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Paper Plane: Towards Disposable Low-Cost Folded Cellulose-Substrate UAVs

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Abstract

Disposable folded cellulose-substrate micro-Unmanned Aerial Vehicles (UAVs) — paper planes — have the surprising potential to be effective platforms for deploying remote sensors at low-cost. With inexpensive inertial sensors and circuits printed on inexpensive structural material, the cost of a mini-scale aircraft can be reduced to the point that discarding the aircraft post-mission is economical. When launched from high-altitude balloons, paper UAVs capable of navigating jet-stream winds could be guided to land anywhere on Earth with no additional power input. This paper discusses paper as a multi-functional electronic-aeromechanical material for use in disposable micro UAVs. A proof of concept paper aircraft with inertial sensors and elevons, is presented and it is show that glide performance of the aircraft is not compromised by added mass.

Figure 1: Disposable Paper UAV.

1 Introduction

While substantial progress has been made in reducing the cost of Unmanned Aerial Vehicles (UAVs), commercially available UAV products remain expensive, even at the very low end targeting the consumer toy market. However, there are many applications where a vehicle — having completed its mission — may not be recoverable: where the flight distance exhausts the power supply of the aircraft and it cannot be replenished (e.g. surveying the Antarctic, or Amazon rainforest) or where the mission necessarily involves destruction of the vehicle (e.g. cruise missiles, or delivering sensors into forest fires). Contemporary designs are cost-prohibitive for one-way flights, outside of specific military uses.

The concept of a 'disposable UAV' is not outlandish. The advent of cheap Micro Electro-Mechanical System (MEMS) devices means that the primary cost driver for micro air vehicles need no longer be the flight control equipment required for stability, navigation and autonomy. Where an inertial measurement unit suitable for aircraft guidance once cost thousands of dollars, today a similar unit may be had for tens of dollars. In manufacturing large quantities of micro-UAVs (MAVs), materials processing, fabrication and labour costs may dominate. Consequently, methods identified for reducing the cost of UAV technology are to increase system integration, use lower-cost components, and reduce manufacturing steps.

Recent advances in micro- and meso-scale aircraft highlight the potential of highly integrated aero-mechanical structures. Harvard's robot fly employs micro-machined folded substrates that assemble from laminar sheets [Perez *et al*, 2011]. Similarly, Berkeley's folded meso-scale running robots are fabricated from composite laminated card stock [Hoover *et al*, 2010] and fitted with a drive motor. Both approaches utilise complex ambulatory motions generated from the structure of the folded flexure linkages integrated into their assembly.

The high performance demands of aircraft often drive the use of exotic and expensive materials such as carbon-fibre composite and titanium. Unlike larger systems, MAVs are able to leverage affordable stock such as balsa wood, injection moulded plastics and aluminium. However, while readily available and economical, these materials require substantial processing to fabricate aerodynamic structures. Labour is often the dominant cost driver for product design; even low-cost materials can prove too expensive for disposable devices. Furthermore, any material used in a fuselage that will be discarded where it lands must be inherently biodegradable so as not to pose a risk to the biosphere.

One common material captures all the properties ideal for use in disposable MAVs: paper. Paper — which consists of biodegradable cellulose fibre sheet — is sturdy, extremely low-cost and available everywhere. It has low processing labour input, and it boasts exceptional strength to weight ratio with desirable aeroelastic properties. While origami aircraft fabricated from paper have a long history of use and are regarded as toys, cellulose has a bright future as a serious engineering material. Recent developments in inkjet printing of UV-cured and microwave-sintered dielectrics on paper substrates promise highly integrated, single-fabrication aeromechanical-avionic structures [Polzinger *et al*, 2011; Mei *et al*, 2005; Allen *et al*, 2011]. Siegel *et al* found that paper-laminated circuits could be creased repeatedly, and formed into three dimensional shapes without compromising circuit function [Siegel *et al*, 2009]. By leveraging traditional PCB manufacturing technology, the cost of fabricating the airframe is subsumed by the fixed-cost of circuit board manufacturing set-up — paid once, and then amortised over thousands of units.

However, the true potential for paper-substrate MAVs lies in the incredible ability for passive paper aircraft to travel long distances. In 2011, Project Space Planes released 200 paper aircraft, each carrying an onboard memory chip, from a balloon 23 km above Germany [Paper Space Planes, 2011]. Some were eventually recovered from around Europe and — by traveling the jet-stream — North America, India and even Australia. Other efforts by Shinji Suzuki at Tokyo University aim to launch a paper plane from the edge of space, to be recovered on the ground [Funuyo, 2008]. By adding light-weight avionics and GPS sensors to miniature disposable aircraft, the author aims to develop a completely passive UAV to traverse the atmospheric jet-stream 'highway system', and land small sensor payloads anywhere on Earth for under $100.

This paper discusses the merits of cellulose sheet as an engineering material for fabricating extremely low-cost robot aircraft for deploying sensors in environmental monitoring applications, and its application as a multi-functional electronic-aeromechanical component. Section 2 describes the mechanical, aerodynamic and electronic aspects of paper and paper aircraft, and anticipated practical tradeoffs. Section 3 presents a proof-of-concept platform, and describe its aeromechanical features and avionics. The aerodynamic performance of the system laden with avionics package, in comparison to a 'stock' paper aircraft, is reported and future directions of the technology are discussed. A brief conclusion completes the paper.

2 The Case for Paper as an Electro-Aeromechanical Material

2.1 Mechanical Properties

Paper consists of a matrix of interlinked cellulose fibres — a knit structure of tangled natural pulp. These fibres give paper good tensile performance and formability with low bulk weight. When paper is bent, fibres in the matrix are disturbed and the paper maintains the crease. By repeatedly working a crease, a low-stiffness hinge can be formed. Thus, simple bending and forging operations are sufficient to make permanent deformations to the shape of a paper structure, greatly reducing processing cost.

The tensile strength of paper can be as high as 30 MPa, and comparable to low-end carbon fibre and some aluminium alloys [CUMG, 2012]. While variable, the stiffness of paper is very similar to that of oak and medium-density-fibreboard, at 2.5 GPa [CUMG, 2012]. The density of paper is given in "grams per square meter" (referred to as 'gsm'); paper is available in a wide variety of gsm stocks. Typical office paper is 90 gsm, with a thickness of 0.11 mm. The specific strength of paper (tensile strength per unit mass) is 30 kNmkg^{-1}, superior to that of some aluminiums.

The density-cubic specific modulus of paper — which dictates bending performance — is approximately 3.4 $\text{m}^8\text{kg}^{-2}\text{s}^{-2}$, very close to the 3.5 $\text{m}^8\text{kg}^{-2}\text{s}^{-2}$ of aluminium [CUMG, 2012]. The very high bending performance of carbon fibre reinforced plastic (CFRP) clearly makes it a superior material for cantilever fuselage construction, but its very high labour requirements make it unsuitable for disposable aircraft. A summary of the principal material properties of paper and comparable aircraft structural materials is given in Table 2.1[1].

In comparison with these other popular UAV materials, paper weighs less, has comparable tensile strength and specific strength, and is competitive in bending strength. Paper clearly outperforms polystyrene, a common light-weight UAV and radio-controlled aircraft material. The major weakness of paper is in its low stiffness. Importantly, in the application of micro-UAVs the structures to be assembled are small. The bending stress σ of a cantilevered wing is given by:

$$\sigma = \frac{L \cdot l}{2J} z \tag{1}$$

1. Materials property data drawn from Cambridge University Materials Group Interactive Charts [CUMG, 2012]. Here only isotropic random-fibre paper is considered, although anisotropic paper, such as newsprint, may have properties useful for airframes.

Table 1: Mechanical Properties of Selected Aircraft Structural Material Families

Material	Density/kgm^{-3}	Tensile Strength /MPa	Stiffness/GPa	Specific Strength /kNmkg^{-1}	Density^3 Specific Modulus/m^{8}kg^{-2}s^{-2}
Isotr. Paper	900	20–30	2–4	15–30	3.4
Polystyrene	1000	30	2	25	2.8
CFRP	1300	30–60	60–200	200–350	44.5
Aluminium	2700	80	70–80	7–110	3.5
Titanium	5000	400	100	20–250	1.2

where z is the vertical deflection distance at the wing tip, $L \cdot l/2$ is the lift force L times half the wing length l (applied bending moment), and J is the second moment of area. In the case of a rectangular wing cross-section approximation:

$$J_{xx} = \frac{c \cdot h^3}{12} \tag{2}$$

where c is the chord length and h is the airfoil thickness. The lift that must be provided by each wing is half the mass of the aircraft; this scales with the cube-law of linear dimension, chl.

If an aircraft is scaled down by reduction factor x, the dimensional parameters z, c, h and l will all be correspondingly scaled by x. Thus, it can be seen that:

$$\sigma \propto \frac{x^3 \cdot x}{x \cdot x^3} x \tag{3}$$

which reduces to $\sigma \propto x$. Thus, a half-scale aircraft would experience half the bending stress at the wing root.

Consequently, vehicles at a diminishing scale (such as paper craft and insects) can exploit materials that would be insufficient for larger scales — any material could be used, provided the vehicle designed is sufficiently small. In practice, paper and card stock have proven to be excellent substances for small fabrications [Hoover *et al*, 2010; Siegel *et al*, 2009]. Furthermore, the fixed thickness of paper stock means that in practice decreasing the scale a paper aircraft wing is not accompanied by decreasing thickness; thus, the effective rigidity of a paper aircraft will greatly exceed that anticipated by cubic variational analysis.

2.2 Aerodynamic Properties

The aerodynamics of delta wings, miniature aircraft and paper aircraft are well explored, including analysis postulating applicability of paper aeroplane aerodynamics to MAV applications [Traub *et al*, 1998; Mueller, 2007; Bing Feng *et al*, 2009; Phipps *et al*, 2002]. At the meso scale and velocities encountered by paper planes, Reynolds Numbers (RE) are very low. In this domain, the flat structures produced by folded paper sheet are advantageous as ideal low-RE airfoils are typically sharp, with low ratio of thickness to chord length [Pounds and Mahony, 2005]. Paper aircraft, which typically align the leading edge of the wing with a fold line, gain the advantage of a robust, sharp leading edge.

This is important, as a substantial fraction of lift is derived from vortex lift generated by the highly-angled delta shape of most paper aeroplanes [Bing Feng *et al*, 2009]. Separation at leading edge of the wing induces spiral vortices to form, running parallel to the wing boundary (see Fig. 2) [Bernard and Philpott, 1989, p60]. Leading edge suction captures the vortices over the surface of the wing, which entrains air down over the aircraft, producing lift [Katz and Plotkin, 2001, p517].

The planar airfoil theory for lift and drag of wing gives:

$$L = c_l(\alpha)\frac{1}{2}\rho c l v^2 \tag{4}$$

$$D = c_d(\alpha)\frac{1}{2}\rho c l v^2 \tag{5}$$

respectively, where ρ is the density of air and c_l and c_d are the non-dimensional lift and drag coefficients, v is the air speed, α is the wing angle of attack, l is the wing length, and c is the chord; together, $c \cdot l$ is the area of the wing. Polhamus extends this description to give c_l as the sum of two lift coefficients c_{lp} and c_{lv}, the potential lift and vortical lift coefficients respectively [Polhamus, 1966]. These are in turn each dependent upon corresponding lift factors k_p and k_v [Traub, 2000; Greenwell, 2010], where:

$$c_{lp} = k_p \sin(\alpha)\cos^2(\alpha) \tag{6}$$

$$k_p = 4\tan^{0.8}\left(\frac{\pi}{2} - \Lambda\right) \tag{7}$$

$$c_{lv} = k_v \sin^2(\alpha)\cos(\alpha) \tag{8}$$

$$k_v = (k_p - k_p^2 k_i)\frac{1}{\cos(\Lambda)} \tag{9}$$

where α is the wing angle of attack, Λ is the leading-edge sweep angle, and the constant $k_i = \frac{\partial c_d(\alpha)}{\partial c_l(\alpha)^2}$ is the induced drag parameter [Polhamus, 1966] (see Fig. 2). Most folded paper aircraft will have $\Lambda > 45$, and the k_v term will dominate. Delta aircraft thus have lift performance greater than that anticipated by planar wing aerodynamics. Bing Feng *et al* show that the centre spine of a paper plane plays a critical role in regulating

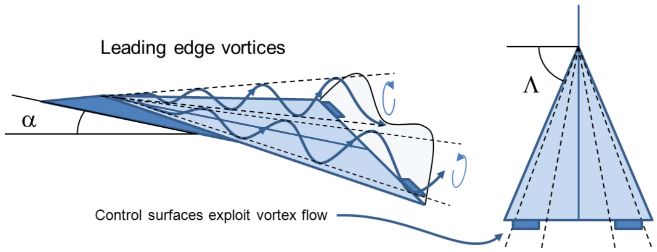

Figure 2: Delta Wing Configuration, Leading Edge Vortices and Angles.

the flow over the surface of the aircraft [Bing Feng *et al*, 2009].

Due to the quadratic proportional scaling between wing area and mass of fixed-thickness sheet, the wing loading of a particular paper "aerogami" design will be fixed for a given weight of stock, regardless of size — the scale of a paper aircraft is limited only by mechanical robustness of a design and specific modulus of its stock, as described in section 2.1. Typical wing loadings of paper aircraft lie in the range of 0.1–1 kgm^{-2}. In contrast, manned gliders, such as the Schleicher ASK, are in excess of 30 kgm^{-2}, while the smallest birds may have wing loadings as low as 1 kgm^{-2} [Alerstam *et al*, 2007]. Lower wing loadings permit flight at reduced airspeeds, due to the higher amount of air that can be moved by the wing relative to the weight to be carried. The glide slope of an aircraft — the ratio of sink to distance traveled — is largely independent of aircraft weight, although aircraft with heavier loading must glide faster [FAA, 2005, p34]. This is advantageous for maintaining higher velocities to cover long distances quickly (some manned gliders carry water ballast for this purpose).

In summary, the combination of vortex lift aerodynamics, low wing-loading and low structure weight allows paper at micro scales to generate efficient lift for long range flight, with the majority of aircraft mass contributing towards payload.

2.3 Electronic Properties

Paper has been noted for its potential as a low-cost material in electronics fabrication. Siegel *et al* note that it is cheap, flexible, foldable, and parts can be robotically loaded as with fibreglass PCBs [Siegel *et al*, 2009]. Rather than using high-temperature soldering, these circuits would employ conductive adhesives to glue parts to the pads. Furthermore, paper circuits can be cut to precise shapes with automatic dies, guillotines or lasers, with selective perforation for tear-outs, folds or tabs, and paper holds tighter bend radii than polyimide. These features greatly reduce the cost of fabrication and labour.

Paper circuits are also lighter than the thinnest polyimide circuits, and substantially thinner — 50 μm vs 140 μm [Siegel *et al*, 2009]. The dielectric properties of paper are useful for RF devices, and paper circuits have already found application in flexible RFID tags, and UHF circuits have been demonstrated. Potentially, a paper aircraft's transmitter antenna could be laminated directly into its 3D structure. This allows a paper aircraft to be significantly lighter than a comparable structure built out of polymers or metal.

Drawbacks of paper circuits are their non-reworkability, thermal sensitivity and limited current carrying capacity. However, in an aircraft that is cheap enough to be disposable, the inability to repair or modify the device is moot — it need only work for a single mission, no maintenance required. As a fully-passive aircraft has no propulsion system, the properly-functioning avionics will generate no heat, and no large current draws will be required. None of the specific limitations of electronics on paper compromise the performance of a cellulose aircraft.

2.4 Tradeoffs

Despite impressive capabilities, paper is generally not regarded as a suitable material for robust constructions on the macro scale.

The same cellulose fibre structure that allows paper to be creased means that it is easily crumpled by impact or forces exceeding its design tolerance. Unlike conventional precision-engineered aircraft, paper planes are notorious for asymmetry in their flight mechanics due to imperfect folds which result in unbalanced weight and lifting surface area. Automated processes for folding/press forming the aircraft will reduce this variability, but this necessitates onboard feedback control to regulate flight attitude and heading.

The thin, flexible cantilevered construction of folded paper structures suggests they should be susceptible to pathological aerodynamic effects, such as aeroelastic flutter and distortion [Bernard and Philpott, 1989, p351]. In practice, the low mass and low-RE operation of paper aeroplanes discourages flutter [Quackenbush *et al*, 2004]. However, flexure during quasi-static loading of the aircraft undergoing manoeuvres may be considerable. Paper is not rigid under compression, and dynamic flight loads may exceed the buckling strength of tensile membrane wings. Consequently, paper aeroplanes can never be as robust as other aircraft, without adding additional (i.e. more expensive) processing steps such as adhesives or stiffeners.

As paper is made from natural wood fibres, it is completely biodegradable within a short period of time. However, modern paper undergoes numerous treatment processes in its manufacture, which leave trace chemicals. These include bleaching agents, lignin removal agents and pigments. Depending on the final destination and application of the aircraft, these chemicals leaching into the environment may not be tolerable. Specialised papers are available that omit various steps incorporating these chemicals, but this comes at increased cost and decreased mechanical performance due to the smaller production volumes.

Finally, the cellulose fibre matrix is susceptible to moisture. If an untreated paper aircraft gets wet (as is highly likely for long-range flight), the mechanical strength of the vehicle will be compromised. An aircraft intended for circum-global flight must therefore be treated with water-proofing, which may come at the expense of complete biodegradability of the airframe[2].

3 Proof of Concept

A proof of concept platform has been developed for performance and flight control experiments with paper substrate aircraft. The aircraft will be used to develop systems for autonomous gliding flight, and eventual long-distance waypoint navigation. This section presents the weight budget, wing loading and control analysis used in ascertaining that the complete aircraft will be viable, and reports early passive gliding experiments.

3.1 Aerodynamic Design

The structure chosen for the proof-of-concept aircraft is the traditional delta shape, folded from A4 stock, commonly referred to as the 'classic dart'. The A4 size is specified by the ISO 216 standard, stipulating dimensions of 210±2 mm by 297±2 mm. Office-grade paper stock is approximately 90 gsm, which yields an unladen flying mass of 5.6 g. With a sensor board and battery weighing 4.5 g and two actuators weighing 0.25 g each, the fully-laden aircraft is approximately double the empty weight.

The ISO 216 classic dart will always have a wing area of approximately 0.025 m^2, depending on the size of the vertical stabiliser. For unladen 90 gsm aircraft, this will be 0.22 kgm^{-2}. When equipped with the sensor and control module, the proof-of-concept MAV has a wing loading of approximately 0.4 kgm^{-2}. The delta wing has $\Lambda = 67.5$. As the aircraft is constructed from a single sheet of uniform substrate, and there are no span-wise folds, the centre of gravity (COG) will remain at the midpoint of the fuselage. The diagonal folds at the nose of the aircraft put the centre of lift rearwards, close to the aft third-length. This makes the aircraft passively longitudinally stable in trimmed pitch [Bernard and Philpott, 1989, p294]. Adding the mass of the avionics system and battery forward of the unladen COG will not adversely effect stability, but will reduce flight pitch attitude.

3.2 Avionics

Avionics for the first iteration of the disposable MAV include a Microchip 16-series PIC microcontroller, connected to an Invensense MPU-6050 inertial measurement unit, and two Plantraco voice-coil actuators (see Fig. 3). Power is provided by a 20 mAh lithium polymer cell, regulated on board to 3.3 V. A battery protection IC prevents accidental over-discharge of the cell.

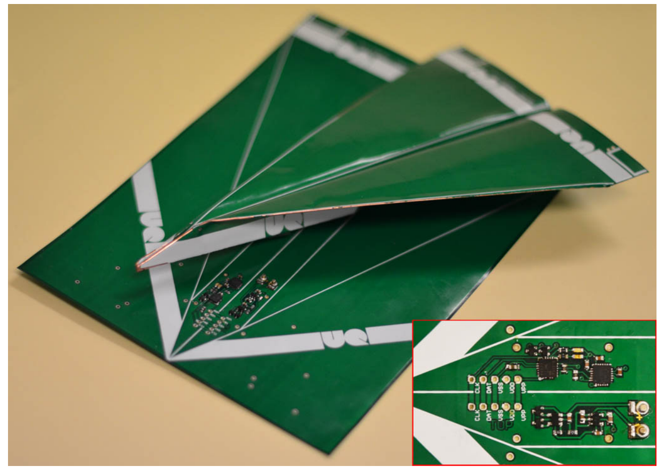

Figure 3: Polyimide Test Article and Circuit (inset).

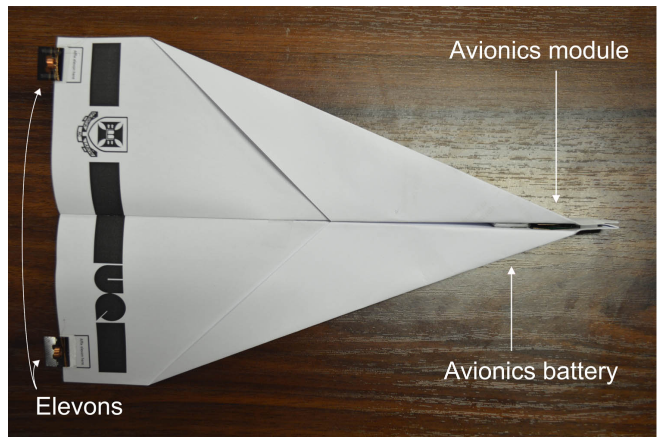

Figure 4: Cellulose Proof-of-Concept UAV.

The voice-coil actuators are controlled with two FETs, allowing single-ended actuation. As the aircraft must fly slightly nose-up to exploit the delta vortex-lift effect, it is not necessary to include a larger H-bridge circuit to allow double-ended activation of the coil; zero duty-cycle applied to the elevons is homologous to negative input.

Prior to fabricating printed paper circuit boards, a conventionally fabricated circuit was developed to prove the avionics design. This consisted of a half-scale (A5) polyimide circuit board with similar substrate and foil thickness to that expected by the cellulose version. The test article is capable of flight in its own right, but has substantially higher weight compared with cellulose.

2. Note that while a paper airframe is biodegradable, electronics generally are not. One solution is to encase miniaturised avionics in inert glass, to prevent or slow the leaching of dangerous substances.

The test design included a copper ground plane to both enable the polyimide to hold a bend, and to test the conductivity of cold-forged flex across the bending radii anticipated in the fabrication of the paper version. The tests showed that the 0.5 mm bend radii at the wing roots could be tolerated without fracture, but it was found that double-layer copper is practically too stiff and heavy — the majority of metal film must be etched away prior to both reduce weight and difficulty in folding.

For initial testing of the flight control system, the cellulose proof-of-concept system employs the avionics module from the polyimide test article laminated on paper (see Fig. 4). It is expected that the ultimate system constructed on printed paper circuit boards will incorporate ICs in caseless chip-scale packages.

3.3 Flight Control

The flight mechanics of a properly-trimmed classic dart are known to be locally stable, with slow unstable coupled pitch and roll. In the low-RE flow regime, viscous forces dominate [Potter and Wiggert, 1997] — oscillatory modes (such as "Dutch roll") are expected to be intrinsically damped. However, spiral instability mode is strongly exerted due to the slender wings and low vertical stabilizer. The key goal in flight control lies in maintaining wing-level attitude and correct α for most efficient cruise performance.

The proof-of-concept system has a 6-axis inertial sensor for regulating flight attitude. Control forces are applied by twin elevon aerodynamic surfaces at the outside trailing edge of the delta wing, where the separated vortices flow parallel to the leading edge [Bernard and Philpott, 1989, p25]. The actuating servo tabs double as the aerodynamic control surfaces, eliminating additional manufacturing steps.

While the design of the classic dart incorporates the centre fuselage as a vertical stabilizer, no rudder has been included. This is to save on weight and avoid adding additional masses at the rear which would move the COG aft. The coupled banking-turning mechanics of aeroplanes, the low mass of the vehicle, and the small size of the aircraft obviates the need for full actuation. However, coupled flight modes of fixed-wing aircraft complicate the control design, as perfectly coordinated flight makes off-vertical gravity vector components unobservable by accelerometers, increasing reliance of potentially biased gyroscopes.

3.4 Glide Performance

The proof-of-concept aircraft consists of polyimide PCB laminated to standard A4 office paper stock, folded according to the pattern given in the appendix, with elevon control surfaces mounted at the wing-tip trailing edges. It was expected that the added mass of the polyimide board would be minimal, and not have a great impact on performance. This assertion was tested by comparing the gliding range of a paper aircraft without avionics, with that of the same aircraft with avionics added.

Figure 5: Example Glide Test Experiment Montage.

A catapult fitted with elastic with was used to launch the UAV. The catapult was drawn back to a fixed distance to ensure that each launch delivered consistent, repeatable energy. The aircraft were launched horizontally from 1440 mm above the ground, using passive stability of the aircraft (without feedback) and the distance to where they first contacted the ground was recorded (see Fig. 5). The experiment was repeated 20 times for the unladen configuration and 20 times for the laden configurations. For consistency, the same aircraft was used for all tests from both sets of tests.

As the energy stored in the elastic catapult is equal across all tests, but the laden aircraft weighs 10.6 g compared to the unladen weight of 5.6 g, the velocity reached by the lighter aircraft will be approximately 1.37 times that of the heavier aircraft. However, as the heavier glider must fly faster to sustain lift, a higher sink rate and shorter distance is anticipated.

To account for this, consider the Newtonian and aerodynamic force equations. For time of flight t, it is known that the horizontal distance traveled x will be:

$$x = t \cdot V_x \qquad (10)$$

where V_x is the horizontal launch velocity. In gliding flight the aircraft will accelerate downward at a rate proportional with mass to gravity minus the lift force:

$$m\dot{V}_z = mg - c_1 \rho c l V_x^2 \qquad (11)$$

It is known that for descent under constant acceleration, distance fallen in time t is:

$$\frac{1}{2}\dot{V}_z t^2 = z \qquad (12)$$

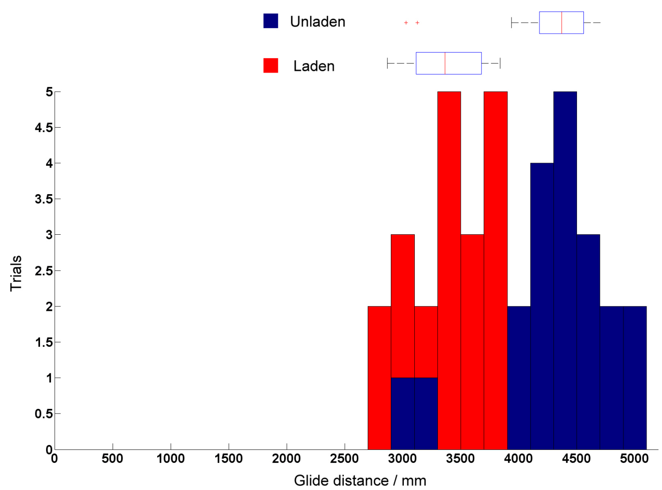

Figure 6: Distance Flown for Constant Launch Energy, Unladen vs Laden Comparison, Histogram-Box Plot.

where z is the launch height. The horizontal launch velocity is dictated by the energy stored in the catapult elastic E, which is constant for each launch:

$$\frac{1}{2}mV_x^2 = E \tag{13}$$

By manipulating these relations, the distance flown can be expressed as a function of mass:

$$x^2 = \frac{4zE}{mg - 2c_l \rho c l E} \tag{14}$$

Given the small energies involved, by variational analysis multiplying mass by 1.9 is expected to shorten the distance flown by approximately 73%.

In practice, it was observed that the unladen aircraft flew 4309±317 mm, and the laden aircraft flew 3390±515 mm (see Fig.6); the mean distance flown by the laden aircraft was 79% that of the unladen aircraft. Thus it is concluded that the addition of the control avionics and elevon surfaces has not compromised the gliding qualities of the classic dart.

Anecdotally, it was observed that flight of the aircraft when laden was more stable than when unladen. This is attributed to the stabilising effect of the high-wing and low COG configuration often employed by cargo aircraft. This arrangement developed a restoring torque during sideslip conditions [Bernard and Philpott, 1989], which counters the unstable spiral turn tendency commonly exhibited by the classic dart.

3.5 Future Work

Even though it is known that the proof-of-concept demonstrator is capable of flight, substantial work remains to be done in developing further capabilities of the platform, and realising the potential of the paper UAV approach. Key areas yet to be explored include flight control and long-range navigation; algorithmic efficiency of trajectory generation on computationally frugal microcontrollers; energetic autonomy; and transferal of the avionics design to paper substrate.

Foremost, feedback regulation of attitude and heading must be demonstrated to advance the design to the next phase. Flight test experiments with the proof-of-concept system are ongoing. Beyond regulation, a low-power compass chip will be required for the aircraft to following a specified heading. Navigation to a specific location will require the aircraft be equipped with a miniature GPS system. Given the size, power and computational requirements of GPS, this challenge is formidable.

Once these measurements are available, the practical task of plotting appropriate trajectories that exploit jet-streams must be considered. Substantial work has been undertaken within the UAV field to explore thermal soaring and flight in high winds, but none have considered passive trans-global flight, and many unknowns remain.

Consequently, it is foreseen that algorithmic efficiency will be vital to successful operation of the craft, both in sensor fusion and trajectory generation. The very limited computational and energetic resources of the aircraft will require minimalist implementations to reduce weight and keep power use as low as possible.

In a similar vein, the addition of onboard solar energy collection will be explored to improve the energetic autonomy of the aircraft, both in the air and on the ground at its destination. Chip-scale photovoltaic cells are possible solutions. Remote power collection is essential for powering transmitters to returning measurement data.

Finally, the synthesised design must be implemented on cellulose printed circuits, and assembled. Numerous aerogami designs, such as those employed by Paper Space Planes, may be tested to find a pattern that is best suited to high altitude flight.

4 Conclusions

A simple disposable MAV platform has been developed, based on the venerable paper plane design. The aircraft was capable of stable gliding flight, and is equipped with small onboard voice-coil actuators and onboard 6-DOF inertial measurement for motion control. The proof-of-concept system demonstrated stable gliding flight, and it was shown that the addition of avionic control systems did not compromise gliding performance. Ongoing work aims to regulate aircraft velocity under feedback control, and eventually allow aircraft released at high-altitude to navigate long distances autonomously, with no further input of energy.

5 Acknowledgements

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6 Appendix: Classic Dart Instructions

See next page.

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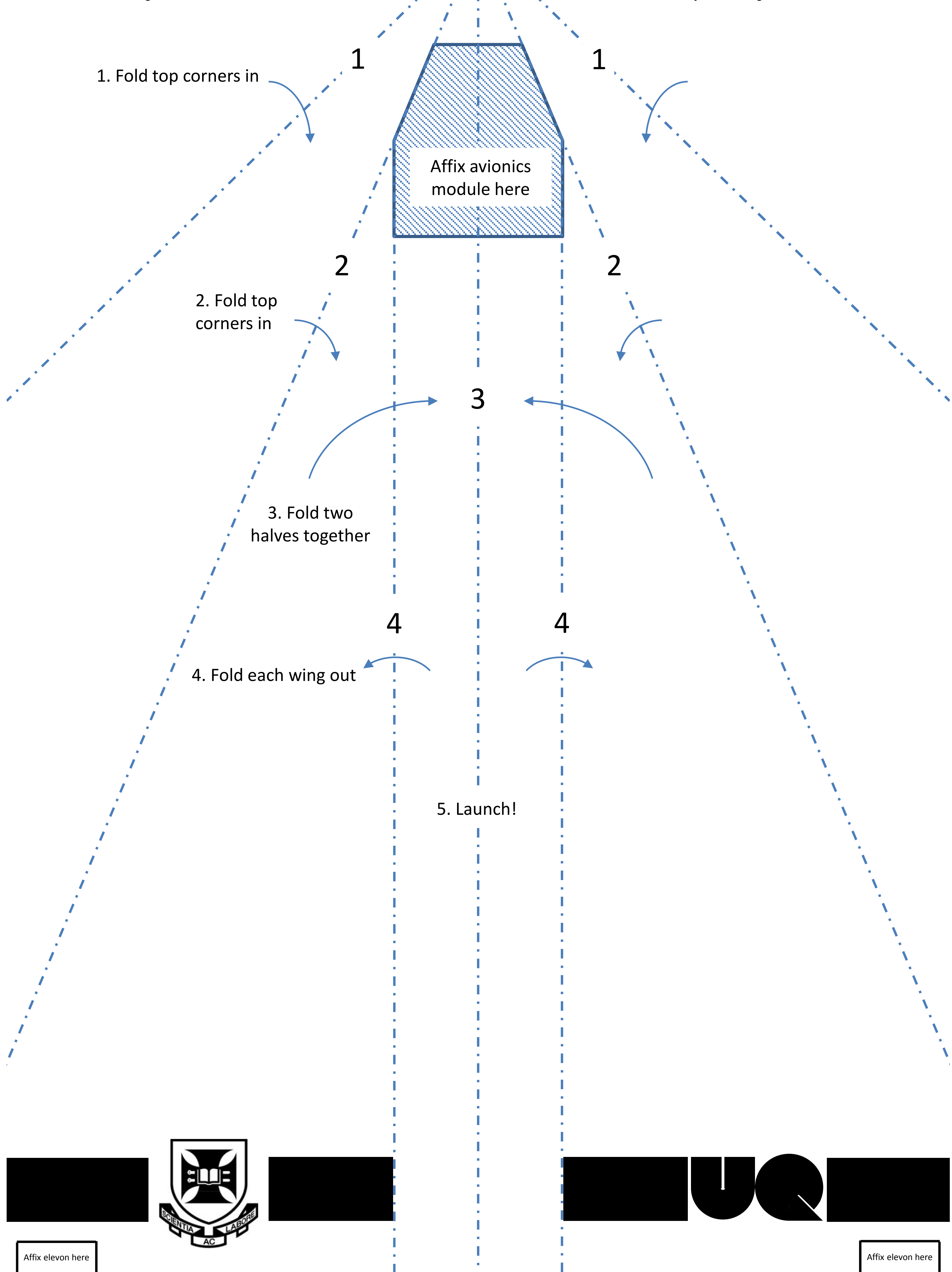
1
1
1. Fold top corners in
Affix avionics module here
2
2
2. Fold top corners in
3
3. Fold two halves together
4
4
4. Fold each wing out
5. Launch!
Affix elevon here
Affix elevon here