

BIOMIMETICS

Forceful manipulation with micro air vehicles

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Micro air vehicles (MAVs) are finding use across an expanding range of applications. However, when interacting with the environment, they are limited by the maximum thrust they can produce. Here, we describe FlyCroTugs, a class of robots that adds to the mobility of MAVs the capability of forceful tugging up to 40 times their mass while adhering to a surface. This class of MAVs, which finds inspiration in the prey transportation strategy of wasps, exploits controllable adhesion or microspines to firmly adhere to the ground and then uses a winch to pull heavy objects. The combination of flight and adhesion for tugging creates a class of 100-gram multimodal MAVs that can rapidly traverse cluttered three-dimensional terrain and exert forces that affect human-scale environments. We discuss the energetics and scalability of this approach and demonstrate it for lifting a sensor into a partially collapsed building. We also demonstrate a team of two FlyCroTugs equipped with specialized end effectors for rotating a lever handle and opening a heavy door.

INTRODUCTION

Micro air vehicles (MAVs) are becoming pervasive across many applications. As electronic components shrink in size and cost, MAVs are finding increasing use in confined spaces and in close proximity to people (1). The small form factor in combination with aerial locomotion has fostered the application of MAVs for exploring and gathering information in cluttered spaces. However, a reduction in size generally comes with a reduction in thrust, which limits the ability to apply forces required to affect human-scale environments.

Forceful manipulation tasks have been the prerogative of large, mobile, terrestrial robots (2–4). Although forceful microrobots have been demonstrated (5), their size entails limited mobility, restricting them to unobstructed, flat environments. In comparison, most MAV applications have been limited to gathering information, without physical interaction with the environment (Fig. 1A). To our knowledge, there are no aerial robots that exert aerodynamic thrust in excess of twice their own mass (6–8). Therefore, tasks such as opening doors (9, 10) and turning valves (11) have only been demonstrated with aerial vehicles of substantial mass [1.7 (9) and 2.31 (10) kg; for (11), mass was unspecified but used 28-cm propellers]. Applying forces with sustained thrust that approaches a vehicle's mass is considered a challenge and requires specialized control (12).

Small biological fliers overcome this limitation by using attachment mechanisms and multimodal locomotion. Similar to MAVs, aerial organisms show scaling limitations concerning the maximum thrust they produce. A biological investigation on maximum lift production during takeoff in birds, bats, and insects showed that no surveyed animal surpassed 5.1× its weight (13). However, small fliers can use ground interaction to exert much larger forces. For example, studies on prey transport in wasps confirmed that, although their ability to produce aerodynamic force was limited by the amount of muscle dedicated to flight (14), they used ground locomotion and attachment to drag large prey back to their nests (Fig. 2A). When a load was too heavy for flight, they attached to the ground with claws and adhesive pads to pull via ground reaction forces.

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We adapted the multimodal locomotion strategy found in wasps to design FlyCroTug MAVs (Fig. 1B and Table 1). Our class of MAVs can transition from air to ground to exploit microspines or controllable adhesion, similar to the claws and adhesive arolium found on wasps (15), and adhere to a substrate for forceful manipulation. However, instead of dragging like wasps, FlyCroTugs tug via a tendon. This strategy is also found in nature. For example, *Pasilobus* spiders haul and manipulate prey by using threads and adhesive attachment (16).

The basic procedure for deploying a FlyCroTug is illustrated in Fig. 1C: (step 1) Fly to a remote object and attach a specialized end effector to it; (step 2) fly some distance away while paying out a tether; (step 3) land, reorient as desired, and anchor to the surface; (step 4) pull on the tether with a large force. This process can be repeated as many times as necessary and by as many FlyCroTugs as needed to accomplish a task.

In the following sections, we present the design of these multimodal robots and examine the comparative energetic costs of flying, crawling, and tugging to transport loads. We also examine scaling considerations. We demonstrate utility of this class of robots through specialized platforms tailored to two scenarios: (i) A FlyCroTug was used as a deployable attachment point for suspending heavy sensors in a damaged building, and (ii) a pair of FlyCroTugs were outfitted with specialized end effectors that opened a door through coordinated tugging.

RESULTS

We designed a class of palm-sized MAVs capable of forceful tugging to interact with objects much heavier than was possible with aerodynamic forces. Flight allowed rapid traversal of uneven and cluttered terrain; the ability to orient and adhere to surfaces allowed the robots to move heavy objects. We call the robots FlyCroTugs in reference to their ground-based counterparts: μ Tug robots, presented in (5).

Each FlyCroTug is composed of three main subsystems (Fig. 3): (i) a system for aerial locomotion; (ii) a forceful actuator to generate high forces, for example, a winch for tugging; and (iii) controllable adhesion [either gecko-inspired adhesives (17) or microspines (18)] to adhere to a substrate when the forceful actuator is operating. In addition, FlyCroTugs can be equipped with ground locomotion mechanisms, to precisely position and orient the drone on a desired surface after landing, and an application-specific end effector, which can be a gripper, hook, or adhesive pad, to interact with the object to manipulate.

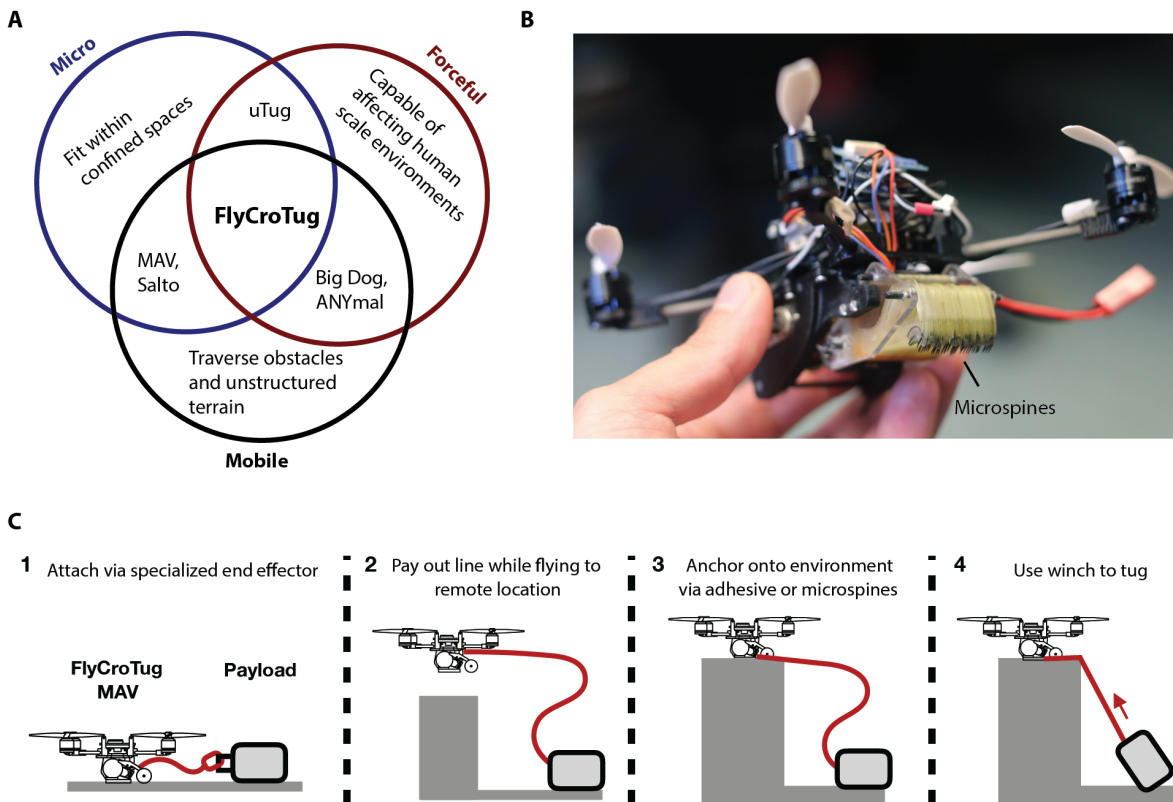


Fig. 1. The FlyCroTug system. (A) FlyCroTugs' multimodal operation allows them to combine small size, high mobility in cluttered and unstructured environments, and forceful manipulation. Several robotic systems demonstrate subsets of these attributes [e.g., MAVs (1), Salto (34), ANYmal (3), BigDog (35), and μ Tug (5)]. (B) A FlyCroTug with microspines for anchoring and a winch for tugging loads weighing 100 g and a 7.3-cm rotor distance from center. (C) Process of operation: Each robot (1) flies to an object and attaches a specialized end effector, (2) flies some distance away while paying out a cable, (3) lands and anchors to a surface using adhesives or microspines, and (4) pulls on the cable using a winch. Wheeled locomotion can be added in steps (1) and (3) for more precise positioning. The sequence repeats as necessary.

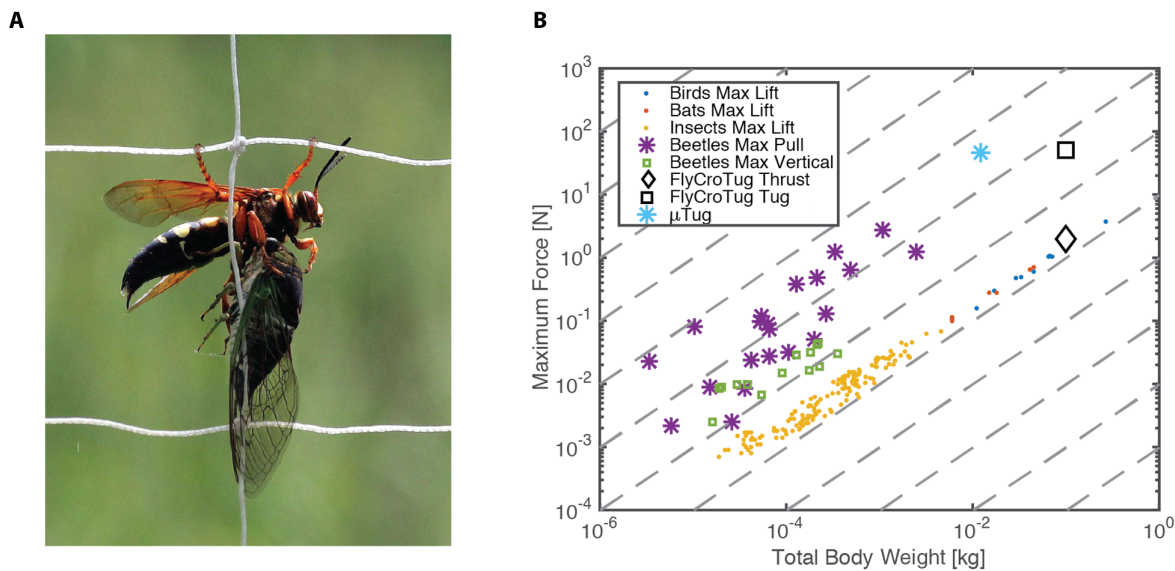


Fig. 2. Biological systems. (A) Like MAVs, wasps are limited by their thrust capabilities when transporting large payloads. Their solution of using attachment mechanisms to generate ground reaction forces suggests a portable approach for small fliers. Photo credit: (36). (B) Scaling trends in whole organisms/robots. Maximum forces reported for various organisms compared against small robots flying and tugging. Thrust data from (13) appendix, beetle pulling data from (19) table I, and beetle vertical force data from (20) table III. Data from diagonal lines show constant force/weight ratios.

Table 1. FlyCroTug specifications.

Mass	100 g
Rotor diameter	7.62 cm
Rotor mount distance from center	7.3 cm
Nominal battery voltage	7.4 V
Motor max power draw at V_{nominal}	12.2 W

The robots have a mass of ≈ 100 g with battery and generate reaction forces of up to 40 N, primarily parallel to the ground, depending on the substrate.

The force capabilities of FlyCroTugs make them comparable with small fliers like the wasp in Fig. 2A (for details, see section S1). We plot the robots' performance in Fig. 2B against data for maximum lift generation in flying animals at takeoff (13). Beetle data while pushing horizontally (19) and vertical forces while wedge-pushing are also plotted (20), where the wedge-shaped head is pushed forward into a crevice and the hindbody is oscillated vertically to enlarge a horizontal crevice for tasks such as burrowing. Plotting diagonal lines of constant force/weight reveals that most flying animals lie within a relatively narrow range, none exceeding 5.1 times its own weight. The thrust/weight ratio for FlyCroTugs is also comparable. In comparison, the force/weight ratios for beetles pushing are considerably higher. The maximum tugging force for FlyCroTugs on a smooth surface is essentially the same as for μ Tugs (21), but they are heavier, which puts them roughly along the trend line for beetles that push.

As with all solutions, the FlyCroTug approach involves trade-offs, and to better understand these, we examined the energetics ("Energetic analysis" section) and scalability ("Scalability" section) of the FlyCroTug robot class.

Energetic analysis

Different modes of locomotion with FlyCroTugs are energetically suited to move different ranges of payloads. For instance, transporting an object with a mass of 20 g would be feasible and fast via flight, most efficient on wheels, but slow and energetically wasteful to tug—if a micro-robot is capable of tugging anything 40 N and below, then that does not mean that it should.

The energetic efficiency to move an object is often characterized by the cost of transport (COT) = $\frac{P}{mgv}$ with m as the mass of the load, g as gravity, and v as the velocity with which the object moves (22). We model COT for moving different loads with different actuators to quantify the efficiency of each mode of manipulation. Calculations are described in section S2. Data and models for an external load moved across a level frictional surface are presented in Fig. 4 for a 100-g FlyCroTug robot using a 25 mm-by-25 mm gecko adhesive pad on a glass surface, operating off a 7.4-V lithium polymer battery. Our chosen frictional setup was a stainless steel object moved along a glass surface. The analysis here assumed tugging in a steady state, which is the dominant mode for continuous tugging and driving. Christensen *et al.* (5) presented alternative choices of actuation in small tugging robots, where a finite amount of work must be dedicated to engaging the microscopic fibrillar features of a gecko-inspired adhesive. For objects exceeding the FlyCroTug mass, tugging is superior. However, for objects of ≈ 10 g, crawling and carrying (driving) is more efficient. Flight efficiency

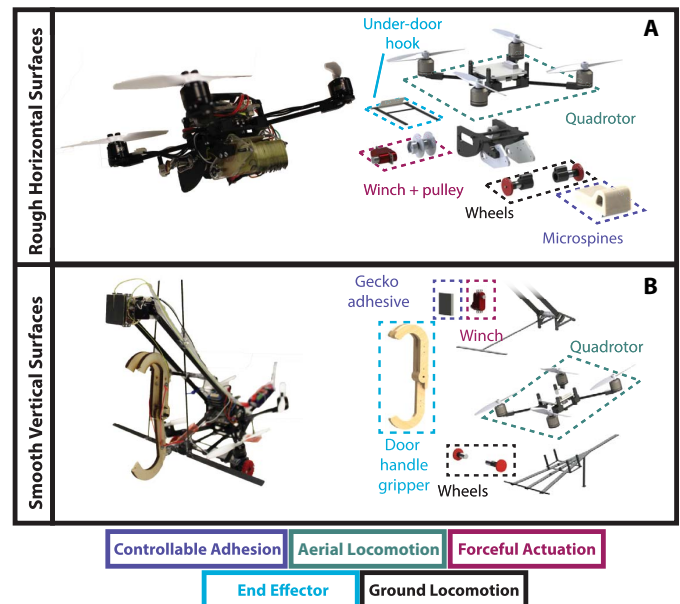


Fig. 3. FlyCroTugs are a modular class of robot with end effectors specialized for a targeted task. Two versions shown here are tailored toward opening a door and pulling a door handle. (A) A spring-loaded hook slips underneath a door to pull, and microspines anchor the robot to an indoor carpet or other rough surface. (B) A deployable gripper is mounted to the robot's frame to grasp a door handle. A pad of gecko-inspired adhesive anchors the robot to a smooth surface, allowing it to pull the handle down.

assuming straight level flight is plotted as a range of possible values in Fig. 4, accounting for variability in aerodynamic drag for different FlyCroTug designs.

There is an energetic incentive to transport heavy objects by using ground reaction forces, because generating large forces with small rotors carries the inherent cost of imparting kinetic energy to the air blowing past the rotors, characterized for our rotors in fig. S2. The theoretical induced power at a stationary hover scales as (23) $P = \sqrt{\frac{T^3}{2A\rho}}$

where P is the power expended, T is the thrust generated, A is the swept area of the propeller, and ρ is the density of the medium. Because the swept propeller area of a MAV is, by definition, small, exerting high forces becomes energetically costly and is compounded by inefficiencies in actuators and electronics at small scales (24). Budgeting of missions can be informed with these energetics in mind. The curves in Fig. 4 will shift somewhat with variations in mass, transmission ratio, etc, but the trends will remain.

Scalability

At 100 g, the FlyCroTug is able to extend its maximum force by up to 20 \times (maximum thrust at 2 N and tugging at 40 N). Scaling for actuators and adhesion suggest that the concept is most beneficial at smaller sizes, though feasible and useful at larger sizes.

Broad surveys of motors used for locomotion have shown that specific maximum force tends to scale differently between motors with slower linear motion and those used for dynamic force generation, such as propellers (25). Marden suggested that actuators progressing at a steady rate to produce translational motion (e.g., muscle, winches, and linear actuators) were often limited by the maximum stress along a cross-sectional area under a near-static load at the extreme of their

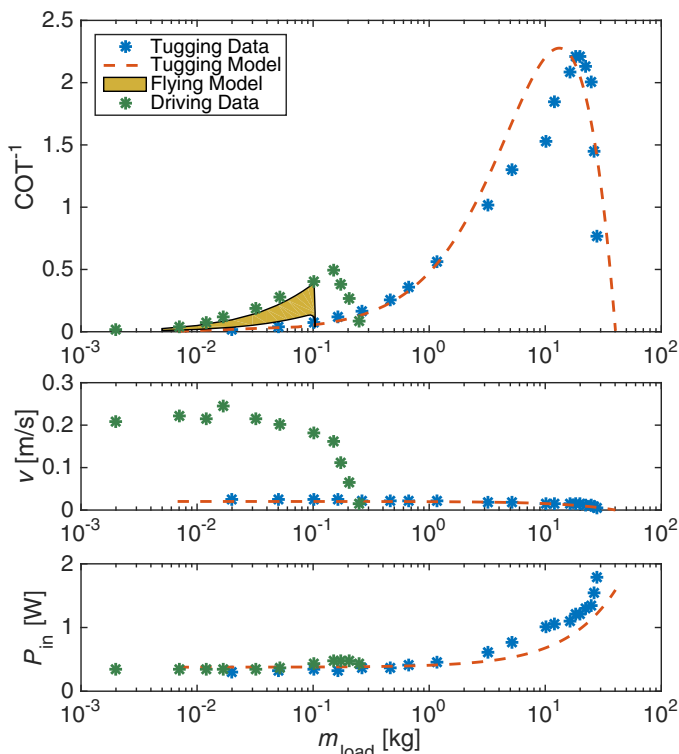


Fig. 4. Energetic efficiency. Efficiency of tugging, driving, and flying with different payloads, m_{load} , across a frictional surface (stainless steel on glass, $\mu = 0.15$) for a 100-g FlyCroTug robot equipped with a 25 mm-by-25 mm gecko adhesive pad oriented to engage with horizontal surfaces. COT^{-1} is plotted, the maxima indicating the most efficient load for a given mode of transportation along with the velocity, v , at which the object moves and electrical power into the system P_{in} . Driving involves towing the object, pulled behind the robot. Aerodynamic calculations for the flying model are described in section S2 (“Aerodynamic modeling” subsection), assuming steady level flight, and a range of drag coefficients to account for variability in the shape of payload and vehicle being transported.

force capabilities. The maximum force of these actuators scaled $\propto M^{2/3}$, with M being actuator mass. In contrast, actuators subjected to multi-axial stresses and inertial forces, such as the muscles of flying insects and birds (13) and electric motors in fliers, followed a more conservative trend. Maximum sustained exertion averaged over several cycles (rather than peak transient force) scales with M and represents a compromise to mitigate fatigue over many cycles. We reproduced the scaling trends presented by Marden (25) in Fig. 5, along with his data for maximum lift for biological flight motors (13). The difference between these two trends suggests that it is beneficial to include a slow forceful actuator on a microrobot (winch forces $\propto M^{2/3}$) on a MAV (thrust production $\propto M$) at small scales.

Adhesion becomes stronger, per unit weight of robot, as size isometrically decreases. Maximum gecko-inspired adhesive forces have been shown to scale with engaged surface area when proper load sharing is used (26), again scaling with $M_{\text{robot}}^{2/3}$ against mass of the system, M_{robot} . Thus, adhesion affords an improvement in force over both friction and aerodynamic thrust (both $\propto M_{\text{robot}}$), as a system decreases in size. Scaling the FlyCroTug concept to sizes larger than 100-g drones should be feasible as well. Hawkes *et al.* (26) demonstrated scaling up directional adhesives with nearly constant stress. Similarly, Wang *et al.* (27) scaled microspines to support up to 710 N in shear on coarse

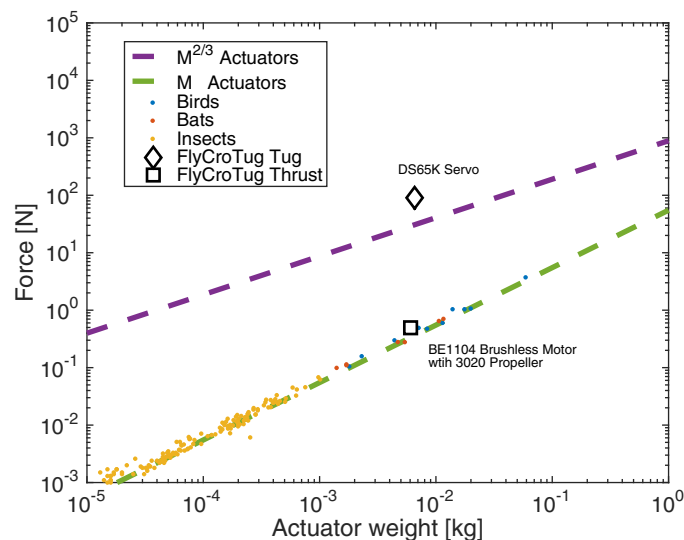


Fig. 5. Scaling trends in actuators. Marden proposes two trends of scaling in maximum specific force of actuators (24). “ $M^{2/3}$ actuators” (e.g., molecules, muscles, winches, and linear actuators) move with slower linear motions, with force outputs limited by maximum axial stress, scaling with $F_{\text{max}} = 891M^{0.67}$. “ M actuators” (e.g., forces from flying birds, bats and insects, swimming and running animals, piston engines, and electric motors) produce force with more rapid cycling and substantial internal forces that risk failure under low cycle fatigue, scaling with a more conservative $F_{\text{max}} = 55M^{0.99}$. We overlay our choices of actuators for FlyCroTug thrust and tugging as discussed in the “Scalability” section along with biological data from (13) appendix.

concrete with a 120 mm-by-100 mm area of densely packed spines. Thus, it should be feasible to scale a FlyCroTug drone to exert forces comparable to those of a typical human.

Single platform for sensor lifting

Perch-and-stare applications, which used a lightweight sensor suite aboard the MAV to inspect structures or to gather environmental data, have been proposed (28). FlyCroTug robots offer the ability to attach to a surface and haul payloads larger than a MAV can fly with, from which personnel can suspend a sensor suite or begin to support more elaborate setups by using FlyCroTugs as anchor points. We demonstrated a single FlyCroTug platform by lifting a sensor load intended for inspection at the Epeisse military training facility outside of Geneva, Switzerland, as illustrated in Fig. 6A (see also movie S1). A camera, panning servo, and dedicated battery weighing twice the weight of the MAV (200 g) were hauled up to inspect the open shelves of a collapsed building. The robot was equipped with a set of 32 microspines capable of attaching to rough surfaces (18), typical of a debris-ridden disaster zone. The MAV was guided onto an overhang where suitable attachment surfaces on exposed concrete faces were able to hold 2 to 3 kg, primarily in shear. Once lifted, the payload hung suspended without energy consumption, aside from communication electronics. Similar operations could be conducted on sloping surfaces or with multiple MAVs attached to set up a tether system to allow the payload to be moved in more than one direction, similar to the cable perching system shown in (29).

Coordinated team for door opening

Multiple FlyCroTug robots can be coordinated as a team for more complex tasks of forceful manipulation. We used a pair of FlyCroTug robots to open a door, as depicted in Fig. 6B (see also movie S2). The

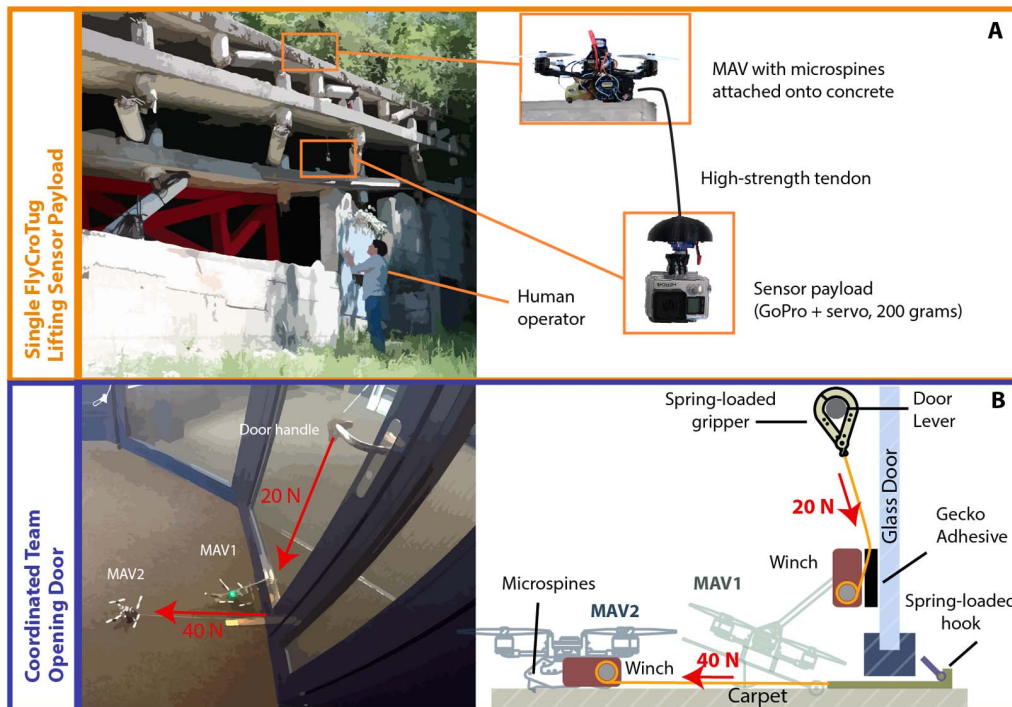


Fig. 6. Several FlyCroTug robots were specialized for different applications. (A) FlyCroTug robot for infrastructure inspection, as described in the “Single platform for sensor lifting” section. The 100-g robot, equipped with microspines, was guided to a suitable attachment point while paying out a cable attached to a sensor. After attachment, a human operator commanded it to lift a 200-g sensor payload, suspending it alongside a collapsed building. (B) A team of two robots opened a door with specialized end effectors, as described in the “Coordinated team for door opening” section. MAV1 attached a gripper onto the door handle and then pressed gecko-inspired adhesives onto the glass pane to pull the door handle down with 20 N of force generated via the adhesive. In tandem, MAV2 slipped a hook underneath the door, anchored onto the carpeted floor with microspines, and tugged the door open, pulling with 40 N.

task required exerting forces up to 40× the MAV weight and a heterogeneous team specialized for attaching to different surfaces. One member of the team was able to grab the door handle with a specialized grappling end effector and then attach to the door glass with adhesive. The other has a spring-loaded hook and an array of spines for attaching to carpeting.

Door opening involved several steps. MAV2 landed, reoriented, and slipped its hook under the door. It then latched onto the carpet with its microspines to generate a horizontal force. Meanwhile, MAV1 hooked onto the door handle in flight and then landed and attached its gecko-inspired adhesive onto the glass. Sequentially, MAV1 pulled the door handle down with 20 N of force and MAV2 pulled the door open with 40 N horizontally.

The maximum adhesion force is dependent on the direction of loading. Hence, the maximum tug force of a FlyCroTug depends on where it attaches in its environment and how it orients itself. The limitation on tangential and normal forces of each adhesive upon a given substrate is characterized by a limit surface, as depicted in Fig. 7 for 25 mm by 25 mm of adhesive on a glass surface (30). Similar force limitations characterize microspines (18). These limitations have implications for planning. For example, considering both the adhesive limitations and task requirements, Fig. 7A shows that it is beneficial to position the robot as far below the handle as possible because the adhesive is stronger when loaded nearly in shear and the pulling force is better aligned for rotating the handle. This example shows how tugging via a long tendon allows one to mitigate the transmission of undesirable moments exerted on adhesives.

DISCUSSION

Multimodal aerial and terrestrial locomotion allows robots and small animals to use different types of environmental interactions for different purposes. On the one hand, flying decouples mobility from step length or obstacle size by relying on the generation of aerodynamic thrust through a continuous medium, providing versatile locomotion at a low cost of complexity (31). This is particularly useful for microrobots where scaling can hinder mobility, especially in cluttered terrain. On the other hand, transitioning to terrestrial locomotion allows them to adhere to a substrate and to recruit strong actuators to apply forces an order of magnitude larger than the weight of the robot.

When FlyCroTugs move objects through a sequence of tugging actions, the process resembles other nonprehensile modes of manipulation studied in robotics. For example, Mason (32) and Lynch and Mason (33) addressed planning for pushing objects with friction on a planar surface. Instead of pushing with friction, FlyCroTug MAVs pull with adhesion, along a straight line of the cable. Pulling offers advantages for our application: Loading through high-strength cables minimizes adverse moments capable of disengaging the adhesives and offers a lightweight transmission of forces without concern for elastic deformations or buckling that could arise with slender members in compression. The cables can also be very long in comparison with object size, affording the MAV many possible landing and attachment sites.

We demonstrated forceful manipulation with MAVs; however, several areas need to be addressed to achieve autonomy and full operation in unknown environments. With a flight time of 5 min on a 300-mAh

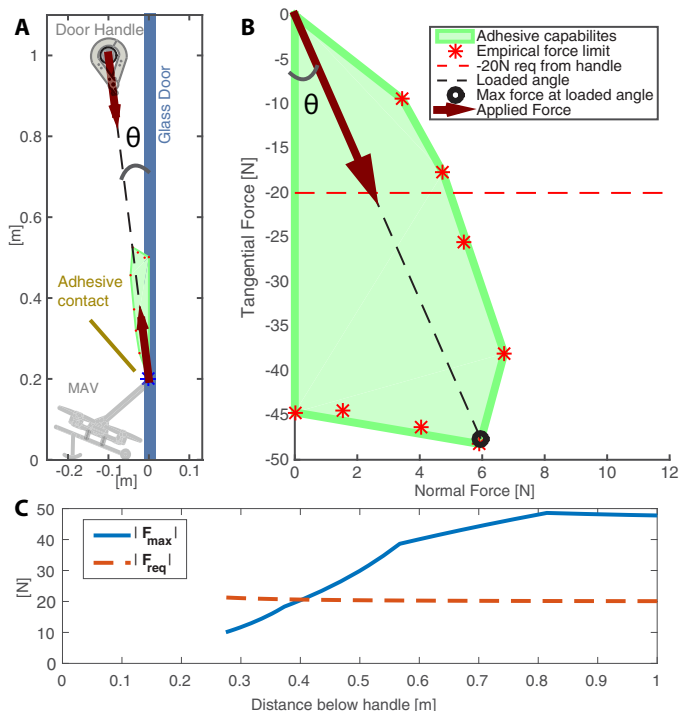


Fig. 7. Adhesive loading angle and maximum load are dictated by the MAV's point of attachment. (A) The door-handle MAV from Fig. 6 placed a patch of adhesive against the glass door, which dictated a loading angle. A force of 20 N oriented vertically downward was necessary to make the handle move. (B) Data taken from (29) show the maximum available force tangential and normal to a glass surface. The magnitude of this limit surface changed with different surfaces. Loaded at an angle of 7° from tangent, the adhesive can sustain sufficient force. (C) Because of the changing loading angle of the adhesive and door handle, the magnitude of maximum available force, F_{max} , is determined by the distance the adhesive is placed below the door handle. This distance also affects the magnitude of net force vector F_{req} required to pull the handle with a component of 20 N downward.

battery, the robots are only suited for brief, short-range operation; a single FlyCroTug would be hard pressed to perform tasks involving multiple steps. The robots demonstrated here were specialized for known tasks, whereas unknown environments would require a variety of attachment solutions for the objects and surfaces encountered. Sensing surface textures and perceiving and planning within three-dimensional environments offer rich challenges unaddressed here. Varying adhesive constraints on different types of surfaces within an environment would surely present a more discontinuous problem than the friction-based pushing presented in (33).

Teleoperation, use of permanent adhesives less sensitive to surface textures, and treating FlyCroTugs as disposable, single-use agents offer promising solutions toward utility in the field. This technology would be well accompanied by a mobile home base for recharging or transporting heavier equipment supporting monitoring and control. Finer manipulation could entail several FlyCroTug robots grasping a single object, a configuration that could exert forces in multiple directions, or even suspend loads similar to perching via cables as in (29).

Forceful manipulation with aerial vehicles could present new methods for search and rescue. Tasks defined in the Defense Advanced Research Projects Agency (DARPA) Grand Robotics Challenge (4) provide a sample of desirable capabilities in rescue robotics. Tasks involving locomotion

become fundamentally different when flight is a possibility (e.g., drive a utility vehicle to a site, travel dismounted across rubble, climb an industrial ladder, and traverse an industrial walkway). Many tasks involving low levels of dexterity lie within the force regime of FlyCroTug robots (e.g., remove debris blocking an entryway, open a door, and enter a building). Tasks involving finer manipulation (e.g., connect a fire hose to a standpipe and turn on a valve or locate and close a valve near a leaking pipe) are harder to accomplish while airborne or constrained to exerting force along a single direction with tugging, although swarm operation of FlyCroTug teams may offer solutions.

MATERIALS AND METHODS

Aerial vehicle

The foundation of each FlyCroTug robot is a custom-built quadrotor based on the TauLabs Sparky 2.0, 32 autopilot. The controller features a PicoC C interpreter module, useful for adding peripheral features such as extra actuators. The vehicle consists of four DYS BE1104-4000KV outrunner motors with plastic, 3020 propellers, both sourced from HobbyKing. A 2S lithium polymer battery powers all electronics and actuators at a nominal 7.4 V. The 6.3-g motor plus propeller actuator can provide a maximum thrust of 0.49 N at 7.4 V, although it is specified to provide up to 1.8 N while drawing 81 W when driven at 14.8 V on a 4S battery.

Each drone was manually operated, communicating between a FrSky Taranis 2.4-GHz radio controller communicating to the XM Plus Mini Receiver. Additional actuation separate from flight was controlled by a TinyDuino microcontroller communicating with the Sparky 2.0 autopilot. Radio controller input channels were passed to the microcontroller via serial communication.

Tugging and ground locomotion

Actuators were as in (21). A DS65K MSK servo was used as a winch, circumventing the potentiometer and position control to operate it as a continuous motor with gear train. The 6.5-g servo was able to exert 88 N at stall, when a cable was mounted at the output shaft's minimum diameter. For terrestrial rolling locomotion, the robots used Solarbotics GM15A gear motors with a 25:1 reduction.

Adhesion

For attaching to smooth surfaces, the robots used a square 25 mm-by-25 mm pad of directional adhesive (17), capable of generating 45 N of shear force. The gecko adhesives still adhered to rougher materials, though to a lesser extent. A video of a FlyCroTug robot equipped with gecko adhesive attaching onto a laboratory counter top and lifting 600 g can be seen in movie S4. In another version, the robot was outfitted with microspines (18); 32 miniature fish hooks were mounted on independent compliant suspensions that provided load sharing.

SUPPLEMENTARY MATERIALS

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Section S1. Bioinspiration from literature on maximum thrust generation and multimodal locomotion strategies observed in wasps

Section S2. Energetic calculations for tugging and flying of a payload using a FlyCroTug robot Fig. S1. Wasps are limited by their loaded flight muscle ratio (FMR_L) when flying with prey.

Fig. S2. Data and calculations for aerodynamic analysis in the "Aerodynamic modeling" section.

Table S1. Parameters used in tugging energetic model.

Table S2. Aerodynamic parameters used for modeling of FlyCroTug flight.

Movie S1. Lifting a payload for building inspection.

Movie S2. Coordinated team of two FlyCroTugs opening a door using gecko-inspired adhesive and microspines.

Movie S3. Initial FlyCroTug prototype lifting 600 g, attaching onto a laboratory tabletop.

Movie S4. FlyCroTug MAV flying in a cluttered environment.

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