Maneuverability and Mobility in Palm-Sized Legged Robots

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ABSTRACT

Palm sized legged robots show promise for military and civilian applications, including exploration of hazardous or difficult to reach places, search and rescue, espionage, and battlefield reconnaissance. However, they also face many technical obstacles, including- but not limited to- actuator performance, weight constraints, processing power, and power density. This paper presents an overview of several robots from the Biomimetic Millisystems Laboratory at UC Berkeley, including the OctoRoACH, a steerable, running legged robot capable of basic navigation and equipped with a camera and active tail; CLASH, a dynamic climbing robot; and BOLT, a hybrid crawling and flying robot. The paper also discusses, and presents some preliminary solutions to, the technical obstacles listed above plus issues such as robustness to unstructured environments, limited sensing and communication bandwidths, and system integration.
Keywords: Mobile Robots, Millirobots, Search and Rescue, Espionage, Reconnaissance, Mobile Sensors

1. INTRODUCTION

Small crawling robots have made forward strides in mobility over the past several years[1-6] but still face formidable challenges with respect to mechanical design, electronics hardware and software, and general robustness. This paper discussed the challenges faced in the field, in the context of two robots and one accessory system.

2. CLASH AND ACTUATOR PERFORMANCE

While most obstacles are significantly larger than the body of mesoscale robots, smaller robots should have an easier time climbing over them. Well-known scaling laws suggest that climbing might be an application where small robots could achieve high levels of performance. As size of the robot decreases, the ratio of foot surface area to volume increases, as does the ratio of available adhesive forces to mass in general. Smaller, lighter robots are also able to climb surfaces that are too fragile or lack the asperities needed for larger robots. Current minimum bounds on available sensors, batteries, and onboard computation, in addition to manufacturing considerations, discourage the development of climbing robots below the mesoscale.

3.1 Design

The platform developed to show the utility of mesoscale SCM robots in climbing applications is CLASH[7], or Climbing Autonomous Sprawled Hexapod (Figure 1). CLASH is constructed with a single DC motor to create a phase-locked alternating tripod gait. CLASH is 10cm long and has a mass of 15 grams including the onboard electronics and battery. CLASH improves on previous designs by significantly lowering the center of mass to reduce pitching moments as well as by moving the center of mass to the posterior to encourage passive yaw stability during climbing.

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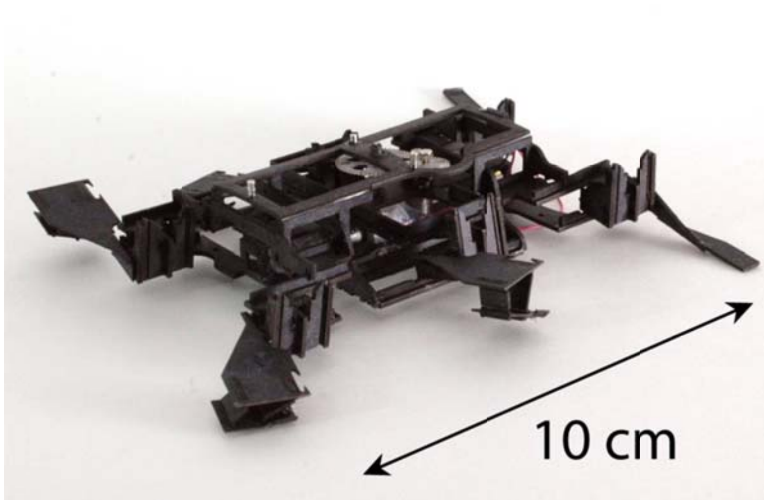


Figure 1 – CLASH with onboard battery mounted internally. The electronics are removed to reveal the body and transmission.

CLASH also improves upon previous designs by better managing the body dynamics created by the SCM transmission. The DASH robot, designed for high-speed locomotion on horizontal surfaces, had a transmission that generated large accelerations of the center of mass in the sagittal plane. The component of these accelerations in the normal direction (Figure 2) signify forces that either increase or decrease the normal load required by the robot to remain attached to the surface, i.e. negative forces push the robot into the surface, reducing the adhesion required, and positive forces push the robot away from the surface, requiring more adhesion from the feet to remain attached to the surface. The design of CLASH reduced the average normal accelerations by 70% from the DASH design.

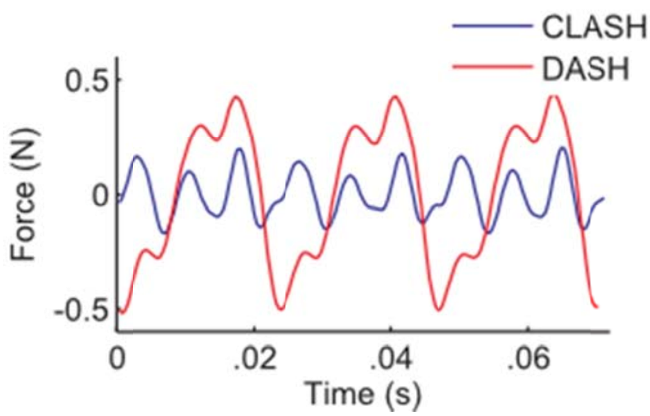


Figure 2 – The normal forces generated by DASH during operation (red) are significantly greater than those generated by CLASH (blue).

CLASH is equipped with a spine-based passive four-bar mechanism that creates a remote center of motion beneath the surface that allows it to climb loose cloth surfaces. By being designed without actuation, the passive feet simplify control and allow the robot to operate at high frequencies as they are not limited by feedback-control delays or actuator delays. The penetration-based spine engagement is largely agnostic to approach angle, which allows the robot to engage a cloth surface that has unpredictable curvature. The design in Figure 3 shows how the remote-center-of-motion design rotates upward to create tensile forces during stance and collapses to reduce normal pull off forces during retraction for easy and rapid disengagement.

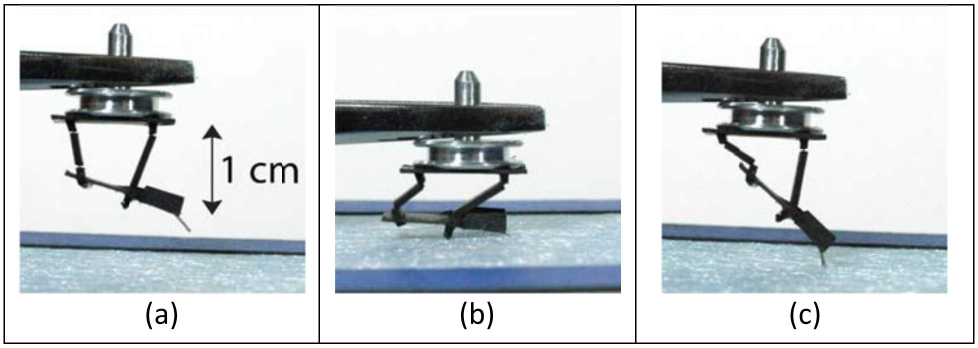


Figure 3 – Photos of the four-bar mechanism. Tweezers and an SEM aluminum mounts hold the leg where it would otherwise mount to a CLASH leg. (a) When not loaded, the spines angle slightly downward to facilitate penetration at impact. (b) When loaded during stance after engagement, the foot deflects slightly under the load and rotates the spines up, hooking the cloth to generate tensile normal forces. (c) When the foot is retracted, the spines easily collapse and rotate downward to be easily withdrawn from the cloth.

3.2 Performance

CLASH is able to climb vertical loose cloth at 15 cm/s and cloth draped over near-vertical backing at 24 cm/s. These speeds, when normalized to body-length, are comparable to the fastest climbing robots. Its small size allows it to climb loose cloth without largely deforming the cloth; a larger robot would likely significantly deform the cloth and make it much harder to climb. CLASH also shares similar manufacturing processes, scale, and mass to DASH, which has been shown to be very robust to large vertical falls[8], which means the system is more forgiving to missteps that result in falls than a larger robot would be.

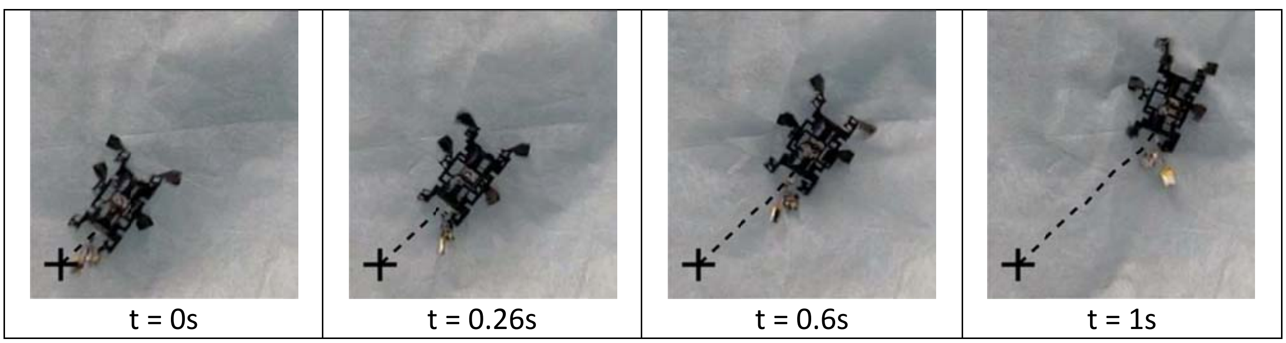


Figure 4 – A sequence of frames showing CLASH climbing loose vertical cloth.

3.3 Actuator Performance

To achieve maximum power density in these platforms for flight or rapid locomotion over various terrains, the mass, power density, and efficiency of the main actuator must all be considered. For intra-stride behaviors, the bandwidth and frequency-dependent operation of the actuator are also important. Table 1 shows a brief comparison of actuators, taken from Steltz[9]

Actuator	Stroke Length	Bandwidth	Efficiency	Power Density
Piezoelectric	★	★★★★★	★★	★★★★
Electroactive Polymer	★★★	★	★★	★★
DC motor	★★★★	★★★	★★★	★★★
Shape Memory Alloy	★★	★	★	★★★★★

Table 1 – Qualitative summary of actuator technologies, adapted from Steltz[9]

Shape memory alloy actuators offer very impressive power density, however they are slow, inefficient, and have low strain. Piezoelectric and electroactive polymers seem to work well for lightweight applications, but both are not ideal for use in mesoscale robots operating in the tens of Hz; piezoelectrics only have high power density when driven at high frequencies (>100Hz) and EAPs have low efficiencies and tend to operate below 10Hz. DC motors have a lower limit around 1 gram, beyond which their efficiencies and power densities drop significantly. However motors with a mass of a few grams have performance that makes them suitable for these platforms without overburdening the structure or size constraints. DC motors also benefit from having simple drive electronics which maintains low electronics overhead. Barring radical new actuation technologies, DC motors appear to be the appropriate actuator choice for palm-sized robots due to their compromise in efficiency, power density, bandwidth and stroke length. If future robots are made at smaller scales and capable of higher operating frequencies, other options such as piezoelectric actuators may be adopted. DC motors are also appropriate for intra-stride behaviors such as tail-based turning due to their bandwidth, stroke length and power density. However, the demands of auxiliary actuators for inter-stride behaviors, such as for gait modification or airfoil actuation, can be relaxed from those of the robot power plant. These actuators might be seldom used and do not require high bandwidth or high power density. Future designs may be able to improve overall performance and power density by choosing lighter actuators such as SMA to operate infrequently used auxiliary appendages or modulate gaits for steering or obstacle traversal.

3. BOLT AND WEIGHT CONSTRAINTS

Navigation of unstructured three-dimensional environments is a significant challenge for small mobile robots. Robots that are specialized for a single capability may encounter terrain they are unsuited for traversing. Large obstacles can impede crawling robots, while aquatic obstacles can prevent even robots capable of climbing from continuing. Gusts of wind and confined spaces often make conditions unsafe for aerial robots. A combination of abilities is often necessary to successfully navigate a truly diverse environment. Instead of optimizing towards a specific ability, we suggest that a hybrid robot capable of aerial and terrestrial locomotion provides an advantage when the environment is unstructured or unknown.

The Bipedal Ornithopter for Locomotion Transitioning, or BOLT (Fig. 5)[10], is a small lightweight robot capable of both aerial and terrestrial locomotion modes. While a few previous hybrid aerial/terrestrial robots have been developed – including MALV[11], its descendant MMALV[12] and the Skyhopper™ by WowWee™ – BOLT is currently the smallest. The total weight of BOLT is 11.4 grams, with a wingspan of 28 cm and a length of 17.5 cm. In addition to being capable of dynamic high-speed bipedal locomotion, BOLT can transition from terrestrial locomotion to hovering in as little as one meter of space, and has demonstrated the ability to takeoff on a variety of surfaces, including smooth tile, foam, carpeted flooring, and plywood. BOLT can also take off from inclined ledges, with up to a 45 degree slope tested. BOLT also incorporates a smart electronic package capable of measuring the dynamics of hybrid locomotion.

Fig. 5 BOLT: A bipedal ornithopter capable of both aerial and terrestrial locomotion.

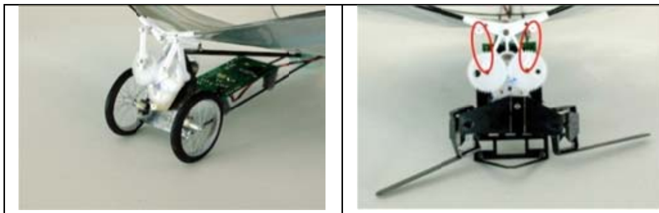
4.1 Design Considerations and Weight Constraints

Our initial exploration of a legged/winged robot design resulted in DASH+Wings[13], a six-legged, two-winged robot based on DASH[8]. DASH+Wings showed many advantages from its flapping wings, but was not capable of flight. However, this initial design illuminated several advantages to a hybrid robot, as well as keys to improving the performance. Flapping wings proved useful during the terrestrial locomotion of the robot, increasing both the speed and stability of the robot. Additionally, it was apparent that a hybrid robot at this size scale would require a tightly integrated design over a modular approach. The interplay between these two key lessons from DASH+Wings enabled the compromises necessary to balance the aerial and terrestrial facets of BOLT.

At small size scales, limits exist on the features of the robot due to the inherent weight and volume limitations. This effect is further compounded by the more stringent weight constraints of an aerial robot. With these limitations in mind, we attempt to balance the various features of the robot to create the most functional overall robot, instead of attempting to maximize any single ability. The use of multifunctional components is critical, as independent modules add too much weight to a design. A key difference between DASH+Wings and BOLT is the reduction from six legs to two legs. By relying on the wings for additional terrestrial thrust and stability, BOLT compensates for the loss of the stability provided by a six-legged alternating tripod gait. The leg mechanism also couples directly to the motor transmission driving the wings, enabling a single motor and gearbox to drive both the legs and wings of the robot. Overall, this integrated design significantly reduces the weight of the robot, and is critical for enabling the robot to fly. However, this ability does come at a cost: the terrestrial cost of transport for the robot is significantly higher than most robots optimized for this mode of locomotion.

4.2 Performance

To analyze the performance of BOLT, we compared the hybrid version with two control cases. To isolate the effects of the wings, we replace the legs with lightweight wheels (Fig. 6(a)). By removing the drive linkage from the wings, we reduce them to passive airfoils with the entire locomotive input generated by the legs (Fig. 6(b)).



(a) (b)

Fig. 6. (a) shows the first control case, the robot with wheels instead of legs, allowing the investigation of the wing effects alone. For the second control case (b), we disconnect the linkage driving the wings, removing any active effects from flapping.

By using its wings when running along the ground, BOLT is capable of accelerating very quickly. Starting from rest, the robot can generate accelerations up to 7.5 m/s^2, reaching 1 m/s in 0.14 s and 2 m/s in 0.38 s. By moving the location of the controller board (and thus the center of mass), BOLT can be configured to have different transition properties. Moving the controller board forward increases the distance required for takeoff (~2 m), while also increasing the maximum terrestrial speed (2.5 m/s). Additionally, it allows the board to be placed on foam offsets, improving the IMU measurements. When the board is moved to the back of the airframe, the takeoff distance is reduced to 1 meter. The speed where takeoff occurs is also reduced to 1.75 m/s. Once reaching the takeoff speed, the robot begins to pitch up and passively enters a vertical flight posture. The robot is passively stable in flight, and has approximately 5 minutes of flight time.

BOLT has also shown the ability to clear terrestrial obstacles, both with a running start and from standstill. With a purely terrestrial gait, BOLT can clear a 2 cm obstacle. With wheels replacing the legs the robot is unable to clear the 2 cm obstacle, clearly showing the necessity of the legs. Without the wings flapping, the robot can clear the obstacle, but does so inconsistently. With a hybrid “hopping” gait, achieved when running fast enough to begin flight, but not sustain flight, the robot can clear increasingly higher obstacles, until eventually sustained flight becomes necessary to surmount the obstacle.

Gait (frequency)		Configuration		
		Wings-Passive	Wings-Only	Hybrid
Quasi-static (9Hz)	Velocity	0.33	0.17	0.50
	Power	0.36	0.65	0.89
	COT	96.8	337.4	155.8
Dynamic (12 Hz)	Velocity	0.35	1.5	1.5
	Power	0.36	0.79	0.91
	COT	89.7	45.9	53.1

Table2: Forward Velocity (m/s) Motor Input Power (W) and Cost of Transport (J/(kg*m))

for different configurations and gaits

4. DYNAMIC TAIL AND UNSTRUCTURED ENVIRONMENTS

The dynamic tail is an accessory that can be added to suitable robots to increase their capabilities in certain domains. Previous work has shown that a dynamic tail can exploit the principle of conservation of angular momentum to execute turns more quickly and on lower friction surfaces than by other means[14], or to perform active pitch control while the robot is airborne[15,16]. This expansion of capabilities however, presents several challenges. Weight and sensor constraints are severe at this scale, and traveling on unstructured terrain also brings challenges of its own.

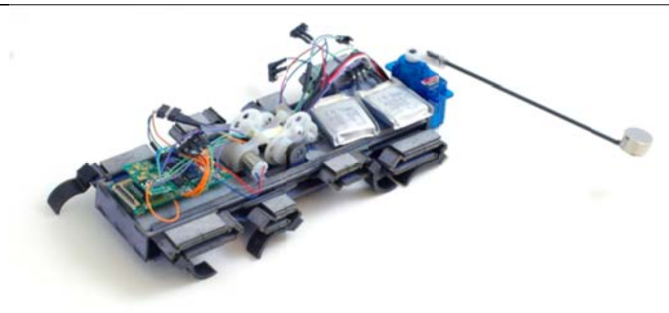


Fig. 7: The OctoRoACH equipped with a dynamic tail, allowing quick momentum exchange and turning capabilities on low-friction surfaces.

4.1 System Description

The tail is 8 cm long, with a 4g mass on the end. Its moment of inertia is approximately 2.5e-5 kg-m/s^2, about half that of the OctoRoACH itself. It is driven by a modified Hitec HS-55 servomotor. Servomotors are generally built for high torque, low speed applications. To produce high speeds, a gear is removed from the servo's transmission, and two gears are welded together, to reduce the numerical ratio significantly.

4.2 Modeling and Angular Momentum Exchange

The tail dynamics are modeled by considering the robot represented by a rigid body, and a point mass representing the tail. The tail is joined to the body by a pin joint, where toque can be applied.

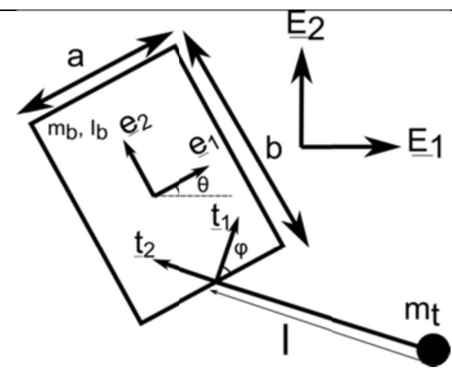


Fig. 8: Model of the robot with tail. I_b and m_b are the robot body's yaw inertia and body mass respectively. θ is its body angle. m_t is the mass of the tail, l is the length, and φ is the angle of rotation of the tail with respect to the ground.

We can define the angular momentum of the system as such:

$$H_{COM} = I_b\omega + m_b r_{b,COM} \times v_{b,COM} + m_t r_{t,COM} \times v_{t,COM}$$

This gives an expression for the angular momentum in terms of the robot's dimensions.

$$H_{COM} \cdot E_3 = \frac{1}{m_b + m_t}\left[\left((b^2 m_b m_t + I_b(m_b + m_t) + blm_b m_t \cos(\theta - \varphi)\right)\dot{\theta} + \left(blm_b m_t(l + b\cos(\theta - \varphi))\right)\dot{\varphi}\right]$$

As we can see, the exchange of angular momentum varies with the angle between the tail and body. Taking the time derivative of the angular momentum will give us the torque on the system, in this case the friction.

4.3 Performance Results

The tail is able to produce turns of about 40 degrees in a quarter of a second. This quick performance was achieved on a low friction tile surface, where differential steering is less effective.

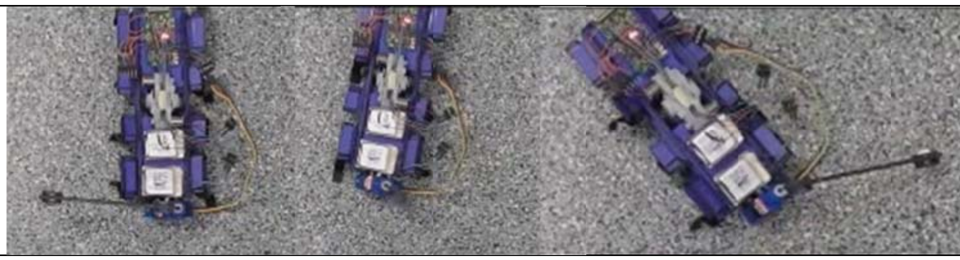


Fig. 9: The robot begins moving its tail CCW, inducing a small CW movement in the body. After impact, however, the body moves CCW significantly.

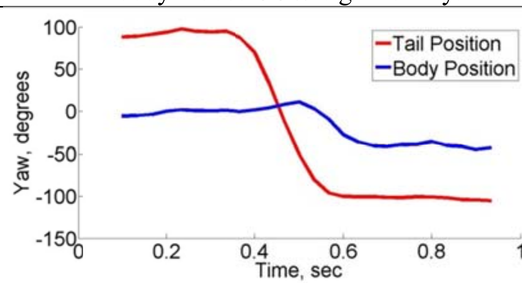


Fig. 10: A plot of tail and body position from the experiment in figure 2. Note that the robot begins to turn slightly when the tail is actuated, but most of the turning occurs after the tail decelerates.

4.4 Challenges in Unstructured Environments

These robots may encounter environments of almost any type, and must be able to tackle them with limited processing power, and limited actuation. This requires an intelligently designed system, using mechanical intelligence to be robust to a wide variety of challenges, while remaining small, light, and elegantly simple. The addition of the tail onto the OctoRoACH allows it to navigate smooth and rough strata with turning ability intact. The tail also may provide balance in an inclined environment. BOLT is able to navigate environments of varying obstacle size by choosing to crawl or fly. CLASH excels in scansorial environments, an especially challenging domain. Its close cousin DASH traverses ground terrain at high speeds, and the integration of these two capabilities would yield a highly robust robot.

Another major advantage of the mesoscale robot is its cost and production time, both very low. This allows thousands to be built for a single task- meaning failure of a particular unit is essentially meaningless. Robustness can be achieved by sending a swarm of robots into the field, of which only a few must be successful for the mission goals to be fulfilled. This decentralized strategy, often found in nature, may be the greatest potential of the mesoscale crawling robot.

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