Anisotropic Collapsible Leg Spines for Increased Millirobot Traction

Jessica S. Lee and Ronald S. Fearing

Abstract— Collapsible leg spines found on insects and spiders provide a passive mechanism for increased traction while running over complex terrain. In this paper we use this architectural advantage as biological inspiration to increase the useful work in pulling a load with a VelociRoACH, a high speed terrestrial robot. These spines exhibit anisotropic properties in the fore-aft and lateral directions, with a 2:1 holding-to-release force ratio on corkboard (0.2 N to 0.1 N). This increase in effective friction coefficient at the foot-to-surface contact points has decreased the Cost of Pulling for the VelociRoACH by ten times, allowing it to transport loads using less energy. The VelociRoACH with spines is able to engage the surface and pull up to 0.36 N whereas without spines it slips while pulling 0.2 N, demonstrating that the robot's performance with spines is now torque limited rather than friction limited. The spines also allow the robot to remain dynamically stable and resist torque disturbances.

I. INTRODUCTION

In recent years, the adaptive evolutionary traits of animals have served as inspiration for contemporary robotic designs [1]. Small insect-like robots have many applications due to the fact that they are easily transportable and able to access small spaces that larger robots cannot. This is especially useful in search and rescue missions in collapsed buildings or monitoring standing structures and areas that are at risk. Yet there are many challenges associated with small robots because their size limits the amount of onboard processing or batteries that can be used.

II. PREVIOUS WORK

By drawing inspiration from animals, robots can be designed to have added capabilities without expensive closed-loop control or heavy actuators and batteries. Substantial performance improvements have been achieved by several bio-inspired robots through passive mechanisms and smart mechanical design, such as SpinyBotII [2], RiSE (Robots in Scansorial Environments) [3], CLASH (Climbing Autonomous Sprawled Hexapod) [4], and RHex (the Robot Hexapod) [5]. SpinyBotII and RiSE draw inspiration from spines

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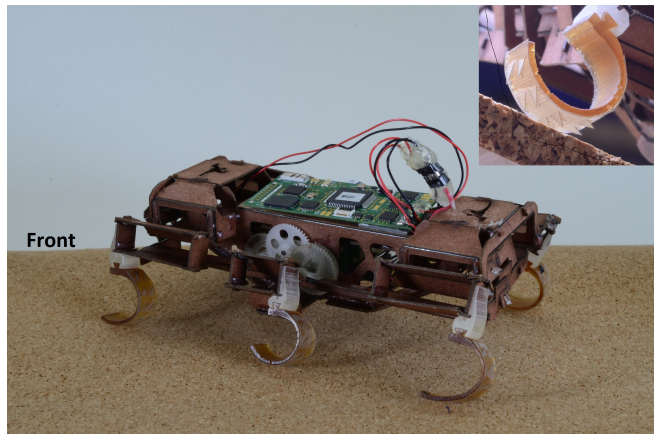
Fig. 1. VelociRoACH with spines shown on cork board. (Upper Right) Expanded picture of the spines for reference.

found on insect legs and use metal micro-hooks to catch onto asperities in walls. CLASH uses passive self-stability and a remote center of compliance to engage and disengage its foot, similar to that found in geckos to climb faster. RHex, designed to be a terrestrial robot, utilized additional spikes at the bottom of its legs to be able to traverse surfaces that had low probability of foot contact, such as mesh. These robots are all accomplished at their specific tasks, however SpinyBotII, RiSE and CLASH are specialized in climbing, and RHex with spines and CLASH are designed for a specific substrate.

In this paper we focus on a foot enhancement design inspired by the collapsible leg spines found on insects and spiders. These spines provide distributed mechanical feedback and are a passive mechanism for running over complex terrain. Anisotropic properties of spines permit engagement of the surface during thrust, but are easily disengaged during swing phase of gait because they collapse toward the leg as the leg slides forward [5]. The spines presented, unlike SpinyBotII, RiSE, and CLASH, are used here for traction on a minimally actuated robot to pull a load, not climb. Cooperative pulling by multiple robots has been explored as a method to maneuver objects [6], but here we examine the traction force limits of a single robot, and its energetic cost.

III. DESIGN

A. Robot Platform

The robot used in this work, the VelociRoACH (Fig. 1), is one of the fastest legged running robots relative to its size (27 body-lengths/sec) [8]. This bio-
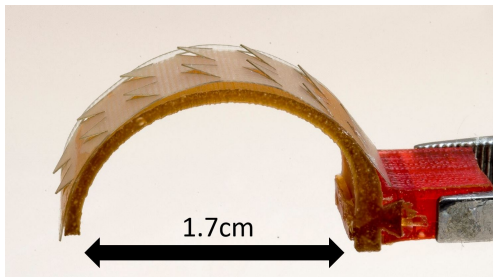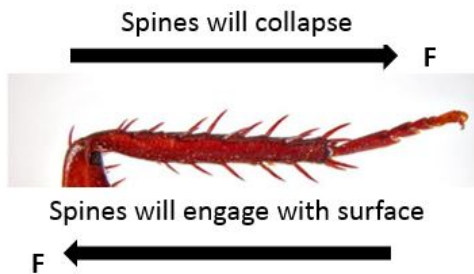
Fig. 2. Spines attached to a leg.

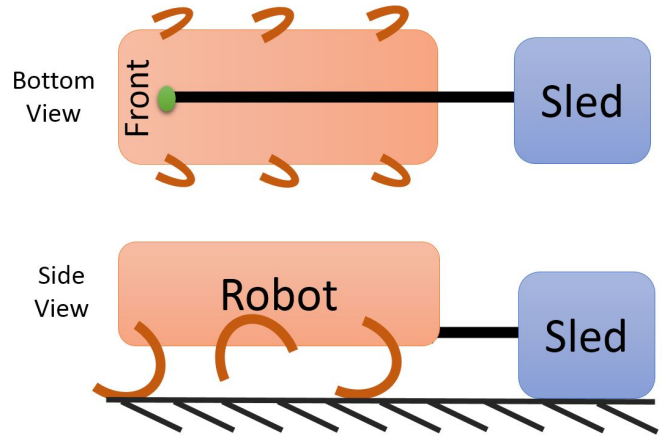Fig. 3. Anisotropic properties of cockroach leg spines.

Fig. 4. Diagram of the robot pulling a load on a sled. On the top is a bottom view of the VelociRoACH showing the attachment at the front of the belly. On the bottom is a side view of the robot pulling a sled.

inspired robot utilizes a hexapedal gait and C-legs, which provide distributed leg contact to help navigate uneven terrain. The VelociRoACH is 10 cm long with a mass of 30 g, and is driven by two DC motors, one for the left legs and the other for the right side. The body is constructed using the Smart Composite Microstructures Process (SCM) [9] and the dynamics were established from dynamic similarity scaling from a cockroach [8]. It should be noted that the C-legs are oriented in the opposite direction used in previous work [8] because spines create high pulling forces on the robot, which might cause the C-legs to buckle in the standard orientation. Additionally, we wanted the legs to be under tension while in thrust stance and to have a well distributed leg contact area. The effectiveness of the C-leg in the hoop orientation can be seen in RHex's ability to run in complex terrain [10].

B. Insect Inspired Spines

The anisotropic collapsible spines shown in Fig. 2 are inspired by the passive leg spines on cockroaches tibia-tarsus joint (Fig. 3). They enable cockroaches to run on horizontal, rough terrain and compensate for the absence of feet on steep inclines [11]. Their anisotropy allows them to collapse when pushed in one direction, but engage and stop at a certain angle when pushed the other way. To mimic this architectural advantage, the spines are fabricated from 0.125 mm thick fiberglass with an array of $45°$ wedges cut out that measure 2.54 mm x 2.54 mm. The uncut fiberglass conforms to the C-leg, causing the released triangles to stick out of the leg. The triangles are also skewed such that only one edge is parallel to the edge of the leg, while the other is skewed

to give it lateral as well as fore-aft anisotropy. For more details on manufacturing process of the spines refer to [7]. While the spines are intended to give the leg better traction by catching on asperities in the surface, they also change the compliance of the leg with the addition of fiberglass. To minimize the effects of stiffer legs, we ran the robot at relatively slow speeds during our experiments.

C. Sled Design

The thrust performance of a VelociRoACH with spines was measured by loading weights into an attached sled (Fig. 4). The sled was a plastic container with an open top for easy access to load weights. A plastic sheet of Stretchlon[1] was hot glued to the underside of the sled. The coefficient of static friction (0.45) was found by analyzing a force balance at the moment of slip on an inclined plane, while the dynamic friction coefficient (≈ 0.4) was found at the incline where it stopped slipping. A string was then glued around the outside of the sled and attached to the underside of the VelociRoACH in front of its center of mass to prevent it from pitching upwards while running.

IV. RESULTS

A. Performance of Leg Spines

Load-drag-pull tests [12] were performed on corkboard with a single robot leg in the fore-aft and lateral directions using a 3 axis linear stage that moved over a force sensor (Fig. 5). For an extended description of this test performed with a leg with spines on cloth refer to [7]. Corkboard was used for all the following experiments because it is a simple first material for spine engagement. The recorded force profile for a
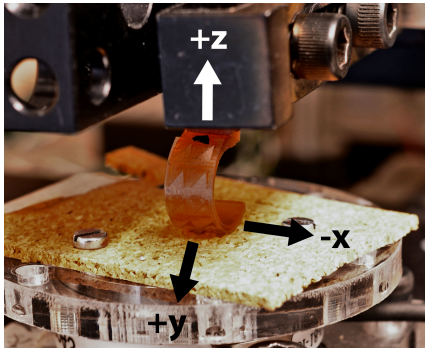
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Fig. 5. Leg with spines during a load-drag-pull test on a force-torque sensor covered with cork board.

Fig. 7. The maximum force limits of the leg with and without spines on corkboard. Arrows indicate the direction of the force and the number indicates the average force.
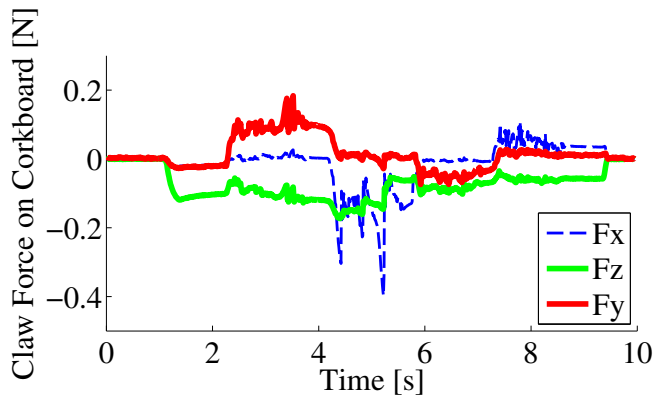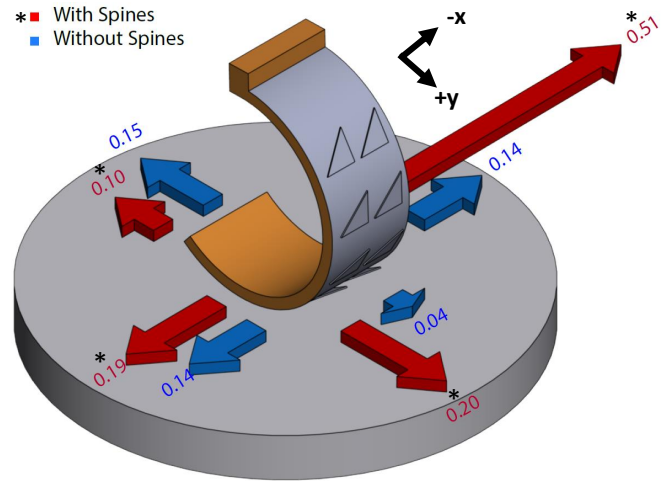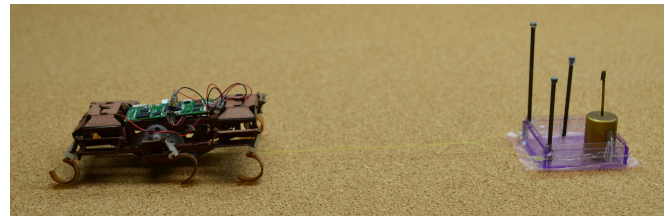

Fig. 6. Plot of forces during a load-drag-pull test of a foot with spines on corkboard. The leg was pre-loaded in the -z direction, then dragged in a square formation in the following directions: +y, -x, -y, and then +x.

Fig. 8. Sled with a weight in it being pulled by a VelociRoACH with spines on corkboard.

representative trial shows the normal loading force F_z, the fore-aft force F_y, and the lateral force F_x (Fig. 6). While the spines are penetrating the surface, the force limit of the foot is 0.197 N. The force limit in the opposite direction to make the spines collapse is 0.104 N, for a 2:1 ratio between the force limits for spine engagement and slip (Fig. 7).

In lateral testing, more force was required to disengage the foot in the direction of the triangle edge parallel to the foot edge than in the direction of the skewed edge. In comparison, the foot without spines has the same force limits in both lateral directions and a very low holding force in the positive y direction (Fig. 7). Although the spines seem to provide a greater holding force in the lateral direction, we chose to utilize the spines so that the point of the triangle engages the surface to better catch onto asperities. Additionally, in its current configuration the spines function similar to a cantilever beam where the root of the beam starts at the leg surface and the leg curves away. If we turn the triangles sideways, the cantilever beam will no longer be in the direction of the curve and the leg will no longer curve away from the beam. This would make

manufacturing more difficult since the spines won't stick out naturally. It should be noted that the high release force in the leg without spines in the positive y direction was due to buckling in the leg during the load-drag-pull test, which happened when the leg tip engaged the ground. Buckling did not occur in the legs with spines because they were less compliant. The buckling behavior can be further explained by a pseudo-rigid body model of an initially curved, end-force loaded cantilever beam [13].

From these tests we can see that to disengage the spines we could either slide the leg forward, making the spines collapse, or pull the leg sideways toward the skewed edge of the triangle. With these results we can also find the coefficient of friction of the foot with and without spines by dividing the drag force by the normal force. In the positive y direction, a leg with spines has a friction coefficient of 1.04 ± 0.19 while without spines it has a friction coefficient of 0.18 ± 0.04.

B. VelociRoACH Pulling a Load

To evaluate the spine's utility on a robotic platform, pulling tests were conducted using a VelociRoACH on corkboard (Fig. 8). It is known from biology that pulling is significantly more energetically expensive [14], so
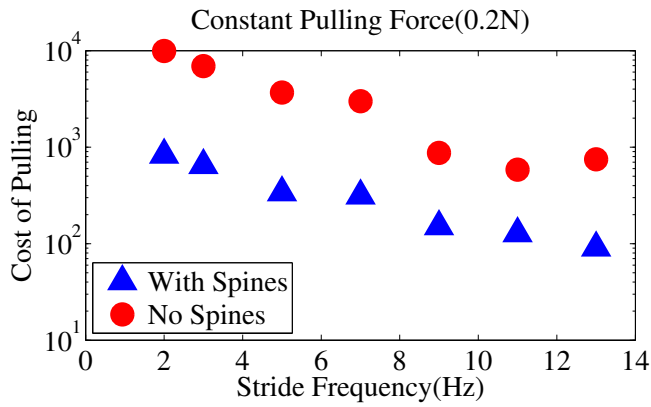
Fig. 9. The Cost of Pulling for a VelociRoACH with and without spines at a constant pulling force using various stride frequencies. All tests were performed with one robot and each trial was tested three times.
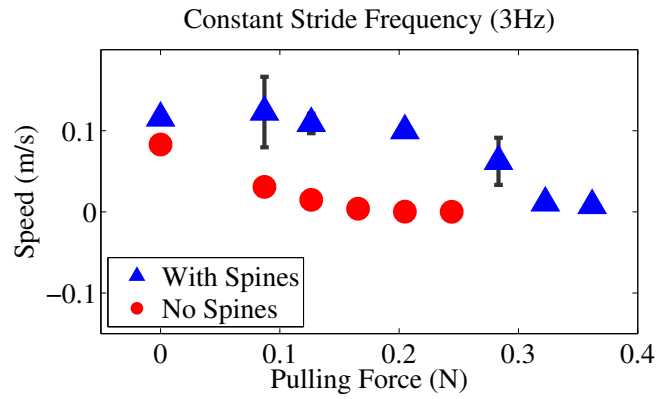

Fig. 11. Speed of sled while the VelociRoACH pulled various forces at a constant stride frequency of 3 Hz with and without spines. All tests were performed with one robot and each trial was tested three times.
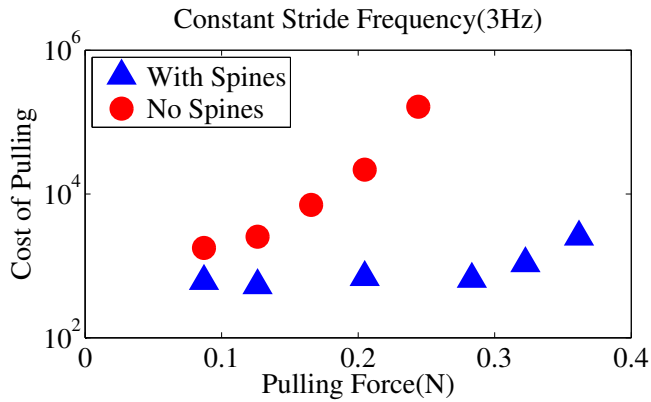

Fig. 10. The Cost of Pulling of a VelociRoACH with and without spines using various pulling forces at 3 Hz. All tests were performed with one robot and each trial was tested three times.
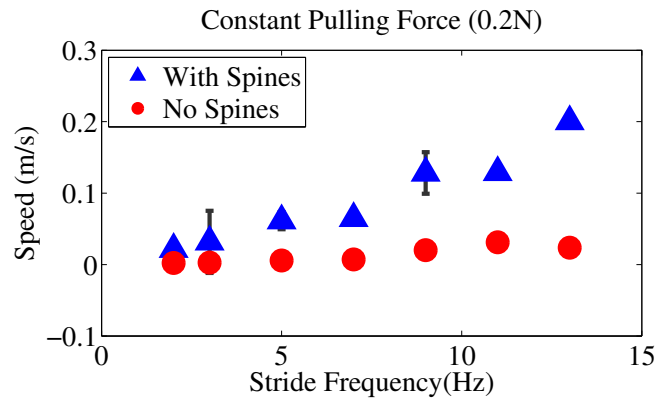

Fig. 12. Speed of the sled at various stride frequencies while the VelociRoACH had a constant induced pulling force of 0.207N with and without spines. All tests were performed with one robot and each trial was tested four times.

pulling tests are a good way to quantify whether spines improve robot performance in difficult tasks.

1) Cost of Pulling: In the first set of tests, the robot had a constant towing load of 0.2 N while the stride frequency was incrementally increased. In the next set of tests, the robot was run at a constant 3 Hz stride frequency while the pulling force of the sled was increased incrementally by putting different weights in the sled. Distance traveled and the electrical power drawn by the motors were recorded in order to find the speed of the robot with and without spines and the Cost of Pulling (CoP), Eqn. (1). Useful work was calculated using the measured coefficient of friction of the sled (0.4), the weight of the sled, and the distance the sled moved. The CoP was found by dividing the energy used by the motors by the useful work of the sled being pulled. We used CoP as opposed to Cost of Transport (CoT) because for CoT the force in Eqn. (1) is only the weight, whereas for CoP the pulling force is used.

$$CoP = \frac{Power \cdot Time}{Force \cdot Distance} \qquad (1)$$

For a constant pulling force, CoP in the VelociRoACH decreases as the stride frequency increases and the VelociRoACH with spines always has a lower CoP (Fig. 9). At a stride frequency of 5 Hz, the CoP of the VelociRoACH without spines has a value of 3700 while the value with spines is 330, showing a decrease of about 10 times. For a constant stride frequency at any amount of pulling force, the VelociRoACH with spines has a lower CoP than without spines and the CoP increases as the pulling force increases (Fig. 10). With a pulling force of 0.2 N, the CoP of a VelociRoACH with spines has a value of 700, whereas without spines the value is 2200, showing about 30 times the increase. This implies that for a certain amount of energy input, the robot could do more useful work simply by adding spines when moving on a material such as corkboard. For example, a VelociRoACH without spines expends 4.2 W of power to tow 0.09 N forward, whereas a
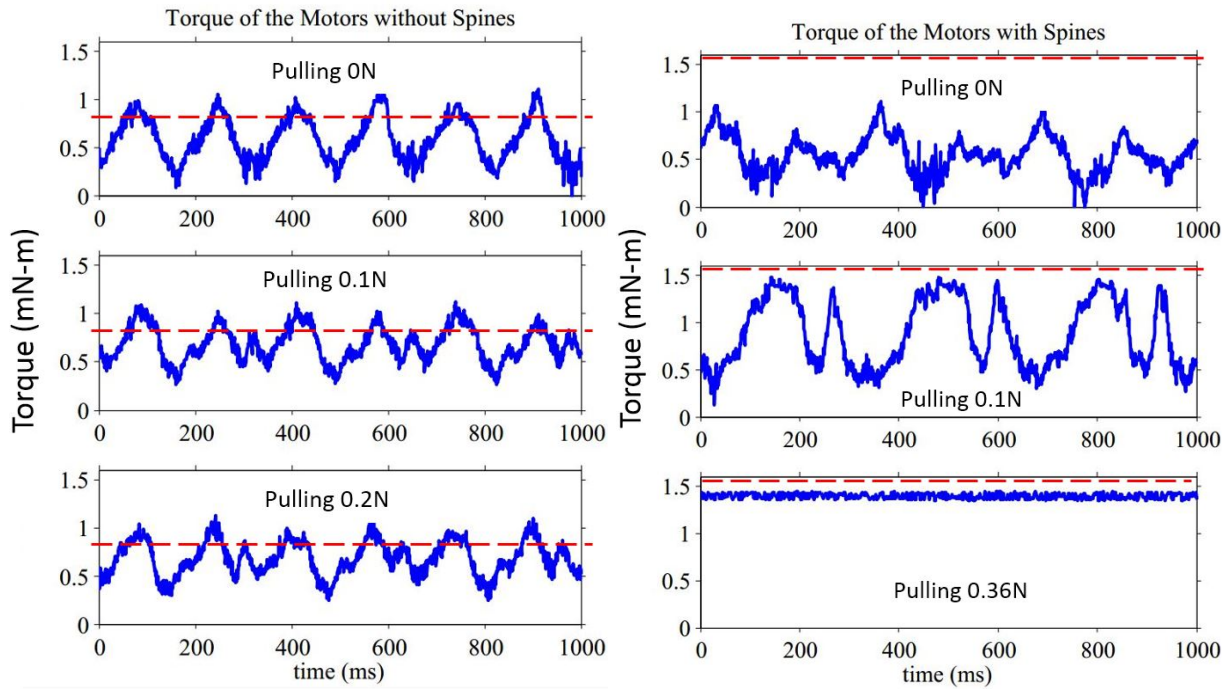
Fig. 13. (Left) Motor Torque of the VelociRoACH without spines taken over 3 cycles with a pulling force of 0N, 0.1N and 0.2N. Red dashed line indicates the torque at which the feet will theoretically slip. (Right) Motor Torque of the VelociRoACH with spines taken over 3 cycles with a pulling force of 0N, 0.1N and 0.36N. Red dashed line indicates the maximum torque of the motor used in the robot.

VelociRoACH with spines using 4.3 W can pull 0.28 N. Therefore with almost the same amount of power, a robot with spines can pull more than three times the amount it could pull without spines and twice the equivalent pulling force of a broken VelociRoACH in a sled (0.12 N). Additionally, this improvement of CoP could increase the range and number of deployments for each robot, which is critical in search and rescue missions.

2) Speed Enhancement of the Robot: Speed was obtained by using the distance and running time recorded during our pulling tests. For constant stride frequency, the speed of a VelociRoACH with spines was significantly greater at all tested loading forces (Fig. 11). The VelociRoACH without spines starts slipping at 0.2 N of pulling force, whereas with spines it can pull up to 0.36 N. During the constant pulling force tests the VelociRoACH with spines was still able to move faster than the case without spines (Fig. 12). Without spines at high frequencies, however, the VelociRoACH was not moving forward even though its legs were still moving rapidly. This implies that the pulling force is exceeding the VelociRoACH's leg friction force limit, which is the product of coefficient of kinetic friction and normal force. The VelociRoACH with spines, on the other hand, engages the surface but is unable to move its legs with a 0.36 N pulling load. Therefore the robot is friction limited without spines and torque limited with spines.

To examine more closely whether the robot is now

torque limited, graphs of the motor torque are shown in Fig. 13 (motor torque estimated from motor current and torque constant). The bottom row represents the motor torque when the robot is pulling the largest force it can, 0.2 N for a robot without spines and 0.36 N for a robot with spines. In the left plots of Fig. 13, the blue solid line represents the motor torque of the VelociRoACH without spines and the red dashed line represents the theoretical torque at which the foot will slip (0.8 mN-m), taking into account the coefficient of friction from the load-drag-pull tests. The motor torque is consistent for all pulling loads and reaches a maximum of 1 mN-m, which is close to the value where the foot will slip. In the graphs of the motor torque of a robot with spines (right plots in Fig. 13), the red dashed line represents the maximum torque the motor can produce (1.6 mN-m). While pulling 0.1 N the motor torque reaches 1.4 mN-m, which is close to the maximum value for the maximum motor torque, and at 0.36 N the motor stalls.

C. Heading Behavior While Pulling a Load

To examine the robot's heading behavior while pulling a load, the sled was attached in the center of the robot while an OptiTrack system tracked the sled and its path was plotted using Matlab. A pulling force of 0.1 N was used while the robot ran over corkboard because this was a configuration easily managed by the VelociRoACH with and without spines. The trajectory of the sled appears fairly straight in Fig. 14 when the sled was attached to the center of the robot. Therefore
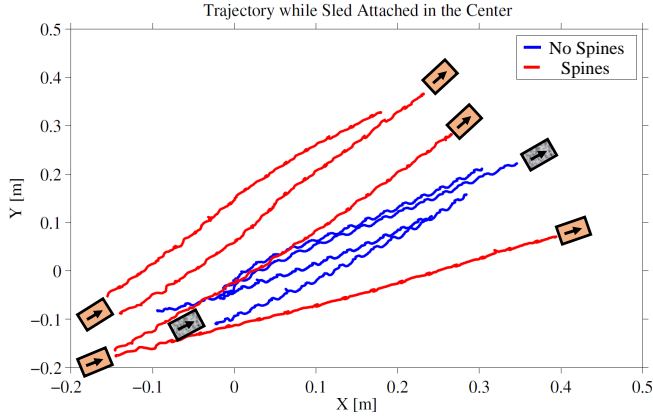
Fig. 14. Trajectory of the VelociRoACH with and without spines while pulling a sled attached to the front, center belly of the robot. Boxes indicate the robot's position while arrows indicate the direction the robot is facing. The orange boxes are the robot with spines, and the grey speckled boxes are the robot without spines. The trajectory for both cases of the VelociRoACH with and without spines seem fairly straight.
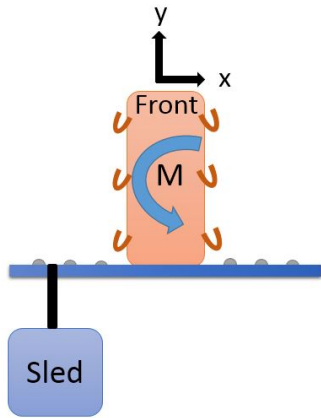

Fig. 15. Top view of the VelociRoACH while testing passive self stabilization. As shown, the string was attached to a rod on the back of the robot.

the robot with and without spines is dynamically stable and can maintain a straight heading.

Next a deliberate yaw torque bias was applied to examine the effect on heading behavior. To induce an initial moment, the sled was attached to alternate sides on a carbon fiber rod with bumps spaced 1 cm apart to hold the sled (Fig. 15). By controlling the lateral offset of the sled from the body, the magnitude of the torque disturbance could be tuned to create a noticable turn in either direction. For the right side an induced moment of 4 mN-m was required to produce a significant right turn for a robot without spines. However on the left side, due to asymmetries in the robot, the VelociRoACH without spines required a 6mN-m moment to produce a left turn of similar magnitude. It should be noted that
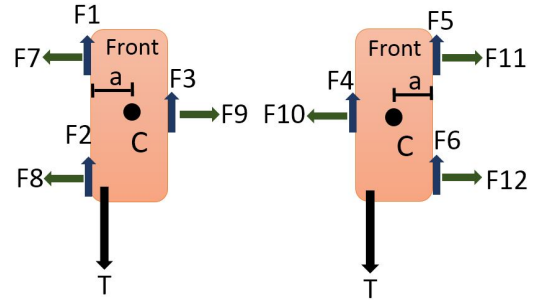

Fig. 16. (Left) Force body diagram of the VelociRoACH while the sled is attached to the left side, where T is the tension induced by the pulling force, the variations of F are the forces due to the friction in the legs using the friction coefficient of the legs and the normal force. C is the center point of the robot and a is the distance from the center to the edge of the robot. (Right) Force body diagram of the VelociRoACH while the opposite legs are touching the ground.

because the moment is induced by a sled attached by a freely rotating string, the true moment to induce yaw shown by Fig. 15 is only applied at the first instant. Once the robot begins to turn, the tension force on the robot will be in a different direction. From the free body diagrams in Fig. 16, we would predict that while the two legs on the same side as the tension force are engaging the ground, the robot would be more likely to counteract the moment induced by the tension force than if the other three legs were touching the ground. Additionally in the case with spines, there are larger lateral forces that could keep the robot from rotating.

From the tracked sled trajectory (Fig. 17), the VelociRoACH with spines seems to show greater resistance to torque disturbance as it tries to run towards positive y. Overall it follows the original heading farther than the robot without spines and curves after traveling farther in the y direction than the case without spines. Similar to the model of a passive dynamic self-stabilizing system of cockroaches by Full *et al*. 2002 [15], the robot with spines seems to be neutrally stable by following a certain trajectory after being perturbed and not returning to its original path. Interestingly, there are even a few runs in Fig. 17 where the robot veers toward the opposite direction that is predicted. For example, the robot runs to the right even though the sled is attached to its left. This could be caused by tension from the sled giving the left feet more traction, over powering the right side and causing the robot to go right. However further work will be needed to confirm this hypothesis.

V. CONCLUSIONS

The bio-inspired spines evaluated in this paper give the VelociRoACH a variety of performance advancements from a simple leg enhancement. The speed of the VelociRoACH with spines is significantly higher than a robot without spines, regardless of the pulling force or stride frequency. Additionally, the Cost of Pulling
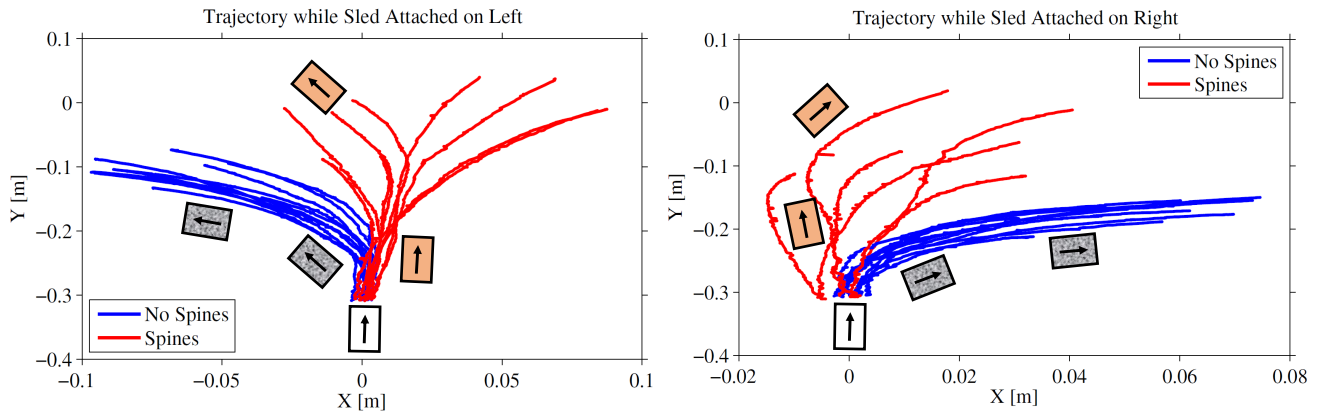
Fig. 17. (Left) Trajectory of the sled being pulled by a VelociRoACH with and without spines with a 3 cm offset on the rod attached to the back of its body. (Right) Trajectory of the sled being pulled by a VelociRoACH with and without spines with a 1 cm offset. Boxes indicate the robot's position while arrows indicate the direction the robot is facing. The white box is the starting position of the robot with or without spines, the orange boxes are the robot with spines, and the grey speckled boxes are the robot without spines.

in the VelociRoACH has decreased by an order of magnitude when pulling a significant load force, which has increased its towing capacity per unit energy. This is useful in the world of small robotics where weight and body real estate is critical. Although towing is an energetically expensive task, this could be used for short periods of time when other robots need assistance relocating or for transporting equipment. The spines also stop the robot from slipping and allow it to pull 0.16 N more than without spines, making the VelociRoACH torque limited instead of friction limited on corkboard. Finally, the VelociRoACH with spines resists torque disturbances better and is neutrally stable. All these improvements make the VelociRoACH a more useful robot for applications such as search and rescue, where the robot will have to navigate challenging terrain and possibly pull payloads.

ACKNOWLEDGMENTS

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