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Toward a Rapid and Robust Attachment Strategy for Vertical Climbing

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Abstract— **This paper is an update on the investigation of Distributed Inward Gripping (DIG) as a rapid and robust attachment mechanism for vertical and inverted climbing. DIG is implemented on an 18-DOF hexapod, DIGbot, with onboard power and control system. Passive compliance in the foot, which is inspired by the flexible tarsus of the cockroach, increases the robustness of the adhesion strategy and enables DIGbot to execute large steps and stationary turns while walking vertically on mesh screen. Results of vertical climbing are shown.**

I. INTRODUCTION

VERY few terrains on Earth cannot be traversed by an animal with legs. The ability to use obstacles as stepping stones is a valuable locomotion tool that few wheeled and tracked vehicles can match. Further, there is a class of legged animals that can scale up obstacles too large to step onto, and yet another class of climbers that can walk and run on surfaces with any orientation with respect to gravity, such as inverted on a ceiling or sideways on a vertical wall. Robots that could achieve rapid and robust locomotion in any orientation with respect to gravity will play a valuable role in time-critical search and rescue and many other critical tasks.

Several legged robots have effectively scaled vertical surfaces [1], [2], [3], [4], [5], [6] but most can only travel upward, some of which rely on gravity to oppose attachment mechanisms, and only a few can make sharp turns. This work further investigates the biologically-inspired Distributed Inward Gripping (DIG) attachment strategy, which allows legged robots to walk in any direction on surfaces with any orientation with respect to gravity, including inverted on a ceiling. Specifically, this paper describes the use of passive compliance in the foot to improve the performance of the adhesion strategy and enable the robot to execute large steps and stationary turns on a vertical surface, and presents results of climbing in multiple orientations with respect to gravity.

Figure 1. DIGbot is shown posed statically on chain-link fence. This 18-DOF hexapod is designed to perform complex maneuvers on a vertical surface using the Distributed Inward Gripping (DIG) attachment strategy.

DIG was previously shown viable for straight walking on vertical and inverted mesh screens [7], and is now applied to an 18 degree-of-freedom (DOF) system, DIGbot (Fig. 1), designed for more complex maneuvers such as sharp turns and transitions between orthogonal surfaces. DIGbot primarily climbs on a mesh screen, which mimics rough natural terrains by requiring the system to search for an adequate foothold around the initial touchdown position of the foot.

Figure 2 shows the bending of a cockroach tarsus from touchdown to a mid-point during a step [8.] The passive compliance allows the cockroach leg to change orientation with respect to the ground without changing the direction of the ground reaction force. Because of this capability, the cockroach only needs to test the strength of a foothold in a single direction. Once the foothold is established, the compliant tarsus ensures that force is primarily applied in this direction as the cockroach executes a step. This passive mechanism provides a simple and lightweight solution to a problem that would otherwise require additional actuation and sensing at the distal end of the leg. Passive compliance has been added to the DIGbot foot to achieve these same results. An added benefit of this passive compliance is the

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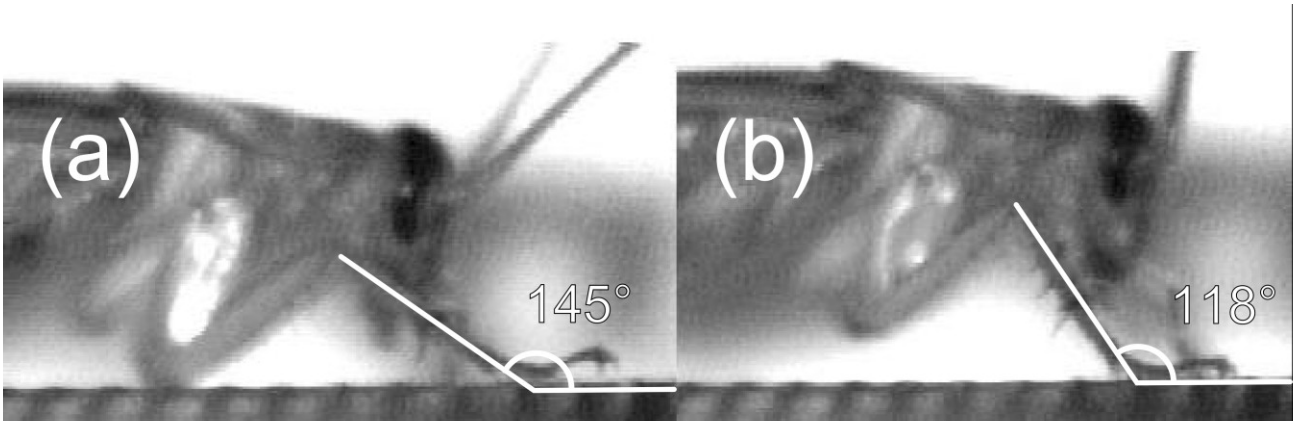

Figure 2. Passive bending of the cockroach tarsus from touchdown to a mid-point during a step (originally presented in [8]). The passive compliance allows the cockroach leg to change orientation with respect to the ground without changing the direction of the ground reaction force. During this part of the step, the leg angle with respect to the ground changes by 27 *deg* and the tarsus angle passively bends to facilitate this motion. These photographs were taken from high-speed video of a running cockroach.

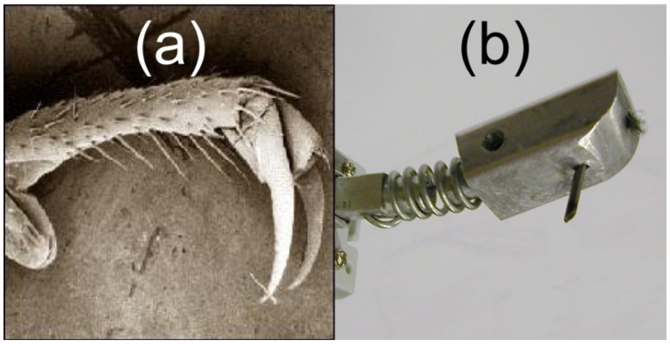

Figure 3. Subplot (a) shows a cockroach claw and spines [3]. Subplot (b) shows the DIGbot claw. When the claw is pulled inward toward the center of the body, it engages with the surface and is capable of supporting normal attachment forces during climbing.

ability to attach and detach from the screen using a very simple algorithm.

The RISE project [6] has had great success in climbing vertically on smooth and coarse surfaces with passive compliance in the feet that serve a different purpose. The compliance allows for multiple spines in the feet to independently move normal and tangential to the surface during the search for small asperities to use as attachment points. The RISE project also seeks to achieve motion on vertical surfaces with reduced actuation, two actuated degrees of freedom per leg, whereas DIGbot is designed with three degrees of freedom per leg. Although engineering optimizations were used in the design of DIGbot, the primary purpose of this project is to evaluate DIG during complex maneuvers, and a leg that could achieve 3D motions better serves this purpose.

A further description of Distributed Inward Gripping is presented next. This is followed by a description of DIGbot and the flexible tarsus. Results for vertical climbing are then shown, and the paper concludes with some discussion.

II. DISTRIBUTED INWARD GRIPPING

Distributed Inward Gripping (DIG) utilizes contralateral legs pulling inward toward the body to activate directional attachment mechanisms. These mechanisms, which exist in many forms, only provide attachment forces normal to the terrain when pulled tangentially in a single direction. Forces normal to the surface are required to keep an animal, or robot, from pitching backward. Unlike other adhesives such as tape, sticky pads, or Velcro®, directional attachment does not require an applied normal force during attachment or detachment, which could push the body away from the surface. To disengage, the foot must only be pushed in the opposite tangential direction. This type of attachment strategy has been observed in wall-climbing insects [7], flies [13] and geckos [14]. Figure 3a shows a cockroach claw and spines [3], and 3b shows the DIGbot spine. When the claw is pulled inward toward the center of the body, it engages with the surface and is capable of supporting normal attachment forces during climbing. Using DIG, the activating forces for the attachment mechanisms are produced internally through the robot's mechanisms, instead of using gravitation pull. This is precisely what allows DIG-based robots to climb on surfaces with any orientation with respect to gravity and potentially in zero-gravity scenarios.

Spines and mesh screen are used to demonstrate DIG because they rely on well-understood friction and interlocking principles, as opposed to the adhesion models being developed for microscopic adhesive materials. These other types of directional adhesion, such as microstructure polymer adhesives [9], [10], [11], [12] are being developed to operate on a more versatile set of substrates, but rely largely on the same principles observed in this work with spines and mesh screen. The algorithms and peripheral attachment mechanisms developed in this work, such as DIG and the biomimetic passive tarsus, are designed to be applicable for climbing with these microstructure adhesives as well.

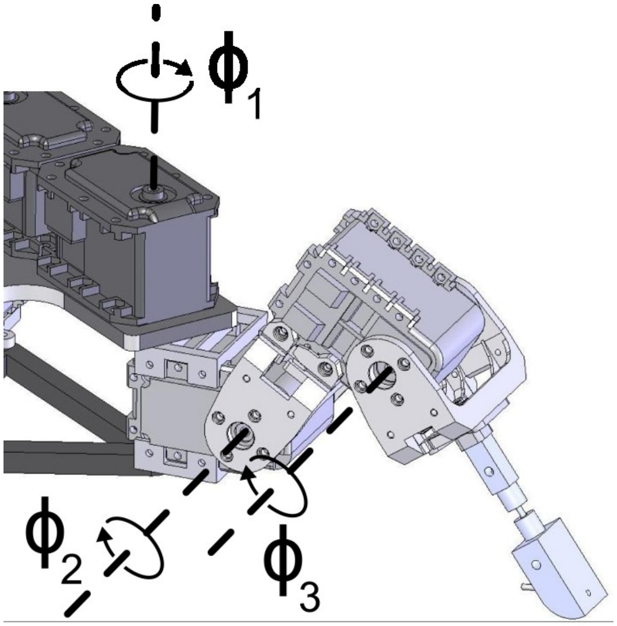

Figure 4. Each of the hexapod legs is identical, containing three actuated degrees of freedom. One servo controls fore-aft leg protraction and retraction through motion φ_1, while the two remaining servos control levation and depression of the foot through motions φ_2 and φ_3.

Directional attachment stipulates that the foot should only produce a gripping force when pulled from a single direction, and DIG further requires that the direction of pull be in opposition to the contralateral legs. In order to properly maintain spine adhesion during stance, the foot and spine must be angled perpendicular to the sagittal plane of the robot. The leg is pulled inward during the stance phase, causing the spine to seek the inward wire and develop a gripping force. As each leg actuates the body through a step, the leg angle changes with respect to the desired inward gripping direction and the foot must rotate about its ankle to maintain the desired orientation.

III. DIGBOT

A. Hexapod Parameters

DIGbot measures 36 *cm* long between the fore and hind hip locations and 8 *cm* between contralateral hips. The mass of DIGbot with onboard power and control system is 1.8 *kg*. Processing is supplied by a 200 MHz ARM single-board computer (TS-7260 from Technologic Systems) running C code in the Linux operating system. Each of the six legs has three independent degrees of freedom controlled by Dynamixel AX-12 servomotors (Robotis Inc.), diagrammed in Fig. 4. One servo controls fore-aft leg protraction and retraction through motion φ_1, while the two remaining servos control levation and depression of the foot through motions φ_2 and φ_3. These motors are interfaced using half-duplex serial communication to access real-time feedback capabilities such as position, angular rate and current consumption.

DIGbot walks using the alternating tripod gait, keeping the middle leg on one side of the body in phase with the fore and hind legs on the opposing side of the body. During stance, the inward gripping force created by the three legs is such that the net force on the body due to gripping only causes negligible lateral motion. The tripod gait is the fastest hexapod gait, but requires that each foot maintains adhesion throughout the entire step.

B. Flexible Tarsus

The foot design allows for passive spine reorientation using a sprung tarsus joint. The flexible two-DOF tarsus joint is made of three key segments; a stainless steel spine which is embedded in an aluminum foot, which is attached with a sprung joint to the rest of the leg. The aluminum foot geometry is such that the face of the foot containing the spine can be presented prone to the substrate for any leg approach angle. This allows the spine length and orientation to be optimized for a single foot-substrate angle

After lowering the spine into a screen spacing, each foot is commanded to servo a distance of 2 *cm* laterally inward toward the body's left-right bisector. The mesh screen being used has a maximum lateral spacing of 1 *cm*, so the foot is guaranteed to engage the inward spine regardless of where it was initially lowered into the screen spacing, and an inward force results from the remaining error. The inward force bends the passive tarsus element toward an angle perpendicular to the bisector, such that regardless of the leg angle with respect to the body, the foot always achieves the same perpendicular orientation relative to the body.

After inward gripping is initiated, the inward force is checked by reading the three motor torques of each attaching leg. If the inward gripping force is above a chosen threshold for each leg, the tripod is ready to bear the weight of the robot. Once this is confirmed, the opposite tripod disengages and DIGbot is moved through a step. When the spine is removed from the screen, the passive spring returns the foot to its default straight angle in preparation for the next step.

The two tarsus degrees of freedom are shown in Fig. 5. The arrow in each subfigure shows the inward gripping direction. Fig. 5a shows rotation through the tarsus vertical angle to two positions encountered during walking and turning. Fig. 5b shows the rotation through the tarsus swing angle in two positions. The torsional spring constant for the compliant tarsi is 0.21 Nm/s. Notice that in each subfigure, the foot remains oriented with the inward gripping direction in both of the shown leg orientations. These two angles represent the relative position of the foot and resulting inward gripping force with respect to the leg.

The control algorithm for body motion is not included here because it is beyond the scope of this paper, but is described in [15.] Simply, feedforward leg trajectories that produce the desired body motion are computed offline and approximated online using neural networks. The leg trajectories are computed based upon the starting positions of the feet. The leg trajectories are only computed once, immediately before retraction begins, and cannot adjust to spines slipping from the touchdown screen space to an inward space. The flexible tarsus drastically reduces the

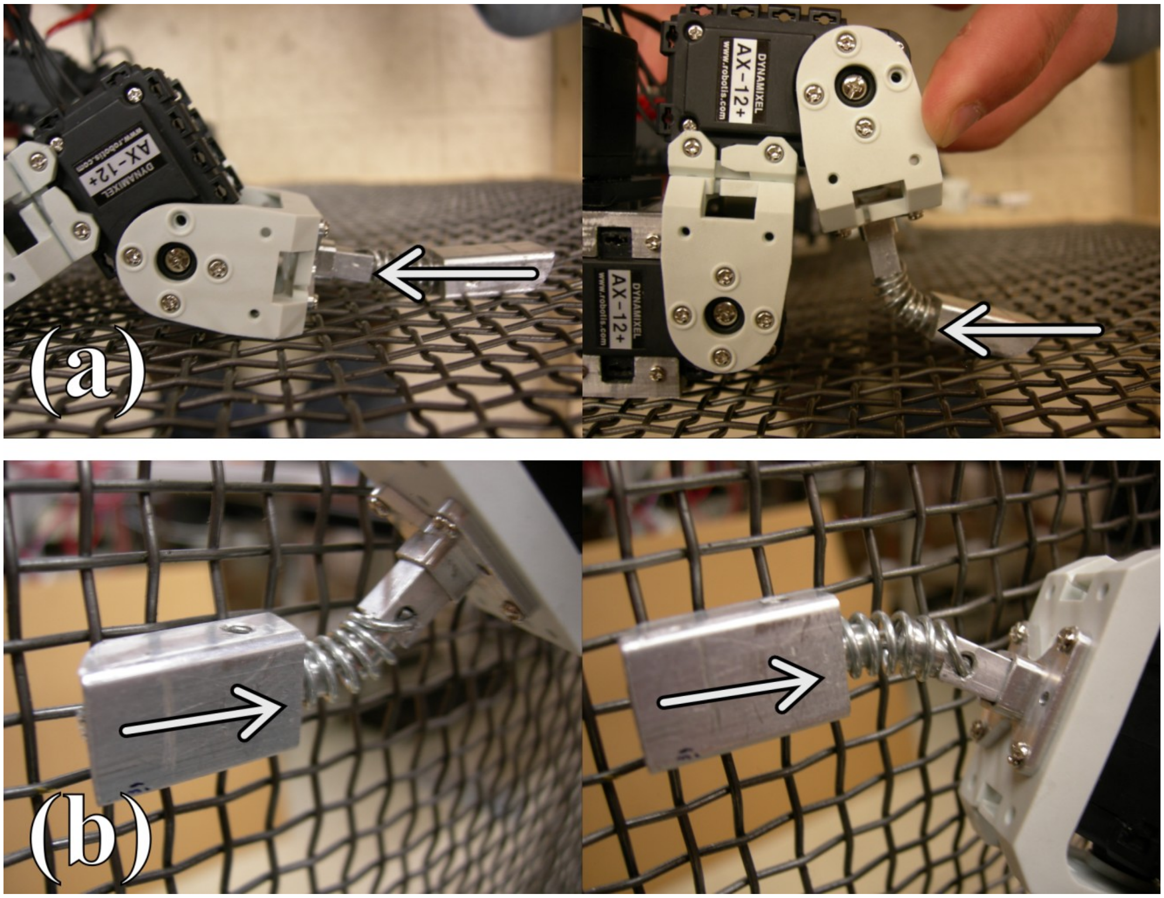

Figure 5. As the body moves through a step, the angle of the leg changes with respect to the desired inward force, and the spine rotates about its pivot to maintain the desired inward gripping direction. The arrow shows the direction of inward gripping in each subfigure. Subplot (a) shows rotation through the tarsus vertical angle to two positions encountered during walking and turning. The type of flexibility is similar to what is observed in Fig. 2. Subplot (b) shows the rotation through the tarsus swing angle.

frequency of inward slipping during forward steps and stationary turns, and assists the system in overcoming the slippage when it occurs. The stiff foot previously described in [16] could rarely overcome the slipping, which occurred more frequently using those feet. Results of DIGbot climbing are presented next.

IV. RESULTS

A. Tarsus Angle

DIGbot successfully climbs on vertical screen using Distributed Inward Gripping. Tarsus deflection angles for a tripod set during a stationary turn are shown in Fig. 6. The left subplot shows the tarsus vertical angle, which is kinematically measured from the nominal straight position. This angle is indirectly proportional to the radial length of the leg. Longer leg lengths require smaller amounts of tarsal bending (see left subplot of Fig. 5a). For foot positions closer to the hip, the tarsus vertical angle becomes larger as the tarsus spring bends more sharply (right subplot of Fig. 5a). Similarly, the right subfigure in Fig. 6 shows the tarsus swing angle. This angle varies as the leg protracts or retracts while in contact with the screen (Fig. 5b). These two angles represent the two orthogonal components of the angle between the leg and the inward gripping direction.

As can be seen in Fig. 6, the tarsus angle bends 50 *deg* during a step. Maneuvers such as transitions over orthogonal surfaces may require up to 90 *deg* of motion range, which highlights the need for a compliant tarsus.

B. Body Motion During a Step

Body motions during two steps and a turn are presented in Fig. 7. Forward motion in two different orientations with respect to gravity is shown in the left two subfigures with a stationary turn shown in the right subfigure. The data was obtained through video analysis of DIGbot climbing, recording the position of the body at eight points during the stance phase. In the left subfigure, data is presented for eight forward steps up a vertical screen surface. The data mean and the desired position are overlaid on the figure. The forward motion does not reach the desired motion for two primary reasons; 1) the swing motors are not powerful enough to overcome gravitational forces, which oppose the desired motion, and 2) spines shift out of their initial screen space to a further inward space, and the control system cannot compensate for this.

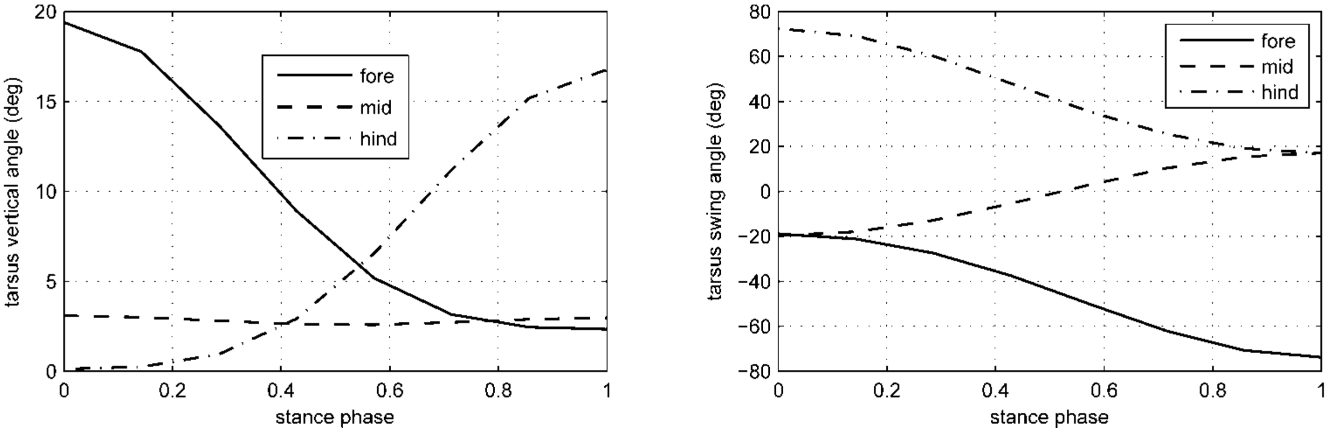

Figure 6. Calculated tarsus angles measured from the straight orientation for a stationary turn. The angles are shown for all three tripod legs during a single stance phase. The left subplot shows the vertical angle which is related to the radial distance from hip to foot. The right subplot shows the tarsus swing angle which varies as the leg protracts and retracts. At its peak flexure, the tarsus bends 50 *degrees* to maintain the correct gripping force angle.

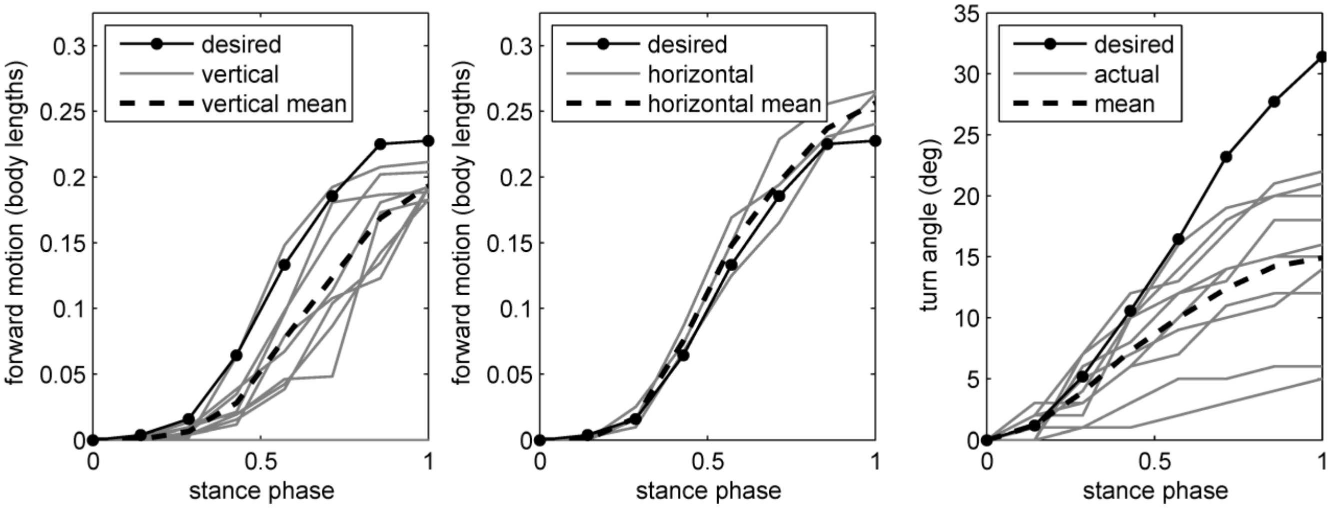

Figure 7. Body motion during forward steps and a stationary turn. The desired values are kinematically calculated and show, along with the mean values from the trials shown. Subfigure (a) shows the motion during a forward step up a vertical surface. In this orientation, the weight of the robot works against the motion and causes the actual motion to fall short of the desired motion. Subfigure (b) shows the motion during a forward step with the robot oriented horizontally on a vertical surface. The weight of the robot does not act against the motion and the actual motion approaches the desired motion. Subfigure (c) shows the rotation of DIGbot during a turn in place on a vertical surface. Problems result from spine slipping, but the legs maintain adhesion with the surface and the body moves through controlled turns.

First, forces to maintain posture and generate motion are both vertical, so the inability of the swing motors to oppose gravity appears as motion error. Second, although DIG feedback helps ensure that proper gripping occurs at the beginning of each step, some slipping occurs as the weight of DIGbot shifts when the leg angles change during a step. The spine can shift within a single screen space, but occasionally a spine jumps to another inward screen space. The feedforward control system does not compensate for this and error cannot be eliminated once this occurs.

Such errors do not exist during a horizontal step on the vertical surface, results of which are shown in the middle subfigure of Fig. 7. Only three steps are shown because the relative success is clearly evident. During this motion, the vertical forces used to oppose gravity and maintain posture are decoupled from the horizontal forces that generate the desired motion. Restated, the weight of DIGbot is not working against its progress. The motors achieve their desired position and result in more accurate steps.

In the right subfigure of Fig. 7, data is presented for a 30 *deg* stationary turn on a vertical screen. This motion results in a larger deviation among the data. Spine slipping is more common during turns, when the leg angle changes are large during a step, resulting in large tarsus angle deflections. Despite this, the body executes the turn and the legs remain in contact with the surface.

In order to reduce the tipping moment of the robot, the bottom face of DIGbot is kept in contact with the substrate. For rough substrates such as the screen mesh, the body occasionally catches on asperities, which temporarily snags the body motion. This results in occasional errors during steps in any orientation with respect to gravity, and may be responsible for some of the error apparent in Fig. 7. Also, the compliance inherent in the body, legs and tarsus of

DIGbot causes some error in the actual position of the robot even when the servos reach their commanded positions.

V. DISCUSSION

This paper presented the use of a biologically-inspired passive compliant tarsus in the foot design of a wall-climbing robot to increase the robust performance of the Distributed Inward Gripping (DIG) algorithm. The implementation of the flexible tarsus was described, and its performance during climbing was illustrated. The compliance serves to maintain the orientation of the foot with respect to the terrain throughout a climbing step. This allows DIGbot to quickly test the strength of a foothold by only needing to verify a single direction of force, perpendicularly inward toward the right-left bisector of the body. Contralateral legs pulling inward toward the bisector offset each other and cause only minimal lateral displacement. Using DIG, the activating forces for directional attachment mechanisms, in this case spines, are produced internally through the robot's mechanisms, rather than relying on gravitation pull, which can limit the realizable climbing directions. DIGbot was shown to climb in multiple orientations with respect to gravity using DIG and the passive compliant tarsus design.

DIGbot is currently being altered to perform more complex tasks such as interior and exterior transitions between orthogonal surfaces. These tasks require an additional actuated joint near the middle of the robot body to keep the hips close to the surface. These maneuvers also require additional stability and reliability which may warrant the use of a different gait which maintains more than three feet in stance at all times.

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