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Skywriting Unmanned Aerial Vehicle Proof-of-Concept Design

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***Abstract*— With the goal of a skywriting unmanned aerial vehicle, a proof-of-concept design is presented. Drone swarms act as illuminated pixels for night-time aerial imagery. By contrast, this proof-of-concept employs a single quadcopter for day-time skywriting with smoke. This paper describes hardware and software selection and mounting configuration. A Snellen Chart approach is used to calculate appropriate sizing of letters written in the sky. Testing-and-evaluation reveal higher letter-shape fidelity when flight path factors in wind speed and direction. The proof-of-concept's efficacy present a platform for future work with multiple UAV coordination to acts as a *dot-matrix* or *ink-jet* printer for the sky.**

I. Introduction

Fig. 1. Letter *O* from Skywriting.

A skywriting unmanned aerial vehicle (UAV) presents an alternative method to generate aerial images. Drone swarms have recently popularized creative expression with aerial imagery. Here, each rotorcraft UAV acts as a programmable light pixel. The swarm is synchronized to yield an image but is difficult to see during the day. Perhaps prosaic is skywriting, which started in the 1900s when airplanes stroked the daytime sky with smoke trails, painting images and messages [1]-[4]. As television and radio arose as the medium for mass advertising in the 1950s, skywriting lost popularity. This paper explores skywriting with rotorcraft UAVs for several reasons. First, a single skywriting UAV can emit a trial of smoke[1] to essentially stroke a continuous image in the sky. By contrast, drone swarms demand synchronizing many (100s) aircraft to form a pixellated image. Second, a skywriting UAV can emit dots of smoke. This is an important distinction because the UAV is analogous to a single nozzle of an ink-jet head; a small number of UAVs can then programmably *squirt* smoke to *print* the sky.

[1]According to the Academy of Model Aeronautics (AMA) 2014 Safety Code 2i, smoke producing devices are permitted if they are securely attached to the model aircraft during flight.

Beyond the notional value proposition over drone swarms, to the authors' best knowledge, there is no literature on skywriting UAVs. This paper presents its pursuit of a proof-of-concept UAV: Section II describes the selected components; Section III presents usage of the Snellen Chart to derive technical requirements on smoke trail sizing; Section IV illustrates testing-and-evaluation results; and Section V concludes and thoughts on future work.

II. Hardware and Software Design

Both fixed- and rotor-wing UAVs can be employed for skywriting. Gas-engine radio-controlled airplanes have been used by hobbyists to skywrite. The hardware is rather straight-forward; low-viscosity oil is released over the plane's exhaust to create white smoke. However, the authors decided to employ a battery-powered quadcopter to gain insight. This choice stemmed from the belief that hovering would yield more insight for defining technical design requirements.

To generate smoke-trails, a 3-min Grainger emitter and jumbo smoke cannister flare were employed. (See Fig. 2) The quadcopter consists of off-the-shelf components: Q450 V3 glass fiber frame; Pixhawk autopilot; and 920kv (RPM/V) brushless motors fitted with 9.5 inch props. The selected batteries (3-cell, 2.2 A, 11.1 V lithium poly) yields a UAV that can carry up to a 4.5 kg payload. A 3D printer was used to customize a suitable battery holder (see Fig. 3).

Fig. 2. Mass property of Smoke emitter and cannister.

Test flights revealed a need to consider both wind and rotor downwash when mounting on a quadcopter. Four different configurations were executed (see Fig. 4). Fig. 4(a) and 4(b) show the smoke emitter placed horizontally backward on top of battery case and vertically downward under the motors.

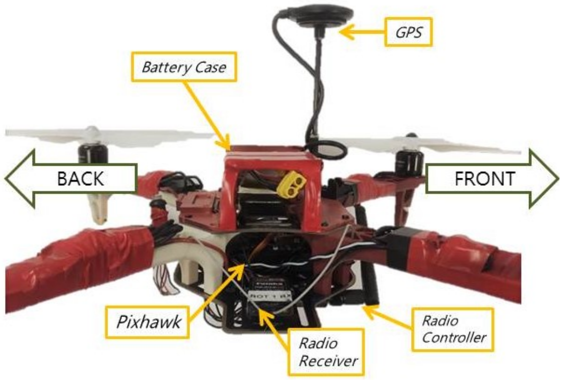


Fig. 3. Final construction of Quadcopter.

The smoke must be dense so that wind does not rapidly disperse it. As such, a generator was fabricated from a 5.3 cm × 5.3 cm × 12.7 cm plastic bottle and a 40 mm × 40 mm, 0.15 A brushless DC cooling fan. The generator is mounted battery-case top. The coooling fan faces upward to avoid side-wind. A bottle diameter of 20 mm was selected to be smaller and larger than that of the cooling fan and smoke emitter respectively. This selection helps smoke to flow quicker and resist wind dispersion (Bernouilli's Principle). The generator is internally layered with aluminum foil for heat protection (see Fig. 4(c)). The smoke emitter mounts inside the generator and is ignited when the quadcopter lifts off. Fig. 4(d) shows the jumbo smoke cannister secured in the 9.2 cm diameter, 12 cm corex drain pipe. Figs. 4(a) and 4(b) respectively show horizontal and vertical emitter-mounting options. The former mounting was observed to be better at emitting smoke trails. Mission Planner is the open-source software used for testing and calibration. A 915 MHz USB radio-controller (3DRobotics) connected the ground station computer and quadcoptor.

III. Waypoint Mission Modeling

Skywriting demands defining design requirements on the smoke trail's size. The *Snellen Chart* was the approach used in this paper to capture insight. Optimetrists use such lettered wall-mounted eye-charts to assess a patient's visual acquity. A patient with 20/20 vision can read a specific line of letters on the Snellen Chart from 20 $feet$ away. This principle can be scaled to skywrite letters at a defined altitude.

Table I depicts letter size in SI units at various acquity levels. In optometry, the minimum distance between two lines is characterized by an angle. The angle is 1/60 of a degree (1-minute) for a person with 20/20 vision. The three bars and two spaces in Fig. 5 illustrates this concept. Here, the total letter height is five minutes with one minute between each line [5].

With Table I, the minimum letter size for skywriting for someone with 20/20 vision would be given by (2):

$$\frac{D}{S} = \frac{6}{8.75 \times 10^{-3}} \tag{1}$$

(a) Smoke emitter on battery case. (b) Smoke emitter under the motors.

(c) A generator on battery case. (d) Smoke cannister on battery case.

Fig. 4. Hardware designs for Skywriting

TABLE I
THE SIZE OF LETTERS FOR EACH VISION.

Vision	Testing Distance $[m]$	Letter Size $[mm]$
20/20	6	8.72
20/40	6	17.44
20/100	6	43.62
20/200	6	87.24

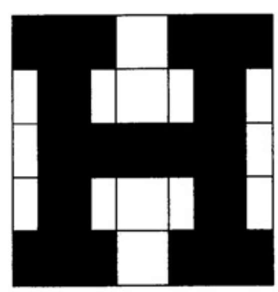


Fig. 5. Typical Letter in Snellen Chart.

Here, D is the distance between the person's eye and skywriting point and S is the minimum size the letter should be. From Fig. 6, d is the distance between the observer and the letter's projection on the ground. By pre-defining the quadcopter's cartesian location with respect to the observer, one can calculate S.

A. Preliminary Skywriting Calculations

The letter *O* was chosen to confirm this Snellen Chart approach. The circular flight path is not particularly challenging but is also non-trivial given that wind can rapidly disperse

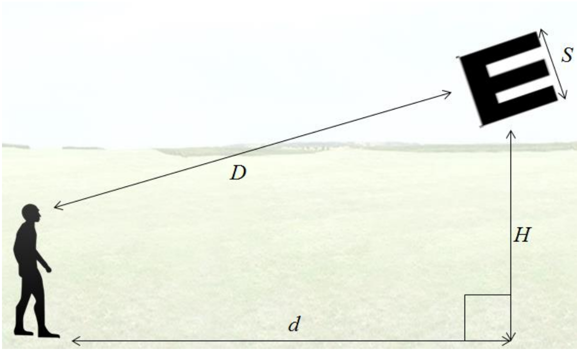


Fig. 6. Description for the letter size measurement.

the smoke trial.

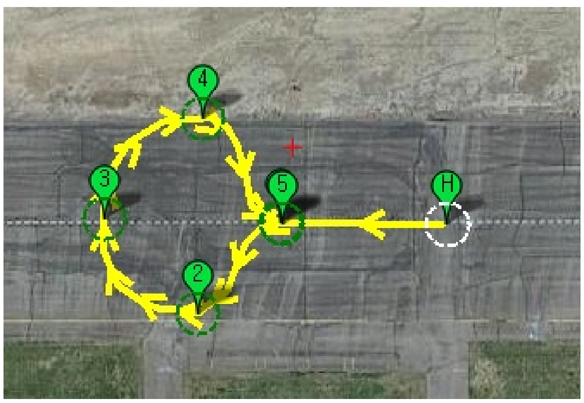


Fig. 7. Minimum waypoints for letter *O*.

Mission Planner path plans a square with 5 waypoints. For circles, Mission Planner's spine feature plans a curvilinear path between the defined waypoints. Fig. 7 shows this feature to successfully skywrite the letter *O*. Waypoint dimensions were calculated using Fig. 8. The intersection of D and H was used to mark the center position of the letter *O*.

With (2), one can calculate the radius r and the viewing angle θ (see Fig 8). Mission Planner can then be set to manually prescribed distances and altitudes for each waypoint. Referring to Fig. 7, one sees the line between the point H and 5. This is because in the current configuration, once the cannister is lit at take-off, smoke is continuously emitted until depletion. As such, waypoints were calculated using the algebraic functions in Table II

TABLE II

THE SIZE OF LETTERS FOR EACH VISION

Waypoint Number	Distance $[m]$	Altitude $[m]$
1	$d\text{-}r*sin\theta$	$H+r*cos\theta$
2	$r*\sqrt{1+sin\theta}$	H
3	$r*\sqrt{1+sin\theta}$	$H\text{-}r*cos\theta$
4	$r*\sqrt{1+sin\theta}$	H
5	$r*\sqrt{1+sin\theta}$	$H+r*cos\theta$

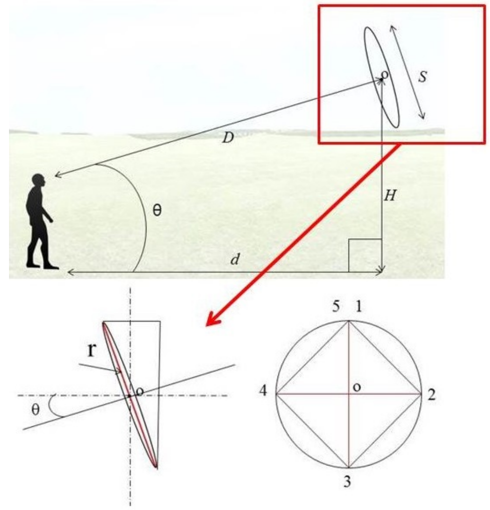


Fig. 8. Waypoint Dimension Calculation.

B. Rotor Downwash Effect on Smoke

The duration of trails from smoke is critical for Skywriting. Smoke from the smoke cannister is not heavy enough to stay longer in the sky due to the nature wind. The wind keeps smoke dispersed easily. To solve this issue, downwash effect from rotors is addressed in this section. (See Fig. 9)

The rotor is conceived as an actuator disc. There is a

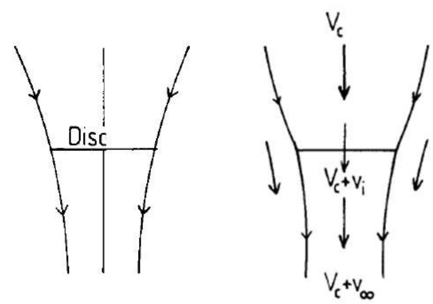
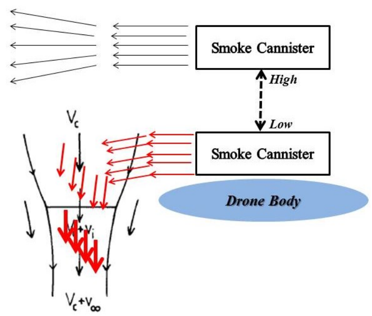


Fig. 9. Actuator disc concept and Flow field.

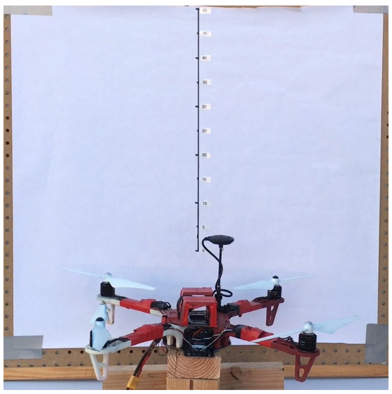
sudden increase of pressure, uniformly spread across the disc. In hover the column of air passing through the disc is a clearly defined steamtube above and below the disc. Applying the momentum theory and the conservation of energy, downwash velocity can be derived as in equation (1) [1].

$$V_c = 0; v_\infty = 2v_i \tag{2}$$

In the equation, V_c is upward velocity which starts from zero. v_i is induced speed from upside of the propeller. It continues to increase to a value v_∞. Therefore, it is possible for air passing the streamtube above the disc to be sucked together into the below with faster speed. It can be a solution for dispersion of the smoke.

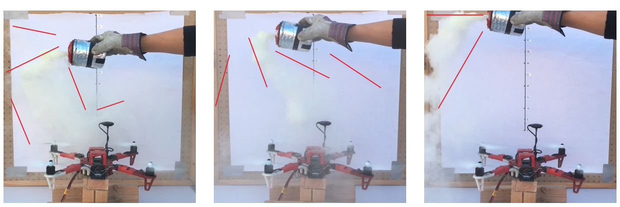


(a) Experiment Concept



(b) Experiment Construction

Fig. 10. Experiment Concept and Construction.

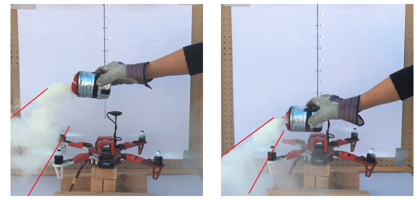


(a) $30cm$ High (b) $40cm$ High (c) $50cm$ High

Fig. 11. Flow of smoke without downwash

A smoke cannister is chosen for the proof experiment due to its high smoke density. The model is addresed in Fig. 10. The quadcopter is mounted on a heavy wood stand, so it can't fly while the propeller rotates with 75 percents throttle. Then, ignited smoke cannister is moved between $0cm$ to $50cm$ high altitude from the quadcopter to capture flow of the smoke. This figure supposes that smoke will flow naturally in certain high altitude, but be sucked uniformly into the disc from above to below when in lower altitude.

The results are shown in Fig. 11, 12. The smoke is easily dispersed by nature wind at $30cm$ to $50cm$. However, The smoke starts to flow uniformly from $20cm$ to the low. The iginited smoke is sucked into the disc without dispersion. In conclusion, the rotor downwash effect allows the smoke trail to stay longer while skywriting mission flight. The results above depicts the smoke from quadcopter in hover. In addition, the smoke looks different while quadcopter takes



(a) $20cm$ High (b) Low

Fig. 12. Flow of smoke with downwash.

(a) Take-off (b) Land

Fig. 13. Flow of Smoke in Take-off and Land.

off and lands. (See Fig. 13) The speed of take-off and land are set to $350cm/s$ and $150cm/s$. The smoke flows down vertically in both flight modes. While taking off, the smoke looks uniform but less dense because it flows in opposite direction to the flight. However, it looks much more dense while in land as it flows in same direction with the flight.

Therefore, large smoke density with rotor downwash effect is preferred; it is more visible in the sky and disperses less in the wind. A 3-step sequence was used in this paper: First, the emitter and flare were ignited and the quadcopter was commanded to hover. Second, the smoke density was qualitatively assessed. If rotor downwash did not have a large impact on dispersing the smoke, then the quadcopter was commanded to the desired altitute. Third, the smoke trail (both straight and curve) was again assessed. If the wind did not disperse the trail, then the quadcopter was commanded to the desired waypoints.

C. 3-Step Sequence and Testing Configuration

The tests are implemented on The Bennett Field, Las Vegas, Nevada, USA[2] The sequence of steps described in the previous section were executed on each configuration.

Horizontally mounted smoke emitter: Fig. 4(a) shows construction. The smoke emitter is ignited before the quadcoptor takes off. However, the flight is aborted; smoke trails disperse quickly and obscure (see Fig. 14(a)).

Vertically mounted smoke emitter: Fig. 4(b) shows construction. Smoke trails are visible (see Fig. 15(a)). Flight is aborted because the trails are easily dispersed by wind.

Smoke emitter in the wind generator: Fig. 4(c) shows construction. The emitter is ignited and then inserted into the generator. Fig. 16(a) shows that smoke density is large with better resistance to wind. Figs. 16(b) and 16(c) show results with straight and curved trails respectively. The latter is less visibile than the former and hence flight is aborted.

[2]Nevada is an FAA designated UAS test site and this area is an AMA-authorized flying area.

(a) Step 1,2

Fig. 14. Horizontally mounted smoke emitter.

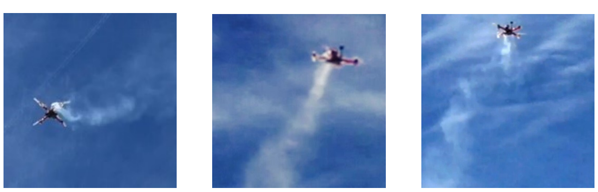
(a) Step 1,2 (b) Step 3-straight trail (c) Step 3-curve trail

Fig. 15. Vertically mounted smoke emitter.

Jumbo smoke cannister in corex drain pipe: Fig. 4(d) shows construction. Figs. 17(a), 17(b), and 17(c) shows successful straight- and curved-trails. This configuration was qualitatively deemed better than the previous two for skywriting experiments.

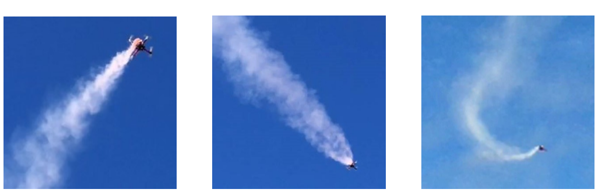
IV. Experimental Results

The jumbo smoke cannister in corex drain pipe configuration described above was employed. The quadcopter ascended 40 m and commanded to its starting position. This position was 80 m and 30 deg from the ground observer. This translates to a minimum letter size of 116.26 mm. Calculations prescribed that skywriting the letter *O* with a minimum radius of 10 m would be visible for someone with 20/20 vision.



(a) Step 1,2 (b) Step 3-straight trail (c) Step 3-curve trail

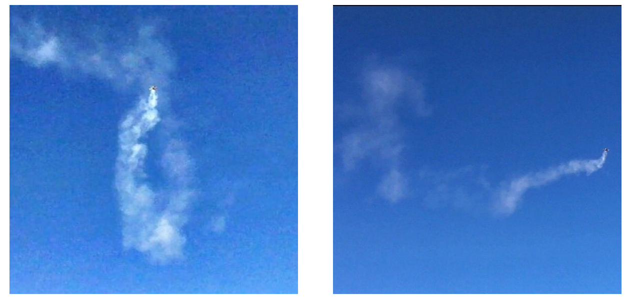
Fig. 16. Smoke emitter in the wind generator.



(a) Step 1,2 (b) Step 3-straight trail (c) Step 3-curve trail

Fig. 17. Jumbo Smoke Cannister in Corex drain pipe.

(a) Windspeed : 4.82 km/h (CCW) (b) Windspeed : 6.59 km/h (CCW)



(c) Windspeed : 9.65 km/h (CCW) (d) Windspeed : 5.13 km/h (CW)

Fig. 18. The experimental results of Skywriting.

Seven waypoints were pre-defined for skywriting. Two of these were for takeoff and landing and five were splines to skywrite the letter *O*. On that particular day, to contrast the smoke trails against a cloud-less background, a east-to-west flight path was planned and the waypoints for letter *O* is prescribed in clockwise and counterclockwise directions. The flight speed is set to 1000 cm/s by Mission Planner. Table III was the resulting coordinates used.

TABLE III
Dimension for a Waypoint Mission

Waypoint Number	Distance $[m]$	Altitude $[m]$
Take off at Home	0	48.66
Home to 1	65.78	48.66
1 to 2	12.25	40
2 to 3	12.25	31.34
3 to 4	12.25	40
4 to 5	12.25	48.66
Land	0	0

Mission Planner's auto mode[7] is used to prescribed waypoints through a telemetry connection with the quadcopter. Fig. 18 shows the results of skywriting the letter *O*. The windspeed and the direction of skywriting letter *O* are also demonstrated. That day, the wind was North-by-Northeast. Fig. 18(d) shows results using a counter-clockwise (top row) and clockwise (bottom row) flight path; the former path yield better letter-shape.

V. Conclusion and Future Work

Recently drone swarms have been employed for creative expression, displaying night-time aerial images. This paper presented a proof-of-concept for a *single* skywriting UAV can paint *day-time* images. Design requirements for hardware (smoke emitter, flare and vehicle) were captured through initial trials and presented. A Snellen Chart approach was used to prescribe letter size and path planning requirements. Results skywriting a single letter proved that the hardware, software, and approach have promise.

Given the proof-of-concept's efficacy, future work consists of more testing-and-evaluation. Examples include a being able to activate smoke on command, instead of igniting the flare at launch. This requires engineering a suitable cannister, perhaps using oil-based sprays that can be heated. This has value because such activation will allow the skywriting UAV to act more like a dot-matrix or ink-jet printer for the sky. Engineering should also factor smoke density and wind speed. The authors are also exploring multiple skywriting UAVs or multiple flares that draw red, green and blue smoke to perhaps create different colors. Beyond being a platform for creative expression, the authors believe such skywriting UAVs are a test bed to better understand formation flight, path planning, and sky-based computer graphics.

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