Design and Autonomous Stabilization of a Ballistically Launched Multirotor

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Abstract—Aircraft that can launch ballistically and then convert to autonomous, free-flying drones have applications in many areas, such as emergency response, defense, and space exploration, where they can gather critical situational data using onboard sensors. In previous work, we presented a proof-of-concept, manually-stabilized folding multirotor that deploys from a pressurized tube mounted on a vehicle moving at speeds of up to 50 mph. This paper presents a larger, autonomously-stabilizing multirotor prototype with an onboard sensor suite, autonomy pipeline, and improved aerodynamic stability margin. We also demonstrate autonomous transition from passive to active stabilization, confirming the multirotor's ability to autonomously stabilize after a ballistic launch in a GPS-denied environment.

I. INTRODUCTION

Unmanned fixed-wing or multirotor aircraft are usually launched via a manual process that requires the attention of a human operator. In contrast, small unmanned aircraft systems (sUASs) that can be launched ballistically without operator intervention will play an important role in emergency response, defense, and space exploration applications, where situational awareness is often required, but the ability to launch conventionally is not available.

Firefighters responding to massive and fast-moving fires, such as the 2018 Camp Fire, could benefit from the ability to quickly launch aerial drones from a moving vehicle. A flying eye-in-the-sky could provide valuable information on the status of burning structures, or safe paths for rapid retreat in the event of a fast-moving flame front. Likewise, military personal in active engagements may not have time to manually launch information gathering drones. Multirotor aircraft are advantageous over fixed-wing systems as they can hover in place and aggressively maneuver in cluttered environments to achieve greater vantage points. However, even if a multirotor could autonomously launch from the ground, its rotating blades are a hazard to nearby personnel (who may be distracted by other obligations) until a safe altitude is reached. In these situations, multirotor aircraft operating in crowded and rapidly changing environments need a precise, highly deterministic, and fully autonomous takeoff method, as failures during takeoff can damage nearby assets and personnel.

A ballistic launch paradigm also provides unique opportunities for the exploration of solar system bodies. The Mars Helicopter Scout (MHS), planned to deploy from the Mars 2020 rover, will provide the first powered flight on another solar system body in history \([1]\). MHS greatly expands the data collection range of the rover, however, it has a multistep launch sequence that requires flat terrain. The addition of a ballistic, deterministic launch system for future rovers or entry vehicles would physically isolate small rotorcraft from the primary mission asset. Moreover, the ballistic launch could loft the rotorcraft over steep slopes, offering access to important scientific targets such as recurring slope lineae.

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Titan is another major candidate for rotorcraft flight where they could be deployed from landers, airships, or buoys, expanding the design space for future Titan missions.

In the application scenarios described above, the multirotor is stored for long periods of time, but then must be launched quickly, safely, and autonomously. Most current drone designs are slow to deploy, often require user intervention prior to takeoff, and cannot be deployed from fast moving vehicles. Furthermore, present foldable designs require the user to manually unfold the arms which slows the process and puts the user at risk if the multirotor prematurely activates. When deployed from a moving vehicle, the drone must be aerodynamically stable to avoid tumbling when exposed to sudden crosswinds. A multirotor that can launch from a simple tube and autonomously transition to flight would solve many of the shortcomings of conventional deployment strategies. The design, development, and testing of such a multirotor is the main contribution of this paper. Our SQUID (Streamlined Quick Unfolding Investigation Drone) multirotor transitions from a folded 6 inch-diameter launch configuration to a fully controllable hexacopter configuration in midair after launch (Fig. 1). The transition is accomplished via passive unfolding of the multirotor arms and an unfolding aerodynamic stabilization system that also doubles as the landing gear. Stabilization of the unfolded multirotor is a fully autonomous process.

While mature tube-launched fixed-wing aircraft are already in active use [2]–[4], tube-launched rotorcraft (both co-axial and multirotor) are much rarer and primarily still in development. Several consumer drones (e.g., the DJI Mavic series [5] and Parrot Anafi [6]) can be folded to occupy a small volume, but these designs cannot fit smoothly inside of a launch system, and the unfolding is manual. Other, manually folded and unfolding rotorcraft can achieve a cylindrical form factor like SQUID: the Power Egg from Power Vision folds into an egg shape [7], the LevelTop drone folds into a small cylinder [8], and coaxially designed Sprite from Ascent Aerosystems packs into a cylinder shape [9]. Automatic in-flight unfolding mechanisms for quadrotors, using both active [10] and passive [11] actuation, have been developed for the traversal of narrow spaces. However, to enable the ability to ballistically launch like SQUID, these existing foldable platforms must be redesigned to withstand launch loads and maintain passive aerodynamic stability post-launch. Ballistically launched aerial systems that combine an aerodynamically stable structure and a foldable airfoil system have been developed in coaxial rotorcraft [12], and multirotor [13] formats, but both these designs are still in the theoretical design phase, and have yet to demonstrate a transition from ballistic to stabilized flight.

In previous work [14], we introduced a small SQUID prototype, a folding quadrotor that launches from a 3-inch tube to a height of 10 meters or more, and then passively unfolds to a fully functional multirotor when triggered by a nichrome burn wire release mechanism. This prior work introduced the basic aerodynamic principles and structural design concepts required to sustain the g-forces associated with a ballistic launch. A prototype was fabricated and ballistically launched from a vehicle moving at speeds of 50 mph. However, the multirotor was stabilized by a remote pilot after the ballistic launch phase.

This paper advances the line of investigation started in [14]. We introduce a full-scale SQUID prototype that can launch from a 6 inch-diameter tube, propelled by expanding CO₂. We also demonstrate autonomous self-stabilization of SQUID after the ballistic phase. Moreover, we demonstrate that SQUID can carry a significant sensor payload, illustrating that ballistically launched multirotors can carry out useful missions.

The paper is organized as follows: Section II reviews the full-scale SQUID design, focusing on key changes from the first prototype [14]. Section III describes the ballistic launch phase, Section III-C describes scale-model testing used to validate SQUID’s passive stabilization design, and Section IV details the autonomous stabilization procedure. Experiments summarized in Section V demonstrate the passive-to-active stabilization pipeline. Conclusions are found in Section VI.

II. MECHANICAL DESIGN

The mechanical design of the new SQUID prototype (hereafter termed SQUID, while µSQUID will refer to the earlier 3-inch SQUID prototype) is dictated by three broad functional requirements. The multirotor must: (i) launch from a tube (6-inch diameter for this prototype), (ii) travel ballistically to a programmable height, and (iii) autonomously transition into stable, multirotor flight. To satisfy these non-traditional flight requirements, SQUID blends design elements from both ballistic and multirotor platforms. The multirotor’s central rigid body houses a battery and the perception and control systems, and interfaces with six fold-out arms with rotors and three fold-out fins which passively stabilize the multirotor during ballistic motion. The layout of key SQUID components is given in Fig. 2 and the configuration in folded and deployed states are shown in Fig. 3. Table I and Table II provide a list of key SQUID components and main design attributes.

| Property                  | Value | Units |
|---------------------------|-------|-------|
| Mass                      | 3.3   | kg    |
| Length                    | 79    | cm    |
| Folded Diameter           | 15    | cm    |
| Unfolded Diameter         | 58    | cm    |
| Thrust at Hover           | 56    | %     |
| Launch Speed              | 12    | m/s   |

### A. Central Rigid Body

In contrast to conventional multirotors, SQUID’s central body must sustain high transient forces during ballistic launch. Unlike µSQUID, which was manually stabilized by a pilot, SQUID requires a perception system comprising a camera (FLIR Chameleon3), rangefinder (TeraRanger Evo...
The placement of the heavy LiPo battery in the nosecone shifts the center of mass (COM) upward. This placement ensures that *SQUID*’s aerodynamic center (AC) trails behind the COM, which improves the passive ballistic stabilization. Passive stabilization is further addressed in Section II-C.

**B. Rotor Arms**

The six rotors are mounted on carbon fiber tubes which attach to the central body with passive, spring-loaded hinges to allow 90° of rotation. The arms can exist in two states: constrained by the launch tube to be parallel to the body axis (closed), or extending radially outward perpendicular to the central axis (open). For *µSQUID*, the timing of the transition was controlled by an arm release mechanism [14]. For *SQUID* however, the transition from closed to open state occurs immediately after the multirotor leaves the launch tube, reducing mechanical complexity.

A torsional spring inside the hinge generates 1.04 N·m of torque when the arm is closed, and half that amount when the arm is open. Vibration in the motor arms during flight dictated the addition of a spring-loaded latch to keep the arms rigidly open after deployment.

**C. Fins**

*SQUID*’s fins provide aerodynamic stabilization during ballistic flight. Aerodynamic forces on the fins shift the multirotor’s AC downward behind the COM, enabling *SQUID* to passively weathercock and align with the direction of motion. Folding fins, rather than fixed fins, are a major design change from *µSQUID* [14] and were driven by a compromise between competing requirements of aerodynamic stability, low drag, constrained tube volume, and design simplicity. This design change was guided by the use of literature-derived expressions [15] and scale model testing.

The span of fixed fins is naturally constrained by the launch tube diameter. Fins require clean, unseparated flow to operate as designed, and therefore fins that remain fixed within the tube area must also be paired with a streamlined tailbox to function as designed. This tailbox streamlining however reduces the wake drag and hence also reduces the stabilizing force it provides. Additionally, small fins which fit within the tube can only be partially effective as they have a limited area.

*SQUID*’s new tubular cross section and foldout fins therefore both increase stability relative to *µSQUID* and simplify launch packaging issues, but at the cost of more ballistic drag. For most *SQUID* applications however, ballistic efficiency can be sacrificed for these gains. The improved stability margin helps *SQUID* to predictably rotate upwind and provides margin for swappable payloads that may shift the COM. Given our selected 30 cm fins, the AC is located 38 cm from the nose, with a margin of 14 cm from the COM. Uncertainties in aerodynamic coefficients, drag on the arms, and the dynamics of the unfolding components can lead to substantial deviations from this calculated margin however. Accordingly, we validated our aerodynamic stability with a
3:1 scale model (50 mm diameter, 150 grams) using an open air wind tunnel (see Section III-C) prior to full-scale tests. While the hinges connecting the fins to the body are similar to the arm hinges, the fins do not use a latching mechanism because vertical vibrations have little impact on their functionality. “Feet” attached to the ends of the fins protect the tips and enable them to double as landing gear.

TABLE II: Key SQUID components

| Component          | Description                        | Mass (g) |
|--------------------|------------------------------------|----------|
| **Flight Electronics** |                                    |          |
| Motors             | T-Motor F80 Pro, 1900kv             | 36 (x6)  |
| ESCs               | T-Motor F30A 2-4S                   | 6 (x6)   |
| Propellers         | 7” diameter x 4” pitch              | 8 (x6)   |
| Flight Controller  | mRo PixRacer (PX4 Flight Stack)     | 11       |
| Receiver           | X8R 8-Channel                       | 17       |
| Telemetry          | HolyBro 100 mW, 915 MHz             | 28       |
| Battery            | 4S LiPo, 6000 mAh, 50C              | 580      |
| **Perception System** |                                    |          |
| Onboard Computer   | NVIDIA TX2                          | 144      |
| Carrier Board      | Orbitty Carrier Board               | 41       |
| Rangefinder        | TeraRanger Evo 60mm                 | 9        |
| IMU/Barometer      | VectorNav VN-100                    | 4        |
| Camera             | FLIR Chameleon3 w/ 3.5 mm Lens      | 128      |

III. BALLISTIC LAUNCH PROCESS AND THE AUTONOMOUS TRANSITION TO STABILIZED FLIGHT

SQUID’s mechanical design and its onboard active controls manage the deployment sequence (Fig. 4). The following sections provide details on the launch stabilization process and our experimental validation of these concepts.

A SQUID-like multirotor can autonomously stabilize itself after being launched out of a tube using a pipeline comprised of two primary phases: passive and active stabilization. In the first phase, the multirotor’s aerodynamic design ensures attitude stability as it travels along a ballistic trajectory after launch. Active stabilization begins once the arms are fully deployed and occurs before the trajectory’s apogee to avoid risking inducing a tumble.

A. Ballistic Launch Process

SQUID is ballistically launched to a minimum height that depends on both the safety requirements of the assets near the launch site and the altitude required for the targeted investigation. All the energy needed to loft the multirotor to the desired height, as well as to overcome the drag of the passive stabilization process, must be generated over the launching tube’s very short length. Consequently, the airframe experiences very large acceleration forces while being launched. Even after leaving the tube, the effects of post-launch vibrations can continue to play havoc on the onboard attitude estimator.

The core of the ballistic launch mechanism is a re-purposed T-shirt cannon [16]. Pressure is supplied by a liquid CO₂ canister that is regulated to between 80 (indoor) and 100 (outdoor) psi chamber pressure. An aluminum stand holds the launch tube in place and allows adjustment of the launch angle.

Prior to launch, SQUID rests in a folded state inside the launch tube, which is generally pointed upwards. A 300 gram carriage assembly sits between SQUID and the tube base, transmitting launch loads generated by the compressed gas directly to the frame’s support columns. A 25 mm-thick polyethylene foam disk at the base of the carriage creates a low-friction seal which maximizes the transfer of energy from the compressed gas into kinetic energy and also prevents the carriage from leaving the tube during launch. After launch is triggered, the compressed gas accelerates SQUID through the tube with a minimum of 16 g’s (IMU saturation point).

B. Passive Stabilization - Launch without Wind

After exiting the launch tube, the arms and fins deploy immediately due to the spring-loaded hinges. This deployment has three effects on the aerodynamic stability: the COM is shifted towards the nose, the AC is shifted rearward due to the fin lift (which also increases aerodynamic damping in yaw), and mass moves outwards which increases yaw inertia.

As described in Section II-C, the lower AC helps SQUID maintain orientation and follow the intended flight path until active stabilization begins. The large displacement between the COM and AC, coupled with the launch momentum, causes SQUID to orient robustly into the apparent wind. When the launch tube is stationary and roughly vertical, this effect helps SQUID to passively maintain orientation during the ballistic phase, which simplifies the transition to active stabilization.
C. Passive Stabilization - Launch in Crosswind

During launch from a moving vehicle, SQUID experiences a strong apparent wind, and will weathercock its nose in the direction of the launch platform’s motion. Accordingly, SQUID’s passive stabilization design ensures that the multirotor travels smoothly during the ballistic phase and that its orientation at the beginning of the active stabilization phase is predictable.

To validate SQUID’s expected passive aerodynamic behavior before field testing, sub-scale wind tunnel tests were performed at the Center for Autonomous Systems and Technologies (CAST) at Caltech. These tests were intended to prove that the new folding fin architecture could provide a sufficient stabilizing effect in the presence of a cross-wind.

![Image](image_url)

Fig. 5: Wind Tunnel Testing. Left - Definition of experiment parameters. Right - Snapshot sequence showing stable upwind pitching of the 1/3 SQUID model.

The sub-scale wind tunnel tests were performed using a 1/3 scale mode of SQUID. Scaling for ballistically launched drones near apogee, discussed in greater detail in [14], primarily depends upon the Froude number \(\frac{U}{\sqrt{gL}}\), launch-to-wind-velocity ratio, geometric parameters, and launch angle. Since SQUID’s tailbox is a bluff-body disc, separation at the base is virtually guaranteed, meaning Reynolds effects can be neglected [15]. To correct the sub-scale results to be representative of the full-scale mode, the trajectories were scaled by a factor of 3 and the velocities by a factor of \(\sqrt{3}\) [14].

Accordingly, the performance from a vertical launch of 4.5 m/s in the 10 m/s tunnel (Fig. 5) can be extrapolated to the behavior of a full-sized drone launched at 7.8 m/s in a 17 m/s (39 mph) crosswind. The aerodynamically stable behavior, as indicated by the upwind turn, illustrates that the multirotor with deployed fins and motor arms produces a sufficient righting moment to predictably orient the multirotor upwind on launch.

D. Transition from Passive to Active Stabilization

SQUID commences the autonomy pipeline once the distance sensor measures 3.5 m, regardless of pitch angle. This range was chosen as the passive-to-active transition point as it allows enough time for the arms to be sufficiently deployed for the motors to spin. Starting the motors early in the ballistic phase of launch is important as the motors need to be fully spooled up and stabilizing the multirotor before apogee. At apogee, the airspeed may not be sufficient to provide enough aerodynamic stabilization, risking the multirotor entering a tumbling state from which it may not recover.

IV. Active Stabilization

We base our active stabilization solution on work from literature on autonomously recovering a monocular vision-based quadrotor after its state-estimator fails due to a loss of visual tracking [17], [18]. For our visual inertial odometry pipeline, we utilize the open-source Robust Visual Inertial Odometry (ROVIO), an extended Kalman Filter that tracks both 3D landmarks and image patch features [19]. Since it tightly integrates image intensity information with inertial data to produce odometry estimates, ROVIO is capable of operating in stark, low-texture environments. This is advantageous for use cases such as launching from moving vehicles over pavement, operating over water, or exploring the surface of other planets.

The first action of the active stabilization phase is to control the attitude to a nominal zero-roll/pitch orientation using the IMU-based attitude estimate. As the air pressure around the multirotor spikes on launch, the barometric altitude estimates become unreliable and the altitude must be maintained open-loop, biased upwards for safety. The barometric readings stabilize within three seconds of launch, and at this point, SQUID begins actively controlling its altitude and attempts to reduce the vertical velocity to zero. As no horizontal position or velocity information is available, active control of the lateral position is not possible and SQUID continues to drift in plane.

Several conditions need to be met before the VIO can be successfully initialized. Firstly, the pitch and roll rates need to be near-zero to ensure that the camera captures frames with low motion blur. Secondly, the vertical velocity needs to be near-zero so the distance between the multirotor and the ground remains constant and the initial feature depth can be well established. Finally, the lateral velocity must be small (once again to minimize motion blur), so the multirotor is allowed to drift for 10 s post spool up to enable aerodynamic drag to bleed off excess speed. The range measurement from the Teraranger is used as the initial guess for the depth to the tracked features.

The VIO is considered initialized when the cumulative variance of the VIO’s x- and y-position estimates drop below a preset threshold, and the pose estimates are then fed into the flight controller state estimator filter to be fused with the IMU. At this point, SQUID has full onboard state estimation and can now control both vertical and lateral position.

V. Experimental Validation

To demonstrate the proposed passive-to-active stabilization pipeline, we launched SQUID in a 42 foot-tall flying arena at CAST (Fig. 6). The arena has two tiers of Optitrack motion capture cameras allowing SQUID’s position and orientation
to be tracked throughout the duration of a flight for offline analysis and VIO verification. A tether system was constructed inside the arena to prevent the multirotor from hitting the ground in the event of a failure, and a small weight was used to passively eliminate any slack.

Fig. 6: Launching SQUID inside CAST.

Fig. 7 shows the position tracking of a full launch to active position stabilization test flight. Launch occurs at time zero, and altitude is quickly gained as the multirotor is accelerated upward at over 16 g’s. The motors turn on at Point 1 and begin actively stabilizing the attitude. By Point 2, the barometer has recovered from the launch and closed-loop altitude control is commenced. Ten seconds after the motors are turned on (Point 3), VIO initialization begins. At Point 4, the VIO has initialized and starts to feed pose estimates to the flight controller which then actively controls the position of the multirotor, successfully completing the pipeline. Once the test is complete, the multirotor is manually controlled for recovery. The pipeline was successfully demonstrated across several days, lighting conditions and launch pressures.

VI. CONCLUSION

SQUID has successfully demonstrated the ability to survive a ballistic launch and transition into autonomous onboard control. In particular, we demonstrate:

1) A 3.3 kg hexacopter with a payload capacity compatible with an advanced sensor package and mission computer.
2) An airframe strong enough to carry and transmit launch loads without damaging onboard components.
3) Passive aerodynamic stability generated by folding fins that set the necessary preconditions for transition to autonomous flight.
4) Wind tunnel testing that validates the proposed multirotor design in cross-wind launches.
5) An autonomy pipeline that carries the platform from launch detection to full 6-degree of freedom stabilization using only onboard sensing (IMU, barometer, rangefinder, and camera) without the need for GPS.

To further validate the robustness of the method developed, future development of SQUID will include launches in windy/gusty conditions (Fig. 8), launches from a moving vehicle, and operations in more challenging visual environments. Planned hardware improvements include a delayed fin- and arm-release trigger to extend the ballistic range.

Fig. 8: Preliminary outdoor free-flight SQUID testing.

This proof-of-concept system validates the capability for a ballistically launched multirotor to deploy without human involvement, opening up new applications in fields such as disaster response, defense, and space exploration. In particular, the possibility of deployment directly from a re-entry vehicle during the entry, descent, and landing (EDL) phase of a planetary exploration mission promises an exciting future application for the technology developed for SQUID.

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SUPPLEMENTARY MATERIAL

Video of the experiments is available at https://youtu.be/mkotvIK8Dmo.

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