The Flying Monkey: a multifunctional mesoscale robot that can run, fly, and grasp

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Abstract— **The possibilities and ease of control make a quadrotor aircraft an attractive platform for studying swarm behavior, modeling, and control. The energetics of sustained flight for small aircraft, however, limit typical applications to only a few minutes. Adding payloads – and the mechanisms used to manipulate them – reduces this flight time even further. In this paper we present the flying monkey, a novel robot platform having three main capabilities: walking, grasping, and flight. This new robotic platform merges one of the world's smallest quadrotor aircraft - the Dragonfly, with a lightweight, single-degree-of-freedom walking mechanism and an SMA-actuated gripper to enable all three functions in a 30 g package. The main goal and key contribution of this paper is to design and prototype the flying monkey that has increased mission life and capabilities through the combination of the functionalities of legged and aerial robots.**

Fig. 1: Our 30g flying monkey . Videos of the experiments conducted are available as a video attachment and at `http://mrsl.grasp.upenn.edu/yashm/ICRA2016.mp4`.

I. INTRODUCTION

Recent trends in robotics showcase the possibilities of novel manufacturing techniques, ever-shrinking electronic systems, and new concepts in swarm behavior. High-power motor/driver systems, small-form-factor lithium batteries, and compact board designs have produced systems composed of tens of quadrotor aircraft capable of stable, controlled swarming flight [1] [2]. Low-cost, single board designs have permitted simple robotic systems to be scaled to thousand-robot swarms [3]. Related manufacturing techniques inspired by origami and popup books have allowed small, electromechanical systems to be tightly integrated into flying and walking systems at a variety of size scales, while providing several possible methods for scaling mechanism assembly to a high numbers of devices [4]–[6].

Despite their many technical innovations, these devices face a common set of problems. Manual processes, such as board population, device interconnection and mechanical assembly steps are required for devices made in small batches. In addition, with small payloads, and thus small battery capacities, devices can move for a matter of hours on the ground and minutes in the air. Furthermore, these devices are typically single-function, making their use-cases extremely limited; this is suitable for toys and educational platforms, but not for general robotics applications.

In order to address the last two challenges, we hypothesize that combining multiple capabilities in the same device will allow robots to more directly interact with their surroundings while allowing the device to trade off energy and usage considerations. Walking, compared to flying, is a relatively safe, low-power state where the impact of a failing battery has fewer unfavorable effects and the cost of not moving is closer to zero. Walking potentially permits the device to carry heavier payloads, and access vertically-limited spaces where flying is not safe. Adding flying to a walking-only machine permits this device to escape from difficult terrain. The option of both modalities allows the device to select how fast to use the limited energy available in its batteries. The combination of both capabilities permits the possibility of hybrid control scenarios where turning capabilities can be provided by propellers, resulting in a simpler, lighter walking mechanism.

Similarly, the ability to grasp objects in the world in combination with multi-modal transportation options permits a device to transport objects, reconfigure surroundings, and to interact with other devices. In this paper, we present a centimeter-scale robot capable of more than just terrestrial locomotion, flight, or grasping. By combining these three functions, we hope to develop a new class of robots capable of not just operating in the world, but and accessing it more completely, interacting with and modifying it.

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Fig. 2: A sequence of photographs demonstrating the multi-modal trajectory tracking capability of the flying monkey .

II. Background

By combining the two modes of locomotion, mobility and efficiency of the mobile robot can be greatly improved. Researchers have tried to minimize additional mass in combining multi-modal locomotion. By morphing wings into legs, the flying robot could walk without the need for additional leg mechanisms, thereby reducing the overall weight of the robot [7]. On the other hand, by adding a simple and light rolling cage, the quadrotor could be able to roll along the floor or fly [8]. There are still a lot of different ways to achieve multi-modal locomotion with simple and lightweight structures. Origami inspired folding laminate devices show promise for testing new designs and mechanisms thanks to their fast prototyping and design iteration capability.

A. Folded Laminate Devices

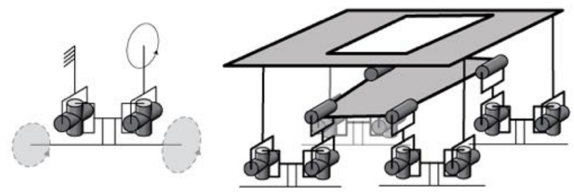
Origami inspired designs and mechanisms facilitate rapid prototyping of robotic systems, saving time and effort. Popup book MEMS processes [4] with smart composite structures [9] and PopupCAD [10] have enabled us to construction a crawler that has a lightweight and simple folding mechanism using sheet materials and an origami-inspired design. Currently, folded / laminate devices have developed and they have proven those can replace conventional mechanical system with simple folding structures with functions of sensing and monitoring, gripping [11], locomotion [12], mobile manipulation [11], self-folding for the assembly of structures [13], [14], and robots [15].

B. Multi-modal Locomotion

In nature, we can observe several species such as bats and flying insects that have multiple modes of locomotion for mobility in various environments, terrains, and to overcome obstacles. In addition, changing the mode of locomotion may save energy used during transport. The benefits of multi-modal locomotion have been proven by various robots. By combining a fixed-wing micro air vehicle (MAV) with a crawling robot, the resulting robot has proved to have a larger range of movement compensating each mode of locomotion. R. Bachmann et al. [16] developed a 30.5cm robot capable of aerial and terrestrial locomotion which move 4.9km by flying and 0.99km by crawling. Jumping and gliding robots increased mobility expanding its size limits and could move much longer with same energy. MultiMo-Bat in M. Woodward et al. [17] jumps 3m vertically and glides 2.3m horizontally with 115.6g in body mass and 30cm in the largest dimension of robot. A. L. Desbiens et al. [18] shows another jumpgliding robot that has a pivoting wing that reduces the drag in jumping mode. The jumpgliding robot achieved a greater range of motion and lower cost of transport than a ballistic jumping robot.

III. Crawler

A. Kinematics of the Crawler's Leg Mechanism



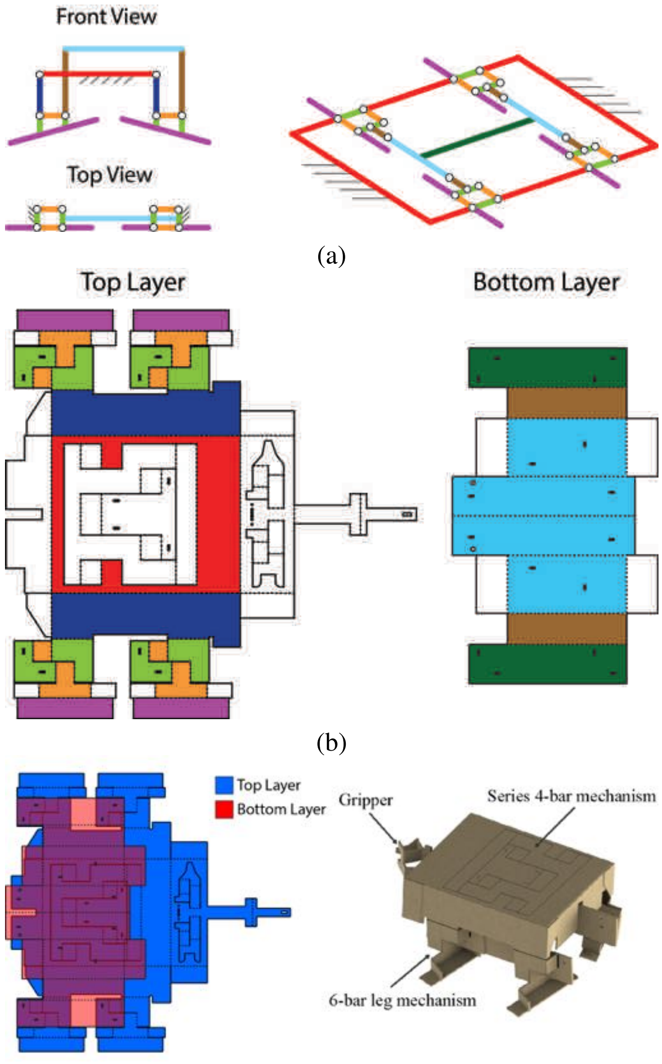
(a) (b)

Fig. 3: Kinematics of the single leg mechanism consists of two universal joints (a), and a mechanism that has four hips and eight feet (b).

The crawling mechanism is based off of the hexapod DASH mechanism developed at UC Berkeley [19]. However, our design has eight feet; four outer feet and four inner feet touch the ground alternately. The symmetry of the eight-legged mechanism allows four feet to bear the weight of the robot equally at all times. In a hexapod design, one foot on one side of the robot bears twice the weight of two feet on the other side of the robot. Due to the compliance of the joints, the symmetric eight-legged mechanism was preferable to a hexapod mechanism because it minimized asymmetries in the deformation of the legs and feet.

The kinematics are shown in Fig. 3. A motor mounted to the frame of the robot is used to rotate the central shaft, which in turn moves the four hips. Each hip has two feet, one pointing in and one pointing out. Both feet follow a circular trajectory but are 180 degrees out of phase, so that the outer foot touches the ground when the inner foot is in the air and vice versa.

A series four-bar mechanism was added to the crawler in order to constrain the degrees of freedom of the leg mechanism to the y and z - directions. The crawler has only one degree of freedom so that it can move only forward and backward. Steering is achieved by taking advantage of the yaw of the integrated quadrotor and compliance in the joints of the crawler.



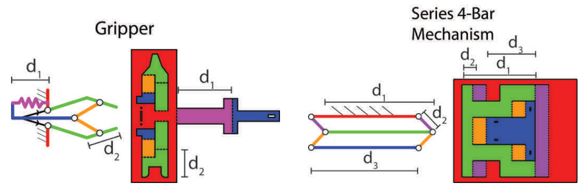
(a) (b) (c)

Fig. 4: Pattern design of the crawler (a, b) Color-coded diagrams of the kinematic structure of the robot correspond to linkages in the 2-D layout of the top and bottom laminates (c) The bottom laminate is overlaid on the top laminate and the structure is folded into a robot

B. Laminate Pattern Design

The crawler has two layers to transform kinematics into a popup design. First, the kinematics shown in Fig. 3 are converted into a linkage structure that consists of rigid links and revolute joints in order to make it easy to transform into a folding pattern as shown in Fig. 4(a). Links are facet and revolute joints based on folding lines in the pattern of Fig. 4(b). Each corresponding link is indicated with a same color.

The gripper consists of two four-bar mechanisms with extensions that can be pulled together and pushed apart. A built-in passive spring pulls the gripper in so that the gripper is closed by default. A shape memory alloy (SMA) is used to pull the main shaft of the gripper out to open it. Fig. 6 shows a closeup of the gripper in its open 6b and closed 6a positions. On the flying monkey , the onboard

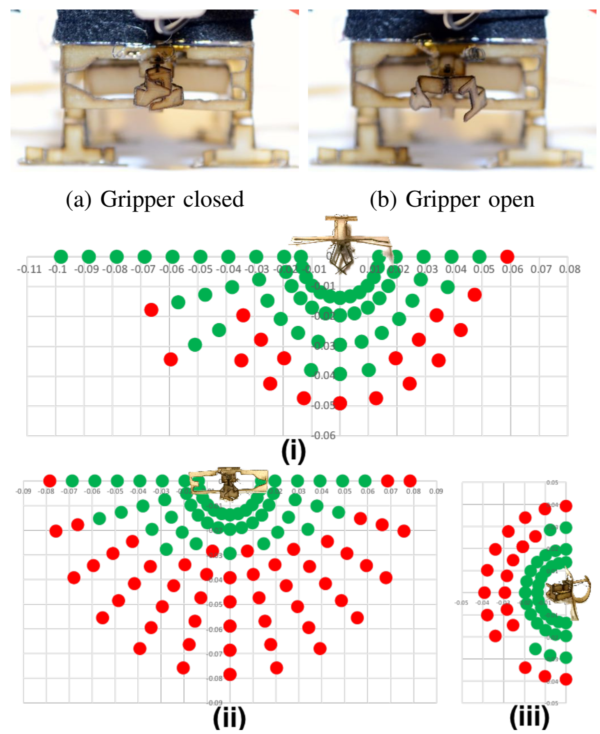


(a) (b)

Fig. 5: Gripper and Series 4-Bar Mechanisms

micro-controller controls the SMA actuator through one of the digital outputs and a high power MOSFET. Section IV describes rest of the hardware of the flying monkey in detail.

Max gripping load was measured by testing what weights the gripper could and could not support. Weights were suspended from a segment of a drinking straw, and the gripper was clamped around the straw. The weights started at 1.4g, then 2g, then increased in 1g increments until the straw slipped from the gripper. A test was considered a failure if the straw slipped out of the gripper and a success if it did not. The results are shown in Fig. **??**.



(a) Gripper closed (b) Gripper open

(i) (ii) (iii)

Fig. 6: The gripper mechanism(a,b), Gripper pull-out force data in (i) yaw, (ii) roll and (iii) pitch. Units are given in Newtons, and directions are in 15-degree increments. Successful grasps are shown in green, and failures in red

C. Fabrication

Recent advances in techniques for analyzing laminate geometries, determining manufacturability, and automating the creation of laminate device manufacturing files have yielded positive results for quickly generating articulated, multi-material electromechanical devices [6]. These devices, though designed and manufactured in-plane, are capable of complex three-dimensional motion and can be linked together to form even-higher-dimensional motion with some guarantees that they can be manufactured using simple, planar, manufacturing processes and straight-line out-of-plane assembly and removal motions [20]. These components can be saved and reused in an object-oriented fashion using a purpose-built software tool called popupCAD [21], a design suite that stores and operates upon layered sets of planar geometries. PopupCAD is also capable of deriving three-dimensional equations of motion from the multibody systems which result from the pattern of hinges and rigid bodies distributed across multiple layers [10].

The walking mechanism was designed and fabricated using this laminate design process. The user must first specify a set of sketches which designates the placement of three basic design components: rigid body material, flexible hinge locations, and gap geometries which separate bodies. Rigid body sketches typically consist of polygons and other filled shapes. Hinge sketches typically consist of one or more line segments which allow the placement and reuse of hinge geometry that will connect rigid bodies together. Gap geometry can be a set of line, poly-line, or polygon shapes which separate rigid bodies, create gaps or slits, or otherwise modify the body geometry. From these three types of design elements hinge and gap geometries can be merged with body geometry using a common sequence of design steps to create a device design. Once the device is specified, popupCAD also assists the user in generating a set of manufacturable cut files which allow the design to be cut and laminated from sheets of flat material. These sheets are laminated together and cut once more to create an interconnected set of rigid elements separated by flexible hinges. Some of these hinges are used during assembly and fixed once the structural elements are in place. Other hinges remain free, allowing the final device to move in the manner intended.

IV. Dragonfly Quadrotor

The Dragonfly is the second generation of the pico quadrotor family [22]. Each 22g robot is constructed from a 0.047" thick double layer fiber-glass PCB. These robots are capable of extremely fast and agile flight reaching speeds of up to 6m/s and coming to a full stop, all within a 4m $\times$ 4m flight space. A modular design approach was employed for rapidly prototyping the circuit boards by creating an expansive design library of subsystem modules [23]. This facilitates rapid iterations in the PCB design, limiting the schematic redesign to mere high-level interconnects with the central processor and other subsystems.

A. Autopilot

In order to build the smallest and lightest autonomous quadrotor, we designed the autopilot from the ground-up. Realizing the true potential of quadrotor MAVs, a wide variety of autopilots are now commercially available. Among the multitude of options, even the most widely used options like

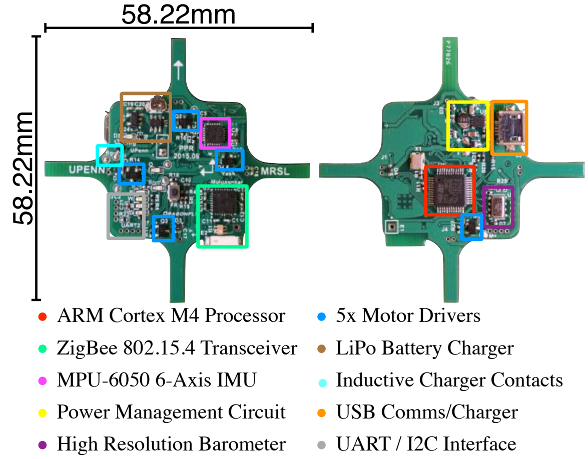


Fig. 7: Components of the Dragonfly quadrotor autopilot

the PX4 Pixhawk [24] though feature-rich, are rather bulky, weighing close to 36g, with a footprint averaging about 40mm^2. In contrast, our custom designed autopilot, shown in Fig. 7 spans a mere 3cm^2 and weighs only 4.8g. The Dragonfly is equipped with an ARM Cortex M4 STM32F373 microprocessor serving as the brain, which interfaces with Atmel's AT86RF212 900MHz 802.15.4 wireless transceiver chip. An InvenSense MPU-6050 6-axis MEMS gyroscope + accelerometer and a Measurement Specialties MS5611 high precision barometer allow for accurate attitude and altitude measurement, while a 3.3v Buck/Boost switching regulator powers all the subsystems while maintaining a consistent logic level throughout the circuit. Five 4A DC brushed motor drivers power the motors and an integrated Lithium Polymer ($LiPo$) battery charging circuit allows for in-system charging of the on-board battery. A micro USB port and two multipurpose I2C and UART ports allow for interfacing with a wide range of external sensors.

This 0.047" thick, double layered autopilot also serves as the main structural component of the Dragonfly, eliminating the need for an additional load bearing frame. 3D printed snap-on motor mounts are used to attach the motors to the autopilot. Finally, a single cell 3.7V, 240mAh Li-Po battery powers the Dragonfly, giving it a 6 minute flight time.

V. Flying Monkey

The primary goal of this paper was to explore the design, characterization and fabrication of a small scale multi-modal robot capable of fast, agile flight and crawl into tight, confined spaces, for reconnaissance or search and rescue (SaR) type situations.

A. Characterization

The remainder of this section provides an insight into the effect of scaling on vehicle mass. Following our previous analysis of the pico quadrotor [22], the predecessor to the Dragonfly, we divide the total mass of the flying monkey into six categories — Battery, Motors + Propellers, Frame, Crawler, Electronics, and Miscellaneous (adhesives, fasteners etc.)

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Fig. 8 shows the mass distribution of various components of the flying monkey . We see that the origami inspired crawler contributes about 17% to the total mass of the robot. The battery and propulsion system are the heaviest components, comprising 27% and 33%, attesting to the fact that LiPo batteries and DC brushed motors scale poorly with reduction in size. The printed circuit board, also serving as the frame of the robot, contributes about 13%, while the electronics contribute a modest 7% of the total mass of the robot.

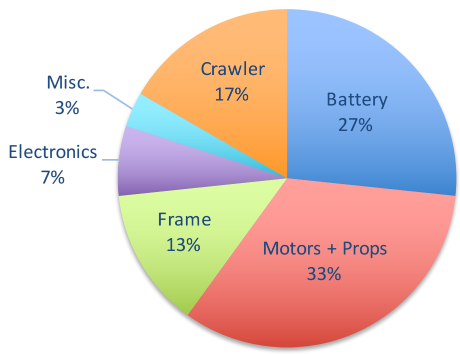

Fig. 8: Mass Distribution of the flying monkey (m = 0.03kg)

B. Mathematical model and control

We use a simple model to study the behavior of the crawler with the quadrotor attached to it while crawling:

$$\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\phi}(t) \end{bmatrix} = \begin{bmatrix} v(t)cos(\phi(t)) \\ v(t)sin(\phi(t)) \\ u(t) \end{bmatrix} \tag{1}$$

where $x(t)$ and $y(t)$ are the cartesian position of the robot in the plane, $\phi(t)$ is the yaw angle, and $v(t)$ and $u(t)$ are the control inputs for the linear velocity and yaw velocity respectively. Let us define $e_\phi = \phi - \phi_d$, where ϕ_d is the desired yaw angle, and assume that $|e_{\phi_{max}}| \leq \pi$. The control law for the yaw angle is selected as follows

$$u = -k_\phi \sin(e_\phi) + \dot{\phi}_d \tag{2}$$

where k_ϕ is a positive constant. For the linear velocity control law we use a controller similar to [25]. Let $\mathbf{x}$ be the position vector in the plane and $\mathbf{x}_d$ the desired position vector. Defining $\mathbf{e}_x = \mathbf{x} - \mathbf{x}_d$, the control law for the linear velocity is selected as follows:

$$v = [-k_x(\mathbf{e}_x) + \dot{\mathbf{x}}_d]^T \begin{bmatrix} \cos(\phi) \\ \sin(\phi) \end{bmatrix} \tag{3}$$

where k_x is a positive constant. Substituting 2 and 3 in 1, it can be shown that

$$\begin{aligned} \dot{\mathbf{x}} = -k_x(\mathbf{e}_x) + \dot{\mathbf{x}}_d \\ +\|-k_x(\mathbf{e}_x) + \dot{\mathbf{x}}_d\||\sin(e_\phi)| \end{aligned} \tag{4}$$

$$\dot{\phi} = -k_\phi \sin(e_\phi) + \dot{\phi}_d \tag{5}$$

Substituting 2 in 1 and rearranging terms, we arrived to

$$\dot{e}_\phi = k_\phi \sin(e_\phi) = 0 \tag{6}$$

Within $|e_\phi| \leq \pi$, the yaw angle has only one stable equilibrium point at $|\phi - \phi_d| = 0$ so that e_ϕ converges asymptotically to 0 in this region. Consider now the Lyapunov function candidate

$$V = \frac{1}{2}\mathbf{e}_x^T\mathbf{e}_x + \frac{1}{2}e_\phi^2 \tag{7}$$

It can be shown that its time derivative is negative definite as long as

$$k_x k_\phi > \frac{\|\dot{\mathbf{x}}_d\|^2_{max}}{4(1 - |\sin(e_{\phi_{max}})|)} \tag{8}$$

where $\|\dot{\mathbf{x}}_d\|_m ax$ is the maximum value of the norm of $\dot{\mathbf{x}}_d$.

While this last constraint on the product of the gains k_x and k_ϕ might seem discouraging, it is important to notice that, since e_ϕ converges asymptotically to 0 independent of the position error $\mathbf{e}_x$, there is no need to use high gains if we allow some time for the robot to get to the right orientation.

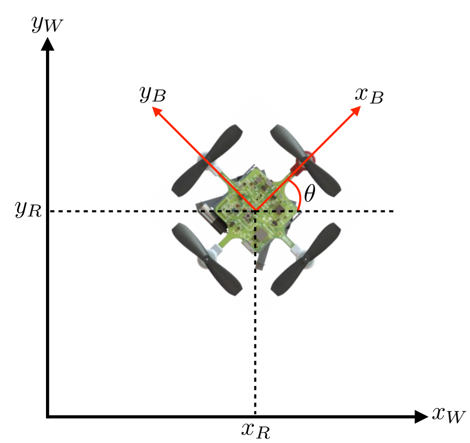

Fig. 9: Placeholder for FM coordinate system

VI. Software Architecture

The control stack for the robot is written in C++ using the ROS [26] (Robot Operating System) framework. The incorporation of ROS greatly simplifies the transition between computation on the base station and onboard the robot.

As seen in the architecture diagram in Fig. 10, a high level mission planner reads in user input in the form of waypoints or time parametrized trajectories. The trajectory generator then sends calculated desired position commands to a state machine which analyzes the position commands and governs the mode of locomotion of the robot, delegating the control to either the 2D crawler controller for terrestrial, planar locomotion, or to the SO(3) flight controller for the current phase of the mission.

The integration of the finite state machine into ROS and C++ allows us to run closed loop controllers by using pose and position estimates from the Vicon motion capture system and the attitude state estimation on-board the MAVs.

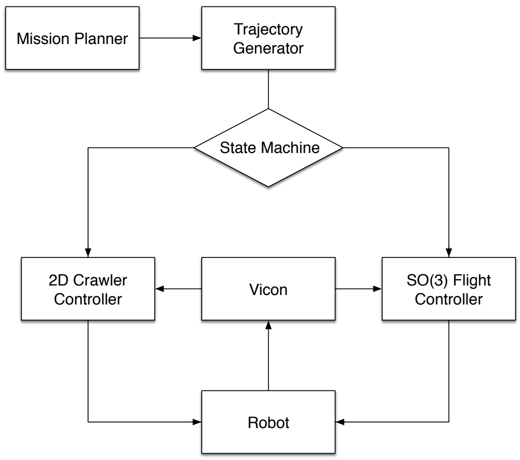

Fig. 10: Software Architecture for controlling the flying monkey .

The selected controller receives the robot's current pose and position from the motion capture system and the desired position from the trajectory generator. Using this information, the controller computes a desired attitude and thrust setpoint and transmits them to the robot through a 900MHz wireless uplink at a 100Hz. With these desired attitude and thrust measurements and its own onboard pose estimates, the robot computes and executes the appropriate motor commands to attain the desired setpoints. This low-level control loop onboard the robot, runs at the rate of 1kHz.

VII. ENERGETICS

Multi-modal insectile robots like the flying monkey , that can crawl, grasp and fly, have tremendous potential in missions involving navigation in highly complex and constrained environments owing to their ability to crawl under or fly over obstacles. A wide range of use cases have sought small autonomous fliers. An inherent limitation of any such robot is the limited battery life, which dramatically affects effective mission life, maneuverability, and onboard functionality (e.g. sensing, computation). Given the ability of crawling, the flying monkey shows immense potential in addressing the issue of limited flight time of small aerial robots, with the added dexterity of ground based platforms. This section highlights the energetics of the two locomotion modalities of the flying monkey individually and as a union.

A. Energetics at hover

To obtain the energetics of the flying monkey , we measured the battery voltage of the robot using an onboard battery monitor and designed a custom power board consisting of a MAX4172 Current-Sense Amplifier to measure in-flight current draw. Fig. 11 shows the power draw of the standalone Dragonfly quadrotor and the flying monkey at hover. We empirically determined the power draw of the Dragonfly and the flying monkey to be 9.7450W and 10.5928W respectively.

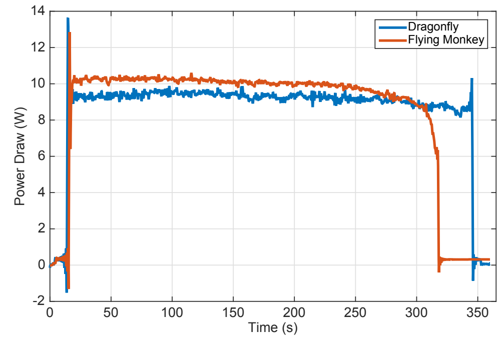

Fig. 11: Hover Power draw of the Dragonfly quadrotor P_{avg} = 9.7450W and the flying monkey P_{avg} = 10.5928W

B. Energetics during crawling

Next, to determine the energetics during terrestrial locomotion, we recorded the voltage and current drawn by the flying monkey while crawling at its maximum speed of 0.16 m/s on a flat surface. We found that the power drawn while crawling was 0.6435W – over 93% lower than the power consumption during flight. This is shown in Fig. 12. The figure shows a 45minute data log, over which the battery voltage only dropped by a few millivolts, confirming the lower power draw for a ground robot.

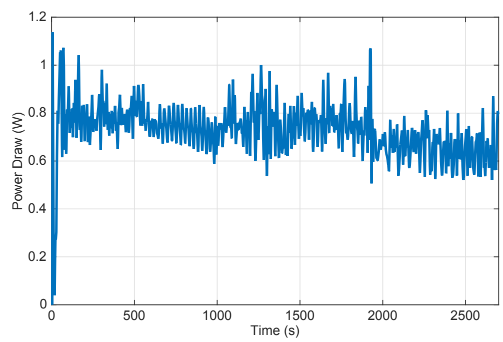

Fig. 12: Power draw of the flying monkey at 0.1m/s . P_{avg} = 0.6435 W

C. Cost of transportation

Next, to calculate the *Cost of transportation* (COT), we assumed that for all practical purposes, the power consumed P by the flying monkey while flying at a velocity v of 1m/s was equal to the power drawn at hover. Therefore, the cost of transportation for the flying monkey with a mass m = 0.03kg to cover a distance d of 1m, while flying at 1m/s and crawling at 0.16m/s, the cost of transportation is given by:

$$COT_f = \frac{P_f}{mgv_f} = \frac{10.5928}{mg} = 35.99 \tag{9}$$

$$COT_c = \frac{P_c}{mgv_c} = \frac{0.6435}{mg \cdot 0.16} = 13.67 \tag{10}$$

Alternatively,

$$COT_f = \frac{E_f}{mgd} = \frac{P_f \cdot t}{mg} = \frac{10.5928 \cdot 1}{mg} = 35.99 \quad (11)$$

$$COT_c = \frac{E_c}{mgd} = \frac{P_c \cdot t}{mg} = \frac{0.6435 * 0.16^{-1}}{mg} = 13.67 \quad (12)$$

where, COT_f and COT_c are the cost of transportation for flying and crawling respectively.

This analysis builds a strong case for ground robots, showing that a purely aerial robot has a significantly higher cost of transportation compared to a ground robot. However, with some compromise and by combining the two locomotion modalities, the flying monkey can harness the potential of aerial locomotion while keeping the COT low.

VIII. Experimental Data

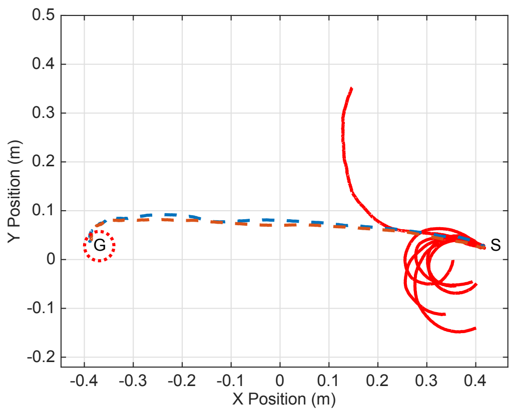

Fig. 13: Crawler performance with and without active controller

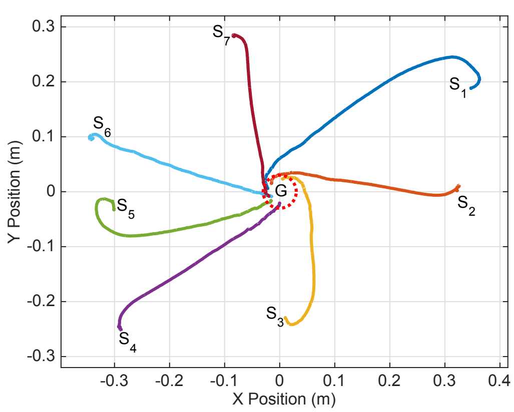

Fig. 14: Position regulation starting from different initial positions ($S_1 - S_7$) and orientations to the goal G.

A. Regulation and Time Parametrized Trajectory Tracking

Fig. 13 shows the performance of the robot at different speeds while trying to crawl from an initial position to a fixed destination: the solid lines in red show its performance without a controller, while the dotted lines show its performance using the controller described above. Fig. 14 shows the performance of the robot under feedback control crawling to a constant position from different initial positions and orientations. Fig. 15 shows the performance of the robot tracking a reference moving in a circular trajectory of radius $8cm$ centered at the origin at approximately $-0.21rad/s$. Fig. 16 shows the performance tracking the Lissajous curve described by $x(t) = 0.2cos(-0.01t)$ $y(t) = 0.2sin(-0.02t)$.

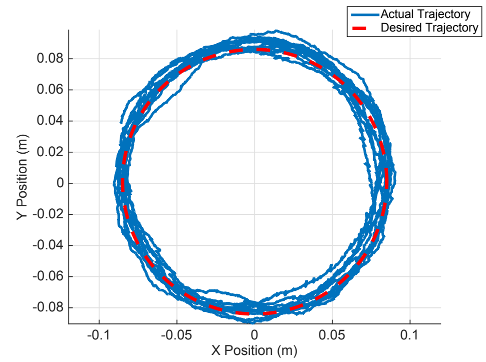

Fig. 15: Trajectory tracking performance along a circle

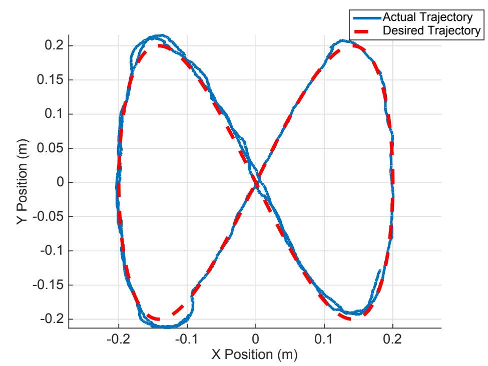

Fig. 16: Trajectory tracking performance along a Lissajous curve

IX. Capabilities

Combining crawling, flying, and grasping into a single small and maneuverable package extends the capabilities of the flying monkey to execute complex tasks. For example, the flying monkey can optimize for speed and energy efficiency, flying to travel quickly and crawling to conserve energy. The flying monkey can hop over obstacles (as demonstrated in Fig. 2), and crawl under or through small openings, such as under a door or through a pipe. The gripper, in combination with these modes of locomotion, can be put to use in a number of situations. The flying monkey can easily pick up small objects (on the order of 6mm and 1-2g), although a larger and stronger gripper should enable it to pick up even larger objects. With its multi-modal capabilities, the flying monkey can pick up an object while in crawler mode, deliver it to its destination by air, and then return to crawler mode to deposit the object. These capabilities make the flying monkey a powerful tool for object retrieval/delivery and, when coordinated in swarms, for the construction and disassembly of structures.

The addition of sensors to the flying monkey would also make it a useful surveillance tool. The flying monkey can fly to a destination quickly and then crawl in order quietly maneuver through tight spaces.

Furthermore, since the gripper is not an integral part of the flying monkey 's structure, it can be replaced by mechanisms with other functions, such as a mating device that allows it to couple with another robot or to latch onto a wall or branch.

X. DISCUSSION & CONCLUSIONS

While the three capabilities enabled in the flying monkey are sufficient to complete a variety of tasks as listed above, we envision the next generation of such devices to include other abilities, such as cutting / milling / machining, heating / cooling, deposition of glue, etc to facilitate a wider set of applications. Future work must draw from research in swarms as such functionality will only be achieved through the coordination and cooperation between groups of devices with different sets of abilities. The autonomy demonstrated in this paper is the first step to realizing these capabilities. The authors would also like to further this research to increase the mission life of the flying monkey by harnessing the immense potential of the multi-modal transport towards energy efficient trajectories and power optimized path planning for a large swarm of these robots.

APPENDIX

Videos of the experiments are available in the video attachment and at `http://mrsl.grasp.upenn.edu/yashm/ICRA2016.mp4`

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