CLASH: Climbing Vertical Loose Cloth

P. Birkmeyer, A. G. Gillies, and R. S. Fearing

Abstract*— *CLASH is an original robot design capable of climbing vertical loose-cloth surfaces at 15 cm per second. The robot has a single actuator driving its six legs which are equipped with novel passive foot mechanisms to facilitate smooth engagement and disengagement of spines. These foot mechanisms are designed to be used on penetrable surfaces and offer improved tensile normal force generation during stance and reduced normal pull-off forces during retraction. Descended from the DASH hexapedal robot, CLASH features a redesigned transmission with a lower profile and improved dynamics for climbing. CLASH is the first known robot to climb on loose vertical cloth.

I. Introduction

The applications of small legged mobile robots are well known. Their size makes them easily transportable, inconspicuous, and able to pass through openings and corridors through which larger robots could never pass. These traits make them the perfect vehicle for search-and-rescue missions in collapsed buildings or mines, long-term environmental observation, and monitoring of dangerous scenarios such as unstable bridges or nuclear fallout zones. Equally well known are the challenges associated with small mobile robots. For example, due to spatial constraints, they cannot accommodate large numbers of actuators significant onboard processing or large batteries. For a small robot to be functional, attention must be paid to designing mechanisms to operate effectively with minimal actuation.

There are advantages to being small, as well. For example, while most obstacles are significantly larger than the body size for small robots, smaller robots should have an easier time climbing. As size decreases, the ratio of foot surface area to volume increases; in turn, the ratio of available adhesive forces to mass generally increases as size decreases. In addition, smaller and lighter robots are able to traverse surfaces that would not be able to support larger robots due to surface fragility or lack of engagement asperities.

Previous research has developed several different legged robots capable of climbing a range of surfaces. Various iterations of RiSE have demonstrated climbing up trees, stucco, and telephone poles using claws [1], [2]. SpinybotII has demonstrated climbing up concrete and stucco surfaces [3], and StickyBot robots have shown climbing up surfaces such as glass and smooth cabinets [4]. Climbing Mini-Whegs has shown climbing with office tape and structured rubber

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P. Birkmeyer and R. S. Fearing are with the Department of Electrical Engineering andComputer Science, University of California, Berkeley - {paulb ronf}@eecs.berkeley.edu

A. G. Gillies is with the Department of Mechanical Engineering, University of California, Berkeley - andrew.gillies@berkeley.edu

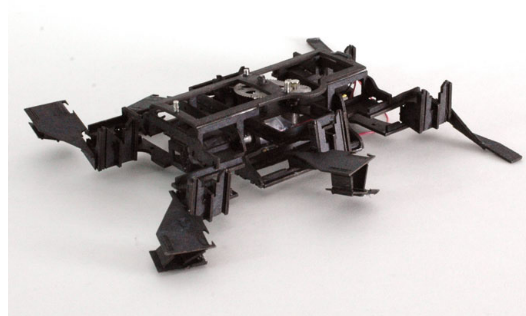


Fig. 1. CLASH is a 10cm 15g minimally actuated hexapedal robot capable of climbing penetrable fabric and loose cloth. It is pictured without electronics to reveal the body and transmission mechanism. The battery and motor are embedded in the robot and slightly occluded in the image.

flaps on glass, and climbing with Velcro on rigid fabric-covered panels [5]. The fastest among the legged climbing robots is DynoClimber, which uses two legs to dynamically climb vertically-mounted, rigidly-backed carpet [6].

The surfaces these robots can overcome are certainly challenging. However, they share the common property of being rigid or having rigid backing. It is not apparent that these or other legged climbing robots can climb a surface when the rigidity of the surface is not guaranteed, such as when climbing suspended loose vertical cloth. In this paper, a novel robot and complimentary spine-based foot design are presented which can climb loose vertical cloth. The Climbing Autonomous Sprawled Hexapod, or CLASH (Figure 1), is a design evolution descended from DASH, a robot capable of high-speed locomotion over horizontal surfaces [7]. The design of CLASH has a reduced profile and improves the body dynamics generated during operation to be more conducive to climbing. A new passive foot mechanism increases tensile forces during stance phase and provides low resistance during pull-off to facilitate smooth and efficient climbing. It can ascend loose suspended cloth at 15 cm/s (1.5 body-lengths per second) and near-vertical fabric draped over a soft surface at 24 cm/s (2.4 body-lengths per second).

II. Design

In order to address the task of vertical cloth climbing, a new robot design and complimentary foot mechanism had to be developed. CLASH is designed to use a single drive actuator to maintain the high-power density required for climbing. It uses sprawled leg positioning that has been demonstrated to provide passive stability even when using

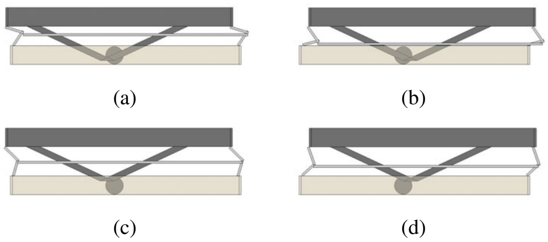


Fig. 2. Model of DASH body transmission during operation at four different points in a stride. The top horizontal linkage moves vertically during operation, creating normal accelerations of the center of mass.

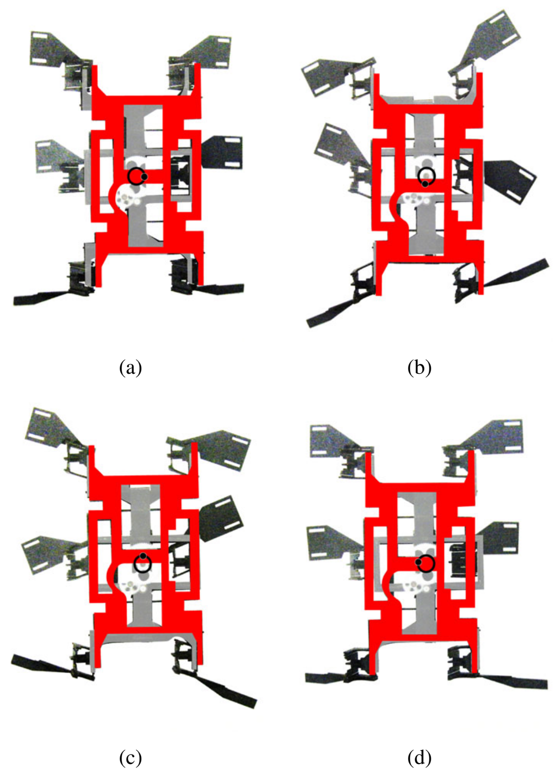


Fig. 3. Illustration of how the COM moves during operation in CLASH, viewed from above. The motor is mounted to a linkage the runs down the middle of the robot, highlighted in white. The output of the motor drives the linkage highlighted in red, rotating in a circular output dictated by the motor. Body motion is confined to being parallel to the surface. The different images show different points within a single stride.

open-loop commands [8], [9], [10]. This allows CLASH to avoid feedback control and its requisite sensors, computation, and actuation to simply maintain stability. The body dynamics also must be designed such that they do not hinder climbing ability unnecessarily. To further maintain a low weight, the foot mechanism should be passive to minimize the number of actuators. For smooth and efficient climbing, it should penetrate the cloth easily, generate sufficient tensile forces required for climbing, and then release easily when retracted by the leg. Due to the unknown nature of the cloth curvature, it must also be able to be released from the cloth across a wide range of angles.

A. Body Design

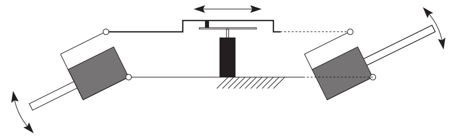
CLASH was designed to address the shortcomings DASH faced when climbing. The body and transmission of DASH were oriented vertically, with two structures of roughly equal mass that moved relative to each other to drive the legs. This resulted in a center-of-mass (COM) that rapidly oscillated orthogonally to the ground. These motions are obvious when viewing DASH from the side, as in Figure 2. These accelerations demanded significant adhesive normal forces simply to overcome the dynamics caused by the body and transmission in order to remain on a vertical surface. Because the masses of these robots are small at around 15 grams, the drive linkages will still represent a large fraction of the total mass and will create non-negligible COM oscillations during operation. These accelerations must be managed in these systems to minimize the negative impact on body dynamics.

With this in mind, the COM oscillation due to the differential drive mechanism in CLASH was confined to the plane of the climbing surface, minimizing normal accelerations during locomotion. CLASH uses a DC motor mounted vertically, with the bottom of the motor flush with the belly of CLASH and the top output gear assembly located dorsally. The final stage of the output gears moves parallel to the coronal plane of CLASH, i.e. parallel to the ground, moving the top drive linkage both laterally and along the anteroposterior axis. Viewed from above, as in Figure 3, the drive linkage, as well as the COM, moves in primarily in a plane parallel to the climbing surface. Any movement of the drive linkage in the dorsoventral axis is minimized, thus reducing the normal forces caused by the drive mechanism.

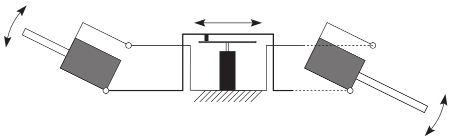
CLASH is constructed using the scaled Smart Composite Manufacturing process, which uses flexible polymer joints with rigid cardboard linkages to create the body, transmission, and kinematics of the robot [11]. The hip mechanism, abstracted in Figures 4 and 5, was designed to be driven by displacements of a drive linkage in the fore-aft direction and the lateral direction as in Figure 3. In these figures, the grounded linkages are rigidly coupled to white-highlighted linkage in Figure 3 in which the motor casing is mounted. The bold linkages are driven by the output of the motor, which is connected to the red linkage in Figure 3.

When the motor drives the linkage laterally, the motion drives opposing pairs of hips as shown in Figure 4. For the front and rear hip mechanisms, the mechanism is driven as in Figure 4(a) with the grounded linkage flush with the belly. For the middle hips (Figure 4(b)), the drive and grounded linkages exchange vertical positioning. This causes the middle legs move in the opposite direction from the front and rear legs as is required for an alternating tripod gait. To achieve fore-aft swings of the legs, the fore-aft motion of the motor output drives the front and rear pairs of hips as shown in Figure 5. The middle legs have a similar mechanism but simply mirrored across the sagittal plane. In this way, the circular output of the single drive motor drives all six-legs in an alternating tripod gait.

To reduce pitching moments caused by having the center of mass away from the climbing surface, the total profile was lowered to 2cm tall (from 5cm in DASH) and all electronics



(a)



(b)

Fig. 4. Kinematic drawings of how abduction and adduction are achieved by moving the top drive linkage (bold) laterally, looking from the front of CLASH. The motor is mounted to the grounded linkage while the output of the final gear stage drives the top linkage. (a) shows how front and rear legs are driven, and (b) shows how the mid-legs are driven. The grey rectangle is the side view of the four-bar mechanism in 5. Linkages are made to be dashed to not obscure other linkages. They do not collide when realized in three dimensions.

were mounted as low as possible. The motor is mounted in the center of the robot, lowered ventrally to be flush with the bottom of the robot. The battery is also placed low along the center of the body, encased by the structure to protect it. The control electronics are mounted low and to the rear of the robot. The placement of these elements in the robot bring the COM to just 7 mm above the bottom of the robot, reduced from an average of 30mm above the bottom of DASH. The design also consolidates the mass of the system to a single element of the drive transmission. This reduces the displacement of the COM motion during locomotion and thus further lowers the accelerations caused by the operation of the differential drive mechanism.

B. Attachment Mechanism

To keep the mass of the robot as small as possible, the number of actuators required for engagement and disengagement of a surface should be minimized by using passive mechanisms. The passive foot design for CLASH has several benefits over actuated foot designs. The foot mechanism can respond faster to external stimuli as it does not have feedback control delays and actuator response times and instead depending upon the mechanics and dynamics of the structure. It also simplifies control of the robot, neglecting the interactions of individual feet with the substrate, instead

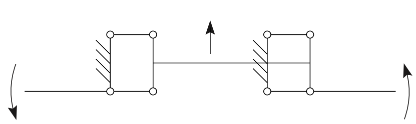
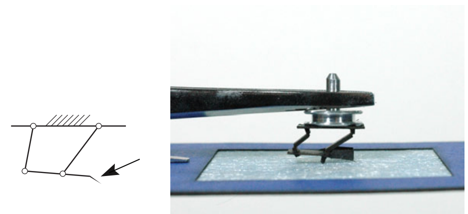
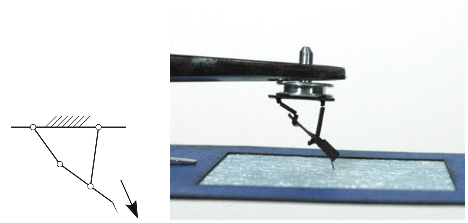


Fig. 5. Kinematic drawing of fore-aft motion of the legs achieved by moving the drive linkage in the middle forwards and backwards. The grounded linkages are coupled rigidly to the motor case. Each pair of opposing hips is driven in a similar manner, though the middle legs are mirrored from the front and rear legs.

(a) Unloaded (b)



(c) Loaded (d)



(e) Retracting (f)

(g) Control (h)

Fig. 6. Kinematic drawings with corresponding photos of the four-bar mechanism. The grounded linkage is where the mechanism attaches to the leg. (a, b) When not loaded, the spines angle slightly downward to facilitate penetration at impact. (c, d) When loaded during stance after engagement, the foot deflects slightly under the load and rotates the spines up, hooking the cloth to generate tensile normal forces. (e, f) When the foot is retracted, the spines easily collapse and rotate downward to be easily withdrawn from the cloth. (g, h) A four-bar mechanism with locked joints serves as the control to compare during force testing. Note how the cloth is being pulled up as the foot is retracted.

relying on design to mediate any interactions. However, without actuation, the mechanism must not only engage and disengage passively, but it must also tolerate a wide range of approach angles, surface curvature, and retraction angles.

The foot mechanism used by CLASH (Figure 6) consists of a four-bar mechanism with the top linkage grounded on the leg and the bottom linkage extending forward with embedded spines. Spines allow CLASH to engage the cloth with a wide range of approach angles and cloth curvatures. The mechanism is designed to move the instantaneous center of rotation of the spines beneath the plane of the climbing surface. Having the center of rotation beneath the climbing surface causes the spines to rotate in the opposite direction, as shown in Figure 6(c). In a passive foot, having the center of rotation above the surface would cause the spines to roll away from the surface during stance, increasing the likelihood that they will lose engagement with the surface. When CLASH's spines have already penetrated the cloth, this rotation actually causes the spines to hook the fabric and pull the robot towards the cloth surface, increasing normal force during the stroke.

Because the leg motions of CLASH are entirely determined by the kinematic structure, the loading and unloading directions relative to the surface during climbing can be loosely bounded. During foot touchdown and stance, the feet are expected to be pressing down and against the climbing surface, with some preload required to embed the spines and tensile forces to keep the robot from pitching backward during stance (Figure 6(c)). In these situations, the foot mechanism will deflect as seen in Figure 6(d). At the end of stance, CLASH will raise its foot from the surface, and the ground reaction forces will be primarily in the normal direction as the cloth impedes the retraction of the spines (Figure 6(e)). The four-bar mechanism was designed to provide little resistance when retracted nearly orthogonally. When the load is oriented in this direction, the foot mechanism collapses to a configuration in which the spines are more orthogonally oriented, where they offer little pull-out resistance (Figure 6(f)). Though the mechanism may deflect through a singularity, the stored elastic energy in the deflected flexures restores it to the unloaded configuration when the load is removed. The direction of the loading vector determines whether the foot will deflect to the configuration shown in Figure 6(c) or in Figure 6(e).

III. Results

With a body that measures only 6 cm wide, 10 cm long and 2 cm tall, CLASH is a small climbing platform. With the legs, the stance spans approximately 10cm. CLASH has a mass of 15 grams, including onboard electronics and battery, and its COM is approximately 7mm above its belly. The robot has a electrical connector to the single DC drive motor, allowing either remote-control electronics or a custom lightweight electronics board to control CLASH. The custom electronics, which include a Microchip PIC microcontroller, 3-axis accelerometer, 3-axis gyroscope and 802.15.4 wireless interface, were developed outside of this project. Preliminary tests on CLASH with the four-bar foot design presented above reveal the robot is capable of climbing vertical loose-hanging cloth at speeds up to 15 cm second^{-1}, or up to 1.5 body-lengths second^{-1}. To the authors knowledge, this is the first robot capable of climbing loose cloth, and its speed is comparable to DynoClimber which had set the current benchmark for vertical climbing when normalized by body length [6]. CLASH only requires the four-bar foot mechanisms on the front and middle legs in order to achieve climbing, and thus the rear hips can be equipped with stiff, oar-like legs originally used in the DASH design [7]. A tail is also not required for vertical climbing on loose cloth, though there room in the design for a tail to be added. Passive tails are currently being tested. In the future, the electronics will be mounted on the tail in order to keep the mass toward the belly and to the posterior end of CLASH to aid in stability.

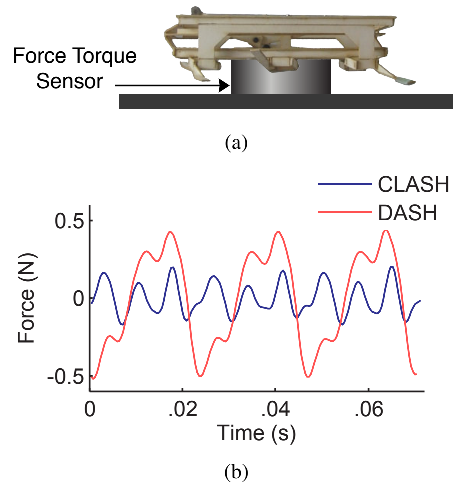


Fig. 7. Mounting robots to the bottom of the robots allows measurement of the the normal forces generated by the body dynamics during operation. CLASH (blue) significantly reduces normal forces generated during locomotion compared to DASH (red).

A. Body Dynamics

The design of CLASH sought to reduce the normal accelerations during locomotion. In order to verify that the new robot achieves this goal, DASH and CLASH were mounted on top of a 6-axis force torque sensor (ATI AI Nano 43 F/T sensor) as in Figure 7(a). Then each robot is commanded to drive the motor and the resulting forces created by moving the drive linkages are measured. Figure 7(b) shows the forces in the z-axis generated during three complete cycles for both DASH and CLASH when operated around 17Hz. These forces

The forces generated by CLASH in the normal direction are significantly less than DASH in these tests. The average magnitude of the normal force generated by CLASH is 85mN, or roughly half of the body weight; the average normal force magnitude for DASH is 283mN. The peak-to-peak normal forces are also 2.6 times larger in DASH than in CLASH. This increases the likelihood that instantaneous normal adhesion required to stay attached to the surface will stay within the force limitations of the foot and thus avoid premature disengagement.

B. Foot Performance

To test foot ground reaction forces, load-drag-pull step tests were performed on a custom built force displacement apparatus (Figure 8(a)) which consists of two main components. The first is an acrylic chuck used to hold the foot that is attached the force torque sensor, a goniometer (Newport GON-U-60) and two linear slides (Newport 423 slide). The second component is a custom built aluminum frame used to hold the substrate. This frame is mounted on two perpendicular stepper-motor-controlled linear stages (Zaber T-LSR 150B) and a second goniometer. The entire

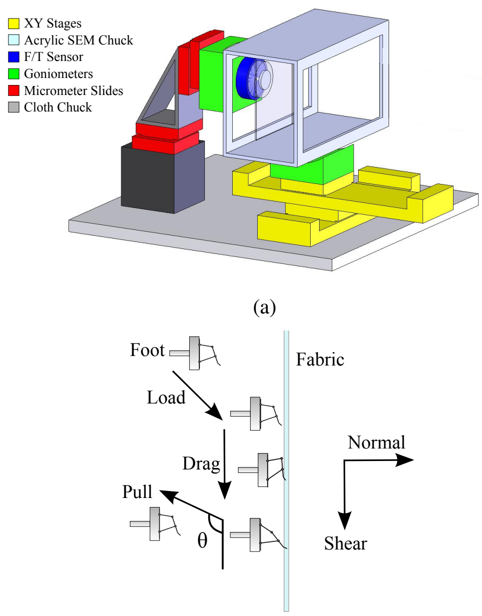


Fig. 8. (a) The force-displacement apparatus used to test the different foot designs. Feet were mounted on a force sensor and simulated steps were performed on a cloth substrate under displacement control. (b) The simulated step taken by the foot showing the varying pull-off angles that correspond to different running speeds.

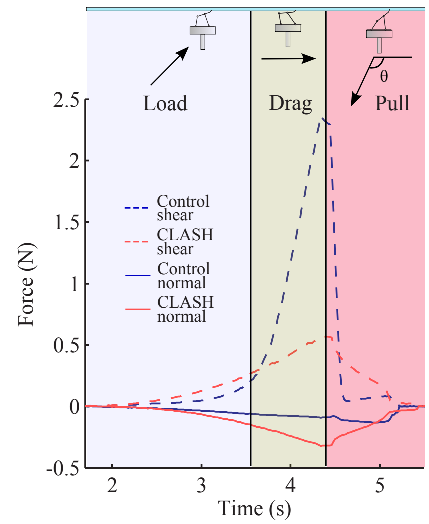


Fig. 9. An example plot of shear and normal forces during a simulated step for the CLASH and control foot. Important to note is the larger normal engagement force and faster disengagement of the CLASH foot.

apparatus is mounted onto an air table (Newport VH series) to dampen vibrations, and is also electrically grounded. This force displacement apparatus enables testing to be performed in a repeatable manner and allows various foot designs to be directly compared with each other.

Load-drag-pull steps (Figure 8(b)) were performed on the force displacement apparatus under displacement control for two foot designs; the first with a working four-bar flexure as found on the CLASH robot, and the second, a control foot with the four-bar locked joints. Each foot was tested on a cloth substrate at a variety of pull-off angles, θ, that simulates the robot running at a variety of speeds.

An example load-drag-pull cycle for CLASH and the control foot (Figure 9) show that during the load phase, the claws start to engage the cloth, and the shear and tensile normal forces grow. For the CLASH foot, the four-bar mechanism hooks and pulls against the fabric causing a larger tensile normal force than the control foot. During the drag phase, the foot engages further with the cloth. Since the control foot is very stiff, it experiences a much higher shear force as the claws fully engage and the fabric pushes against the foot structure. During the pull phase, the CLASH foot disengages rapidly due to the four-bar mechanism, as is seen by a decrease in the normal force. However, as the control foot disengages, the normal force increases as the entire foot structure cannot bend to release as the CLASH foot can. Once the claws finally release, the foot pops off the surface, and the forces return to zero.

One of the key features of a climbing foot is its ability to easily disengage from a surface during climbing with a low normal force. The retraction angle of the foot from the cloth surface not only depends on the leg trajectory and cloth curvature, but it also depends on the forward velocity of the robot. The motion of the foot relative to the ground is the difference between the foot motion relative to the body and motion of the body relative to the ground. Therefore, if the robot is climbing more slowly, the pull-off angle will be closer to vertical, assuming a 50% duty cycle as in

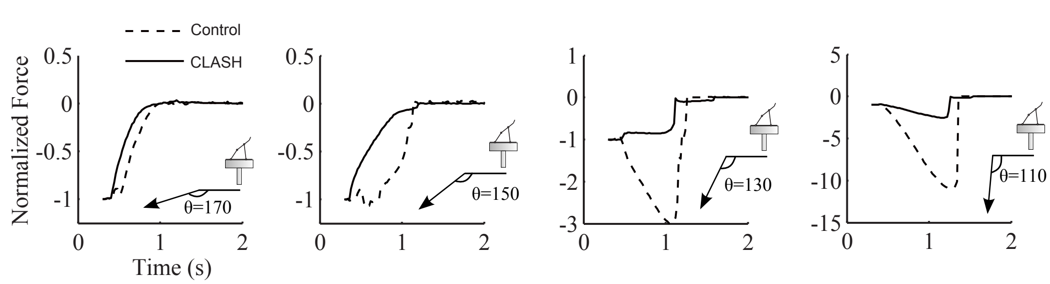
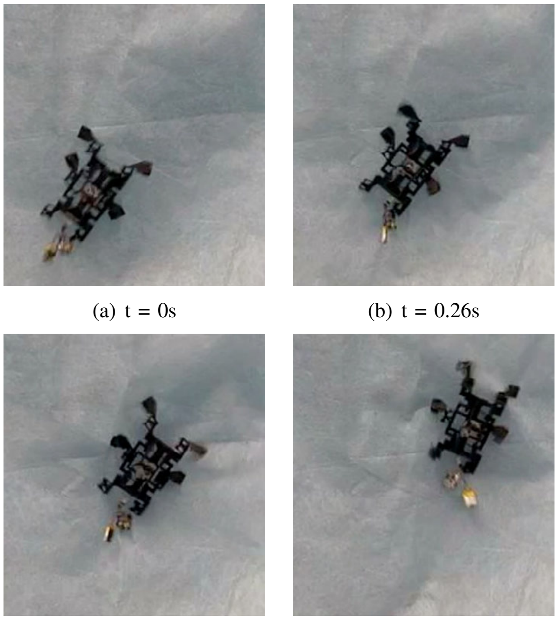


Fig. 10. Normalized forces during the pull-off phase for the CLASH and control foot for a variety of pull-off angles. As the pull-off angle decreases, the control foot requires a large increase in the normal force to disengage, whereas the CLASH foot disengages with a much lower force, a trait necessary for effective climbing.



(a) t = 0s (b) t = 0.26s

(c) t = 0.6s (d) t = 1s

Fig. 11. A sequence of frames from a video showing CLASH climbing a vertically hanging cloth.

CLASH. To determine the efficacy of the four-bar CLASH foot, normal pull-off forces were compared to the control foot at pull-off angles of 170^o, 150^o, 130^o and 110^o (Figure 10). At high angles ($\theta = 170^o$), the control and CLASH foot both decrease rapidly, showing that the feet can easily disengage from the surface. However, at lower angles, the control foot cannot easily disengage from the surface like the CLASH foot can, and this is seen as a large increase in the normal force. Without the four bar flexure in the CLASH foot, large normal forces are required to disengage the foot at low speeds, which makes climbing very difficult.

C. Climbing Performance

CLASH was initially tested on a piece of cloth draped over the edge of a table, thus constraining it only along the top edge. Figure 11 shows frames from these initial trials where CLASH climbs up this loosely hanging cloth. In these trials, CLASH is not equipped with either rear legs or a tail. The electronics, which would otherwise be mounted to the tail, hang beneath it freely. On this vertical cloth, CLASH achieves a forward velocity of approximately 19 cm/s, though its vertical velocity up the cloth is approximately 15cm/s. These correspond to 1.9 and 1.5 body-lengths per second, respectively.

CLASH was also tested on fabric draped over a cushioned surface with an incline varying from 85^o and 90^o above horizontal (Figure 12). In these trials, CLASH was equipped with stiff leg design from DASH on the rear hips, neither with any engagement mechanism. CLASH was also given a passive, rigid tail to which the electronics were mounted. In these trials, CLASH was able to achieve vertical velocities of approximately 24cm/s.

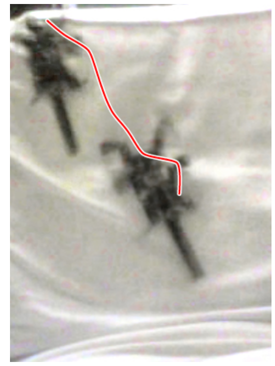


Fig. 12. The red path tracks the nose of CLASH is it climbs fabric draped over a cushioned surface. Two overlaid video frames show CLASH near the beginning and end of the climb. CLASH is equipped with a tail and rigid rear feet in this trial.

IV. Discussion of Results and Conclusions

As the first robot shown to climb on loose fabric (to the best of the authors' knowledge) the Climbing Autonomous Sprawled Hexapod represents a significant achievement in mobile robotics. CLASH achieves a vertical climbing rate of 15 cm/s on loose cloth and 24cm/s on near-vertical draped fabric, velocities that are comparable to the current fastest legged climbing robots when normalized by body length [6].

The new body and foot designs are key elements in the climbing performance of CLASH. The new body and transmission successfully reduced the mean magnitude of the COM accelerations out of the plane of the climbing surface by 70% from the DASH design. It maintains a low mass, moves the average COM position to only 7mm above the surface, and reduces the profile of the robot. The reduced profile, in addition to lowering the gravitational pitching moments, may also improve mobility by allowing it to navigate even smaller openings.

Figure 10 shows that the passive foot design of CLASH provides both enhanced tensile forces during stance and lower pull-off forces relative to the maximum tensile force during stance over the control foot. The foot increases the range of possible pull-off angles of the foot from the surface when compared to the rigid control foot. While the control foot has low retraction forces when the retraction angle θ is aligned with the spines and thus nearly parallel to the surface, it generates large pull-off forces once θ decreases. The four-bar foot mechanism allows for lower pull-off forces across a wider range of retraction angles. It also decreases the time during which the pull-off forces are generated. By reducing both the magnitude of the pull-off force and the time over which it is applied, the foot used by CLASH allows for smooth and efficient disengagement of the cloth surface. Being too easily removed could also make climbing difficult as it may not permit the robot to generate the required normal forces to overcome the gravitational pitching moment. However, as the foot mechanism is withdrawn at angles at 90^o and above, as would be the case when falling down the surface, the mechanism resists retraction and generates significant tensile normal forces.

TABLE I

COMPARISON OF COMPARABLE CLIMBING ROBOTS USING MECHANICAL ENGAGEMENT

	CLASH	SpinybotII [3]	Mini-Whegs [5]	RiSE v3 [2]	DynoClimber [6]
Size (cm)	10 x 5 x 10	58 x 27	8.9 x 5.4 x 3	70 x 51.5	40 x 11.6 x 7
Mass (g)	15	400	87	5400	2600
Mode of engagement	Spines	Spines	Velcro	Claw	Claw
Tested Media	loose cloth	brick, stucco	rigidly-backed fabric	wooden pole	rigidly-backed carpet
Vertical Speed (body-lengths/second)	1.5	0.04	0.28	0.3	1.5
Number of Actuators[1]	1	7	2	9	2

[1]CLASH is currently unable to turn, and would likely require an additional actuator to be able to turn. It is unknown if SpinybotII or RiSE v3 have demonstrated turning during climbing. Mini-Whegs can perform gradual turns while climbing.

For the climbing trials, it was found that the rear legs of CLASH were not necessary for vertical climbing, and if they were included, they did not require feet with surface engagement mechanisms. A tail was also not required for successful vertical cloth climbing, though it was sometimes attached and served as a useful place to mount electronics. Initial observations don't suggest dramatic improvements with the inclusion of the tail. Future work will explore the use of various rear legs to improve horizontal locomotion, and new tails will be examined to determine their utility in stability and turning, as recent biological studies suggest [12].

Other future work includes controllable turning during climbing, using the onboard sensors to provide feedback to guide the robot, and developing different feet that might work on a wider range of surfaces, including non-penetrable surfaces using synthetic gecko-inspired adhesives [13]. Various methods of turning will be explored, including tail-induced turning and turning via altered leg kinematics. Measuring the power to determine the specific resistance of CLASH may also provide useful feedback and educate the design of CLASH [14]. Toward true all-terrain robots, effort will be made to make CLASH attain the horizontal mobility of DASH while improving upon the current climbing results.

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