2008 IEEE/RSJ International Conference on Intelligent Robots and Systems
Acropolis Convention Center
Nice, France, Sept, 22-26, 2008

Screenbot: Walking Inverted Using Distributed Inward Gripping

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Abstract—**Insights from biology have helped reduce the weight and increase the climbing ability of mobile robots. This paper presents Screenbot, see Fig. 1, a new 126 gram biologically-inspired robot that scales wire mesh substrates using spines. Like insects, it walks with an alternating tripod gait and maintains tension in opposing legs to keep the feet attached to the substrate. A single motor drives all six legs. Mechanisms were designed and tested to move the spines into and out of contact with the screen. After the spine engages the substrate, springs along the leg are compressed. The opposing lateral spring forces constitute a distributed inward grip that is similar to forces measured on climbing insects and geckos. The distributed inward gripping (DIG) holds the robot on the screen, allowing it to climb vertically, walk inverted on a screen ceiling and cling passively in these orientations.**

I. INTRODUCTION

GAIT patterns used by insects have often been used in the design of fast, agile robots intended to traverse irregular terrain. One common gait for insect-inspired robots is the tripod gait. During this gait, the front and rear legs on one side and the middle leg on the other side are in stance, while the other three legs swing together. For example, Prolero[1] and RHex[2] both have simple rotating legs, but RHex's tripod gait results in improved fast walking. Whegs™ and Mini-Whegs™ utilize an alternating gait as well, but each rotating hub contains three or more spokes instead of just one, allowing for smoother locomotion [3][4].

In addition to having an appropriate gait, climbing animals must properly apply forces at each foot. In quasi-static motion on a vertical surface, the feet must support the body's weight in shear and the front limbs must provide a normal tensile force to counter the moment produced by gravity about the center of mass. Different animals support these tensile loads using sticky pads, fine hair-like setae, claws, and spines [5].

Past robots built to climb vertical walls have utilized suction [6][7], adhesion [8][9][10] and gripping handholds [11][12] to hold the body to the surface. Later versions of Mini-Whegs™ have been modified to climb smooth walls using gecko-inspired adhesive [13]. Spinybot uses an innovative array of compliant microspines to climb hard, rough surfaces [14]. A 12-degree-of-freedom robot, RiSE, uses spines to climb curved surfaces such as trees [15]. Only a few robots can walk inverted on ceilings. Some examples use suction [16], vortex generating systems [17], and adhesion [8].

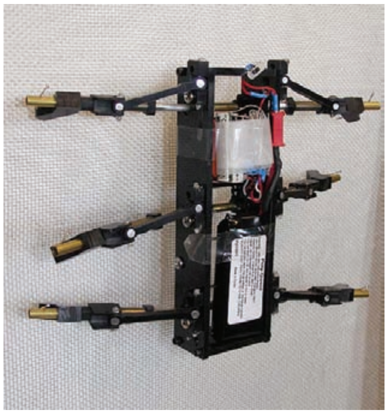

Fig. 1. Six-legged Screenbot walking on wire mesh.

For animals that adhere to surfaces, the motions and forces during attachment and detachment are critical. Geckos have feet covered with tenent (adhesive) setae that conform to smooth and rough surfaces and adhere with Van der Waals forces [18]. Flies also use tenent setae to attach to a surface [19]. Setae on the feet of animals are often angled away from the body, which allows them to support a greater normal tensile adhesive force when a tangential force is applied [5][18]. Flies attach a foot by swinging it onto the substrate and then sliding it inward, toward the center of its body, until the foot attaches. To detach its foot, the animal uses one of four methods: shifting, pulling, twisting or rotating [19]. These motions may reduce the shear force and allow the foot to detach more easily. Experiments with beetles [20] on glass ceilings show that the beetles generally attempt to distribute their contacting feet around the center of mass (Fig. 2). For example, when all but two adjacent ipsilateral feet are severed, the beetle quickly falls from the ceiling. However, if the beetle has two non-adjacent feet, it will stretch its legs to place the feet so that they are directed opposite each other across the center of mass, see Fig. 2E. In these configurations, the animal can cling to the glass. From these experiments, it appears that the animal is using the opposing tension of the legs to increase the shear at the foot of the animal so

Manuscript received Feb 22, 2008. This work was supported by an NDSEG Fellowship, an NSF Graduate Student Fellowship, AFOSR under award number FA9550-07-1-0149, and by the Intelligence Community (IC) Postdoctoral Fellowship Program under National Geospatial Intelligence Agency contract HM1582-05-1-2021

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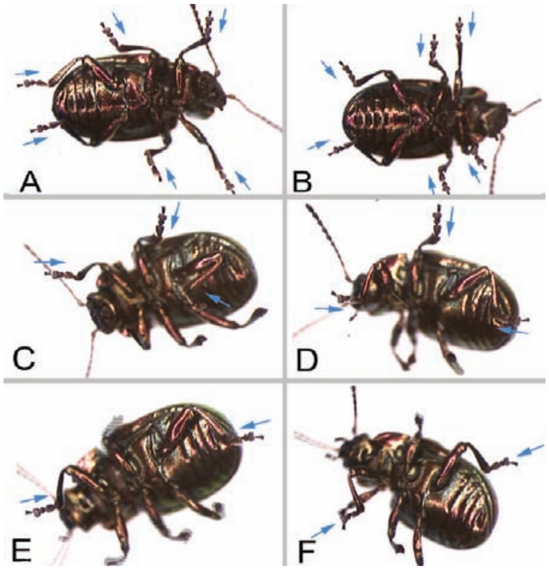

Fig. 2. *Chrysolina fastuosa* beetles clinging to a glass ceiling with six feet (in A and B), three feet (in C and D) and 2 feet (in E and F). The blue arrows indicate the orientation of the shear force applied at the attached feet.

that larger tensile normal forces can be supported. We will refer to this principle of opposing tension of the legs as "distributed inward gripping" (DIG). Because the shear force is created only when opposing legs are pulled inward, a beetle is unable to remain attached to a ceiling with only one foot in contact. Cockroaches move their bodies laterally back and forth while they walk and climb, suggesting that lateral forces applied at their feet play a role in climbing performance [21].

We hypothesized that these lateral forces would also be valuable for climbing using hooks and spines. Spines can be used to penetrate soft surfaces, cling to rough substrates, or hook into holes on porous substrates. Spine-climbing robots, like Spinybot on stucco walls [14] or Climbing Mini-Whegs™ with hooks on steep concrete [22], take advantage of gravity for the shear force that holds the sharp hooks in contact with surface asperities. RiSE robots are designed to be able to pull feet in laterally [15] but, due to the weight of the robot, recent work has focused on the traction in the fore-aft direction and has not included lateral component force data [22]. Relying on DIG instead may allow a robot to climb on surfaces of any orientation or in zero-gravity because the shear force is generated independently from the weight of the robot.

In this paper, we test this hypothesis in the design of a new robot, Screenbot, which uses these principles to climb. Like the beetle, Screenbot relies upon medial-lateral motions of its feet to grasp onto a surface. With a sharp, angled spine on the tip of each foot, the robot can climb and walk inverted on wire mesh screens. Screenbot's unique method of attaching to mesh walls and ceilings may be valuable for future cleaning, inspection and surveillance robots.

II. DESIGN

Each attachment mechanism described above is optimized for some environments but have disadvantages in others, which may explain why animals often have multiple attachment mechanisms. Suction and vortex based robots require a significant amount of power, are inherently noisy, and rely upon the presence of ambient pressure, excluding them from use in some space applications. Magnetic end-effectors only work on ferrous substrates. Adhesion-based robots can cling to smooth surfaces, but can become contaminated quickly by dust, dirt, or other substances on the surface. Gecko-inspired structure may someday solve the contamination problem in adhesives by adhering even when dirty or by self-cleaning, but strong, robust structured adhesives are still being developed. Hooks and spines are able to grasp a wide variety of naturally rough or porous substrates using only frictional and compressive normal forces. However, the application of spines requires precisely timed force distributions and so far spine-bearing robots have relied upon their weights to properly engage spines and, thus, only work in specific climbing configurations. Climbing Mini-Whegs™ is able to climb inclines of less than 60° with pairs of sharp spines [22]. Spinybot [14] can climb up vertically because it has many independently compliant spines and a very low height to length ratio, (see Section V). However, Spinybot cannot climb in other orientations on the surface (like sideways or forward-down).

There are several good reasons for using spines to demonstrate DIG. Sharp rigid spines have directional attachment properties based on well-understood friction and interlocking rather than an adhesion model. The concept of utilizing inward-pulling tangential force to increase the attractive normal force on the feet can be easily observed at a macroscopic scale using spines. Also, spines require less frequent replacement than many of the artificial insect-inspired directional adhesives, which improves repeatability of our experiments. Our design will not require the presence of gravity. Instead, the "activating" force is produced internally through the robot's mechanisms via DIG. We tested Screenbot on screens because the even mesh provides an extremely uniform distribution of possible footholds. In the future, other attachment mechanisms that exhibit direction-dependent load bearing capacity, such as peeled adhesives, anisotropic structured adhesives, and arrays of hooks, could demonstrate DIG on a similar platform in new environments.

For Screenbot to climb vertical surfaces as well as walk inverted under horizontal surfaces, each foot must be capable of supporting both normal and tangential loads. When attached to a vertical substrate, the feet above the center of mass must support tensile normal forces to counteract the moment produced by the weight

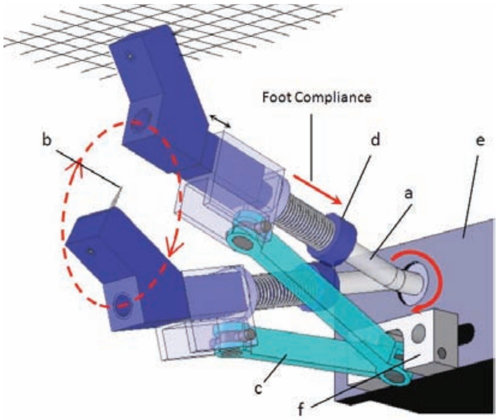

Fig. 3. The front right leg of Screenbot is shown in its uppermost and lowermost positions. The bent aluminum axle (a) moves in a circular path shown by the dashed arrows. When the spine (b) is engaged with the screen, the spring compresses as the spine retraction arm (c) pulls the foot inwards. The preload on the spring is adjusted by moving (d). The spine retraction arm is attached to the side of the chassis (e) with a nut and bolt. Its horizontal base point is adjustable by sliding the connector (f).

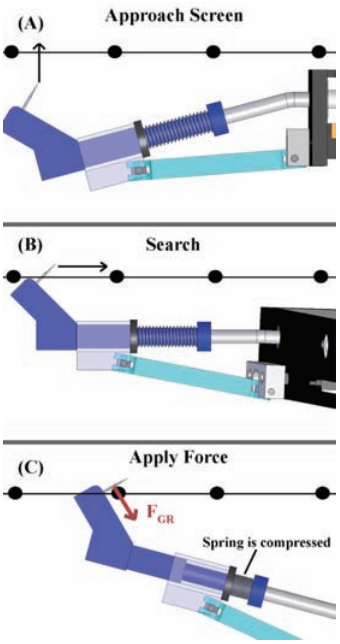

Fig 4. The front right leg approaches the screen on its upstroke (A) and begins to search for a hold as it pulls inward (B). When the spine encounters a foothold, (a segment of mesh wire) the foot complies to apply a ground reaction force at the mesh (C).

of the robot at some distance from the wall. Therefore, the closer the center of mass is to the wall, or the longer the robot is, the less adhesive force is required. Walking inverted drastically changes these force requirements. When the robot clings to the underside of a ceiling, the tensile normal force at every foot must sum to counteract the entire weight of the robot.

Another challenge is to enable the robot to release its feet from the surface during walking. Furthermore, it must not disengage a foot too soon or too late, causing the robot to fall or get stuck on the substrate. Therefore, a mechanical control linkage can be designed to automatically move the feet in the medial-lateral direction at the correct times. As the proper timing was not known during initial construction of the robot, the timing mechanism was designed to be easily adjustable by the user between runs. Also, the adjustable mechanism allows the gait to be changed for walking on various screen mesh sizes.

To minimize weight, the robot is driven with a single drive motor. A tripod gait ensures that the feet are synchronized. The three feet (the front and rear on one side and the middle of the contralateral side) in stance pull inward toward the centerline of the robot, while the other three feet are in the swing phase, pushing outward to detach.

The mechanical linkages (Fig 3.) make this specific motion possible using only a single motor. Each leg of the robot moves through the cycle depicted in Fig. 4. The leg begins at the bottom of its cycle and moves forward relative to the chassis (into the page). The leg then begins to lower towards the screen (Fig. 4A) and the spine engages the screen mesh. The retraction arm then begins to “search” for a hold by pulling the spine inwards (Fig. 4B) and connection is made with the screen wire (Fig. 4C). The relative motion of the spine retraction arm with respect to the foot will be termed “foot compliance.” The stiffness of the compliance is determined by the spring shown. The spring is compressed after the spine engages the screen. The weight of the robot will be supported by the sum of the screen reaction forces shown in Fig. 4C. During the final portion of the cycle, the retraction arm pushes the foot outwards and the leg starts to pull away from the mesh, reversing the process seen in Fig. 4. As the leg detaches from the mesh, it moves down towards it starting position. Note that all three legs in a tripod are synchronized within this cycle, while the legs in the other tripod follow the cycle out of phase by 180°.

III. CONSTRUCTION

The Delrin chassis of the robot measures 127 x 38 x 22 mm, adding the legs extends the width to approximately 140 mm. Spacing between adjacent legs, where they attach to the chassis, is 45 mm. The weight of the assembled robot is 126 grams.

The legs are made from 1/8-inch (3.18 mm) diameter aluminum rod, bent at 15°. Pairs of legs are fit into 5/32-inch (3.97 mm) diameter brass tubes through the chassis and are fixed 180° out of phase of each other with small pins. The drive motor (model Hitec MX-52) is connected to the three pairs of legs via a series of Delrin chains and sprockets, depicted in Fig. 5. The speed of the motor is radio-controlled and a 7.4 V lithium polymer battery powers the vehicle.

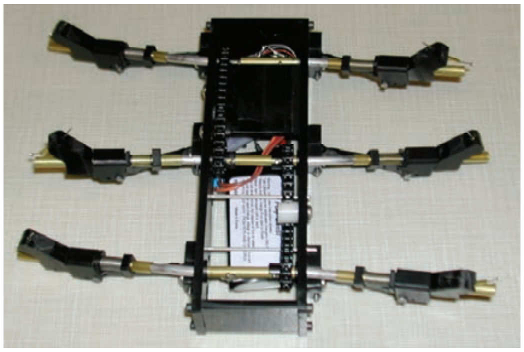

Fig. 5. Underside of the robot, showing the drive system. The drive motor is located behind the flat square panel near the top of the picture.

Each leg consists of an assembly that slides freely along the straight outer portion of the aluminum rod. A brass tube with a sliding fit on the aluminum rod serves as the core of the assembly. A 25 mm long compression spring with spring rate 80 N/m and maximum load of 1.4 N provides compliance to the sliding assembly, which anchors the spine at the end of the leg. The compression and release of this spring is controlled with a spine retraction arm pinned to the chassis with a nut and bolt. The horizontal position of the pin joint at the chassis is adjustable. Delrin spine-bearing feet are press-fit to the sliding brass tube and are interchangeable for easy replacement or modification. Each spine is a sharpened brass pin.

IV. PERFORMANCE

The robot was tested on window screen made from 0.28 mm diameter aluminum wire and a square mesh spacing of 1.5 mm. It was able to climb up vertically, down a vertical surface, and inverted on a horizontal screen “ceiling.” (See attached video.) For the initial test, the spring stop (Fig. 3d) on each leg was adjusted such that the spring was fully compressed, preventing the foot from sliding relative to the spine retraction arm. This was done to observe how the robot behaved with zero foot compliance (completely rigid foot-leg interface). As expected, the robot immediately stalled as the feet attempted to pull the spines into the screen further than the rigid configuration allowed. The spring’s compressive length was then gradually increased by moving the spring stop back until the robot could take complete steps without stalling. This distance of 5 mm was maintained for the remainder of the tests.

Next, for each leg, the horizontal position of the spine retraction arm relative to the center of the drive axle (where it attached to the chassis) was adjusted (see Fig. 3f). The arm position, which we name “spine retraction arm offset,” heavily influences the robot’s performance. Initial testing was done with an offset of 0. Varying this position from 0 to 12 mm forward of center, in increments of 3 mm, the robot was run ten times for each position at an average speed of 10 mm/sec, and an average number of steps was recorded for each position. This parameter changes the timing of the retraction and extension of the foot as the leg rotates through its cycle. As Fig. 6 shows, a greater offset results in a greater average number of steps before falling. In four out of ten trials with a 12 mm offset, the robot stalled. The large offset delays the extension of the spine so much that the legs try to pull out dorsally away from the substrate before their respective spines are pushed laterally outward a sufficient amount for disengagement. This behavior was observed only in the rear legs and not the front or middle legs. This may be because the center of mass is closer to the fore-legs, so the tensile normal force due to gravity is greater in the front, aiding the detachment. Further experimentation found that the best performance occurred when the front legs were set to an offset of 12 mm, the middle to 9 mm, and the rear to 6 mm. This configuration resulted in 10 consecutive trials of at least 10 steps.

The next parameter tested was the angle of each spine with respect to the axis of the leg. Previous tests were done with spine angle of 45°. Running five trials at each angle setting of 35°, 40°, 45°, 50° and 55°, the average number of steps were again recorded for each. As Fig. 7 shows, the best performance is attained when the spine angle is 45°. When the spines were less than 40°, the robot was unable to lift them from the screen, resulting in a stall. At greater than 50°, the spines consistently disengaged prematurely, causing the robot to fall. Further testing was done on a vertically oriented screen to determine how the performance changed when the direction of gravity was altered. When climbing vertically upwards, the robot was most successful when the spine retraction arm offsets were as before, namely 12 mm, 9 mm, and 6 mm for the front, middle, and rear

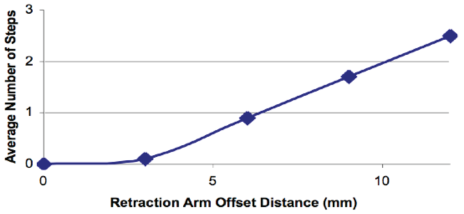

Fig. 6. The effect of the spine retraction arm offset distance on inverted walking ability, measured as number of steps before failure, with 10 trials averaged at each data point.

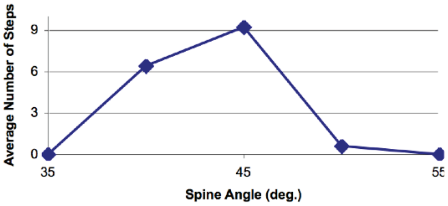

Fig. 7. The effect of spine angle on inverted walking ability with 5 trials at each data point.

TABLE I
CLIMBING ANIMALS FOOT FORCES

	Geckos[a] running vertically	Cockroaches[b] running vertically	Flies[c] walking inverted
Mass	3 g	2 g	0.1 g
Length	5 cm	5 cm	1.3 cm
Tensile Normal[d]	5 mN	7 mN	0.3 mN
Fore-Aft[e]	20 mN	24 mN	1.3 mN
Inward Lateral[f]	0–13 mN	12-30 mN	Not measured
Normal/ Shear	22–26%	17–25%	At least 23%
Lateral/ Fore-aft	0–64%	50–126%	

Measured forces at a single fore leg during stance for various animals.

[a] Gecko *Hemidactylus garnotii* data from [24]

[b] Cockroach *Blaberus discoidalis* data from [21]

[c] Blowfly *Calliphora vicina* data from [20], note that because fly is walking on the ceiling, the fore-aft force is not in the direction of the weight but due to opposing distributed inward gripping in the fore-aft direction. Lateral forces were not measured in this experiment.

[d] Forces normal to the substrate supported by the adhesive attachment mechanism

[e] On a vertically climbing animal, these forces are directed up to keep the animal from slipping down the substrate.

[f] Forces that pull the animal laterally towards the same that the foot is on.

TABLE II
CLIMBING ROBOTS FOOT FORCES

	Climbing Mini-Whegs™[a]		Spinybot[b]	Stickybot[c]	Screenbot[d]
Attaches with:	Office tape	PVS structured adhesive	Arrays of 20 spines	Directional structured adhesive	Single spines at foot
Mass	100 g	130 g	400 g	370 g	126 g
Length	7 cm	25 cm	58 cm	60 cm	8.7 cm
COM Height	2 cm	2 cm	2 cm	3 cm	2 cm
Tensile Normal	~0.1 N	~0.05 N	~0.1 N	0.1 N	~0.3 N
Fore-Aft	~0.2 N	~0.3 N	~1.3 N	2.1 N	~0.4 N
Inward Lateral	0 N	0 N	~0 N	0.1–0.8 N	0.5–1.4 N
Normal/ Shear	57%	16%	10%	6%	19–45%
Lateral/ Fore-aft	0%	0%	0%	5–39%	114–345%

Approximated forces at a single fore leg during stance for some recent robots with directional adhesives.

[a] Climbing Mini-Whegs™ data from [13], approximations calculated by assuming planar quasi-static system, weight distributed evenly between four feet. The directional properties come from the peeling of the adhesive.

[b] SpinyBot data [14], approximate forces calculated assuming planar quasi-static system, weight distributed between three feet in stance, middle feet do not support adhesive normal force.

[c] StickyBot forces measured in [9].

[d] Screenbot data normal and fore-aft forces approximated by assuming a quasi-static system with the weight distributed between three feet in stance, middle feet do not support adhesive force. Lateral forces are determined by observing spring deflection during vertical climbing (0.9–1.8 cm) and multiplying by spring stiffness (50 N/m).

legs, respectively. However, when the robot climbed downwards, the rear legs tended to disengage prematurely using this configuration. By changing the offsets to 6 mm, 9 mm, and 12 mm for the front, middle, and rear legs, respectively, downward climbing could be achieved reliably. These findings support the idea that for the uppermost legs that provide normal tensile force with the screen, a greater offset is required to delay their release as the opposite tripod begins to engage.

The length of individual spines was varied for vertical climbing. The diameter of the spines used was .53mm and the length of the spine in previous tests was 6.4mm. The length of spine was measured from where the spine is connected to the foot to the tip of the spine. Ten trials of vertical climbing were conducted for each spine length and the number of successful steps for each trial was recorded. The failure mode for the last (unsuccessful) step was also recorded. The first type of failure is a binding failure. In this failure, the spines are unable to release properly from the screen. This causes the drive system to bind and the robot to stop forward motion. As shown in Fig. 8, excessively long spines result in increased binding. The second failure mode occurs when one of the spines fails to engage the screen, resulting in the robot falling away from the screen. Shorter spine length increases the chance of a failed engagement. A spine length between 7mm and 8mm minimizes both types of failure.

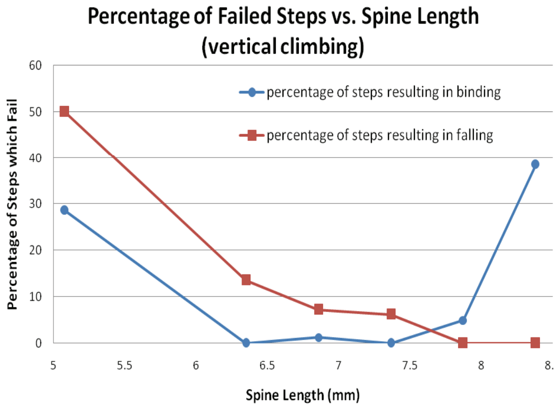

Fig. 8. The effect of spine length on the percentage of steps that result in the robot binding or falling. Ten trials at each spine length.

V. COMPARISON WITH OTHER CLIMBERS

To compare this robot with biological climbers and existing robots, we can consider the forces at each foot. To prevent the robot tumbling backwards from the substrate, the attachment at the front feet is the most important. Table I compares the forces at the front legs for two well-documented vertical-climbing animals: cockroaches and geckos. Both of these animals push outward with their legs when walking on the flat ground but switch to pulling inward (DIG) on vertical walls [21][24]. For these animals, as well as for blowflies [20], the normal forces are about one quarter of the tangential (shear) foot forces during stance. The shear forces have significant components in the lateral direction and in the fore-aft direction. When the animal is climbing vertically, the fore-aft forces at each foot must sum to equal the weight plus any upward acceleration. Table II shows that recent reduced-actuated robots have made increasingly effective use of fore-aft shear forces to sustain attachment. Long, close-to-the-wall robots leverage relatively weak attachment devices like structured PVS or arrays of hooks to cling to vertical surfaces. However, of these robots, Screenbot is the first to take advantage of lateral shear forces of nearly the magnitude of the fore-aft shear forces.

For this reason, Screenbot is the only one of the robots in Table II, to climb inverted on ceilings as well as vertical surfaces using biologically-inspired adhesive. (Climbing Mini-Whegs™ with office tape can walk on ceilings for short periods because office tape was adhesive enough even with little shear [8].) On the ceiling, gravity loads each foot with tensile normal forces, and the shear forces must be provided by a distributed grip of opposing forces, in this case inward forces or DIG.

VI. CONCLUSIONS

Screenbot is the first robot to our knowledge that can climb inverted using only spines. Future versions may include turning capability or even a body joint to aid in transitions between surfaces. While the parameters of the robot may be adjusted to climb on substrates with a less even distribution of footholds, one of the major limitations of Screenbot is that it requires a rough surface that contains pores or asperities.

Screenbot demonstrates the effectiveness of DIG on rough surfaces, but the data in Tables I and II indicate that significant shear forces are important for many different types of successful climbers with many different kinds of biological and biologically-inspired adhesives. Therefore generating opposing forces in the lateral direction as in this work, and in the fore-aft direction as in animals may be important for securing many types of future surface-walking robots whether they are on smooth or rough surfaces.

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