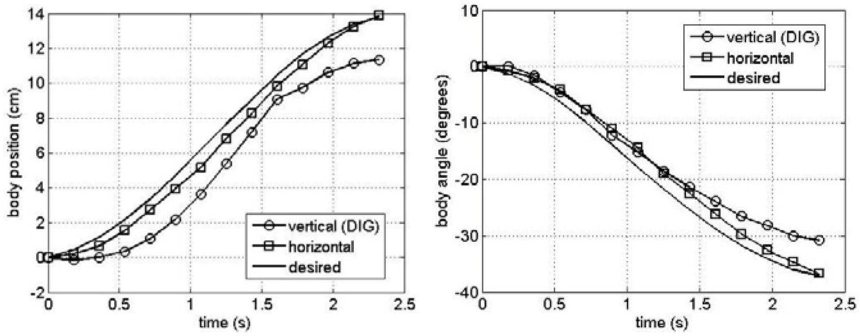


Figure 5. DIGbot climbing vertically (left) and clinging inverted (right, top). Right, bottom shows a leg interacting with the screen.

4. Results

Figure 6a displays the body motion of a forward walking step on a horizontal surface without DIG, and a forward step on a vertical surface using

DIG. The body is commanded to walk smoothly through a step in 2.3 *seconds*. The horizontal step exhibits a delay and negligible error at the end of the step, and the vertical step results in an error of approximately 2.3 *cm*. Figure 6b shows the body angle during a stationary turn. A similar delay appears during horizontal walking, and the vertical turn results in an error of approximately 6 *degrees*.



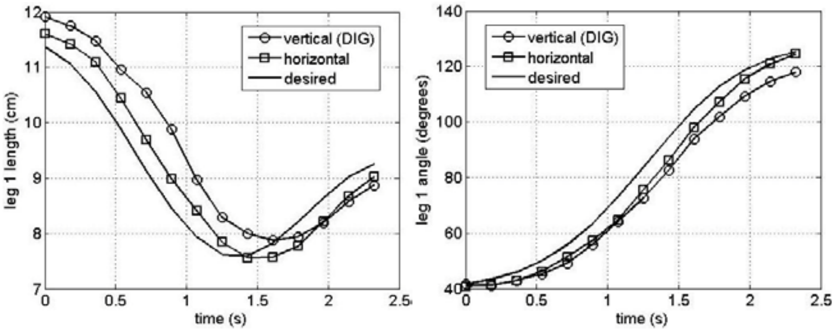
(a) (b)

Figure 6. Body motion for a single forward step (a) and stationary turn (b). DIG is enabled for vertical climbing.

In both subfigures, the horizontal step more closely matches the desired body motion. This is expected because of the inward gripping strategy, which commands the legs to search inward up to 2 *cm* to engage the spines. Because the mesh wires are spaced only 1 *cm* apart, the spines always engage before the full inward stroke is achieved. The remaining position error creates the inward force necessary to maintain spine engagement during the step. This error propagates during the step and contributes to the error in final position. Search distances smaller than 2 *cm* result in occasional spine disengagement during the step. Increasing the search distance above 2 *cm* results in larger inward forces at the foot and higher than necessary motor torques. Additionally, increasing the search distance reduces the workspace available to compute walking trajectories, limiting the maximum step distance and turning angle.

The body error can also be attributed to the coupling of posture and motion forces during vertical climbing. While walking on horizontal terrain, the vertical forces used to oppose gravity and maintain posture are decoupled from the horizontal forces that generate the desired motion. During vertical climbing, postural and motion-generating forces are both vertical, so the inability of DIGbot to perfectly oppose gravity appears as motion error in Figs 6a and 6b. In both the forward and turning step, however, transient motion remains smooth and DIGbot achieves the desired position and angle within approximately 15% of the desired value.

Figures 7a and 7b show the length and rotation of leg 1 during the forward walking step of Fig. 6a. Leg length is measured in the transverse plane from the hip to the foot, and leg angle is measured from the fore-aft axis of the body to the line connecting the hip and foot.



(a) (b)

Figure 7. Length and rotation of leg 1 during a forward walking step on horizontal and vertical terrain. During vertical climbing, leg motions remain smooth and lead to smooth body motion during the step.

5. Summary

Distributed Inward Gripping (DIG) is utilized by animals to achieve rapid and robust movement on a variety of terrains and in any orientation with respect to gravity. DIGbot is designed to further test the DIG strategy climbing vertically and inverted on mesh screen using cockroach-inspired spines. DIGbot is designed to walk vertically and inverted on mesh screen. The robot currently walks vertically and will soon employ a body joint to make transitions between orthogonal surfaces. Ultimately, smaller versions of DIGbot can utilize gecko-inspired, dry adhesive foot pads for rapid motion on both smooth and rough surfaces.

Future work will also include force feedback at the feet to optimize the gripping force throughout the stride. Overgripping uses more power than necessary and undergripping leads to premature spine disengagement. Optimized gripping will also increase battery life during climbing.

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