A Novel Exploration into Gust Resistant Operation of MAVs / UAVs Through Transformation

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Abstract
The Gust Resistant Wing (GRW) research is a collaborative project between the University of Texas in Austin (UT Austin), the US Air Force Academy (USAFA) and the Air Force Research Labs Munitions Branch in Eglin FL. The project focuses primarily on modifications to the wings of a Micro Air Vehicle (MAV) system in order to reduce the MAV's susceptibility to wind gusts. Background research and initial design work were accomplished during the summer of 2006 and a full design effort including cadets at USAFA and graduate students at UT Austin began in Sept of 2006. The design phase involved the implementation of a new Transformational Design Methodology and has resulted in a number of concepts for GRWs. These concepts have been tested in wind tunnel environments as well as in actual flight. Some of the concepts show the potential to improve resistance to gusts by over 50% compared to standard wing configurations. As the work on this research / design has been carried out for only a few months, this paper and technology demonstration represents initial results on gust resistant operation of MAVs and is truly a "work in progress".

1. Introduction:
Significant research is being done in the field of Unmanned Vehicles for air, sea and ground operations. The application of these unmanned vehicles range from search and rescue to surveillance and enemy targeting. The diverse mission profiles of unmanned vehicles are a result of constant research and innovation in this field. Unmanned Aerial Vehicles (UAVs) are typically used in surveillance applications, although they can be equipped for offensive and defensive operation as required by the mission. The success of UAVs has lead to the development of Micro Unmanned Aerial Vehicles (MAVs) which are being extensively deployed in urban or inaccessible areas for surveillance purposes. The interest in use of MAVs is growing because of the dangerous tasks it accomplishes without endangering human life.

1.1 Understanding the Problem:
The video quality captured by these aerial vehicles is vital for the success of any surveillance mission. The effect of wind gusts on the video quality can be very significant; in many cases rendering the video information close to un-usable. In addition, the gusts may also cause deviations in the flight path of the MAV that may create collisions with trees, buildings or other objects. This need drives the requirement of the MAVs to be stable during flight and isolate itself from environmental vagaries such as wind gusts to carry out its mission without interference. Research has been done in the area of flight stability and control caused by gusts [1, 2, 3]. There exist some innovative concepts of "morphing wing" [4] and "free wing" [5] that claim to help stabilize the flight disturbances experienced by an MAV / UAV. The University of Texas at Austin (UT Austin) and the US Air Force Academy (USAFA) have recently begun an endeavor to design and test new Gust Resistant Wing (GRW) concepts. Designs that are somewhat invariant to wind gusts are important especially for small remotely piloted aircrafts as these small aircrafts can have significant changes in all 6 degrees of freedom due to relatively small changes in wind magnitude and direction. The Air Force Research Labs Munitions branch (AFRL/MN) has indicated a particular interest in designs that mitigate the effects of gusts on Micro Air Vehicles (MAVs).

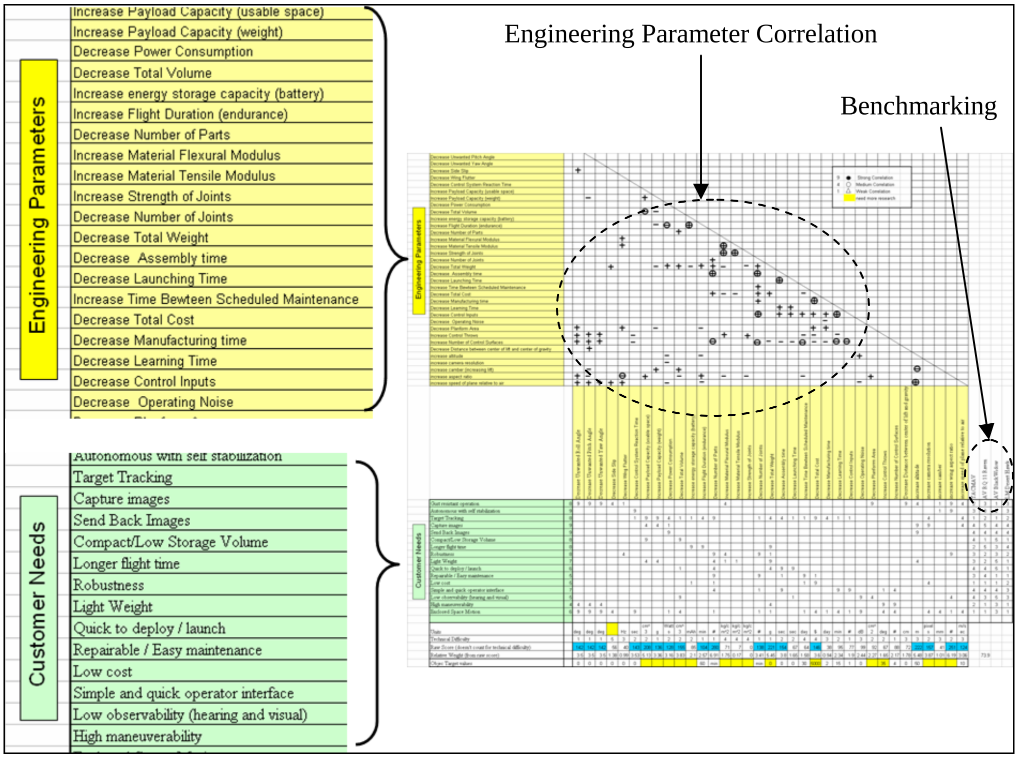

Figure 1. House of Quality for Gust Resistant Wing Problem

2. Design Methodology:

This section discusses the design methods adopted for the gust resistant wing problem. The first step in the process was generating a House of Quality to determine the important customer needs and engineering parameters (specifications or requirements) quantifying these needs. This was followed by implementation of a Transformational Design Methodology, previously developed under an AFRL grant, which will be described later.

2.1 House of Quality:

The customer needs for this problem were gathered from AFRL, special operations troops and research on current developments in the field of UAVs and MAVs. Engineering parameters were generated as a result of background research done in aerodynamics of these aircraft. Figure 1 shows the house of quality relating needs to engineering parameters. The team compiled a list of 35 engineering parameters (specifications or requirements) that quantify the important customer needs gathered. Benchmarking was done with the TACMAV, AV RQ-11 Raven Hawk, AV Black Widow, and LM Desert Hawk. This tool helped the team in decision making through the course of the design process by providing a comprehensive list of engineering parameters and their coupled effects on other engineering parameters and each customer need.

2.2 Transformation Design Methodology:

During the summer of 2006, the research team implemented a new design methodology specifically developed to facilitate the creation of systems with the ability to transform from one state to another in order to facilitate new functionality [1]. In this case the first state would be the normal flight configuration of the MAV and the second state would be one that has enhanced ability to mitigate gusts. This methodology incorporates many of the design tools in the state-of-the-art product design processes [7], but also includes significant new features. As seen from Figure 3, the method incorporates a list of different missions/ scenarios in which the systems must function. Customer needs related to each mission are gathered and are then combined to form a comprehensive customer needs list. Customer needs were gathered and analyzed through officials at AFRL and special operations troops. The most critical overarching customer need was mitigating gust effects on video quality.

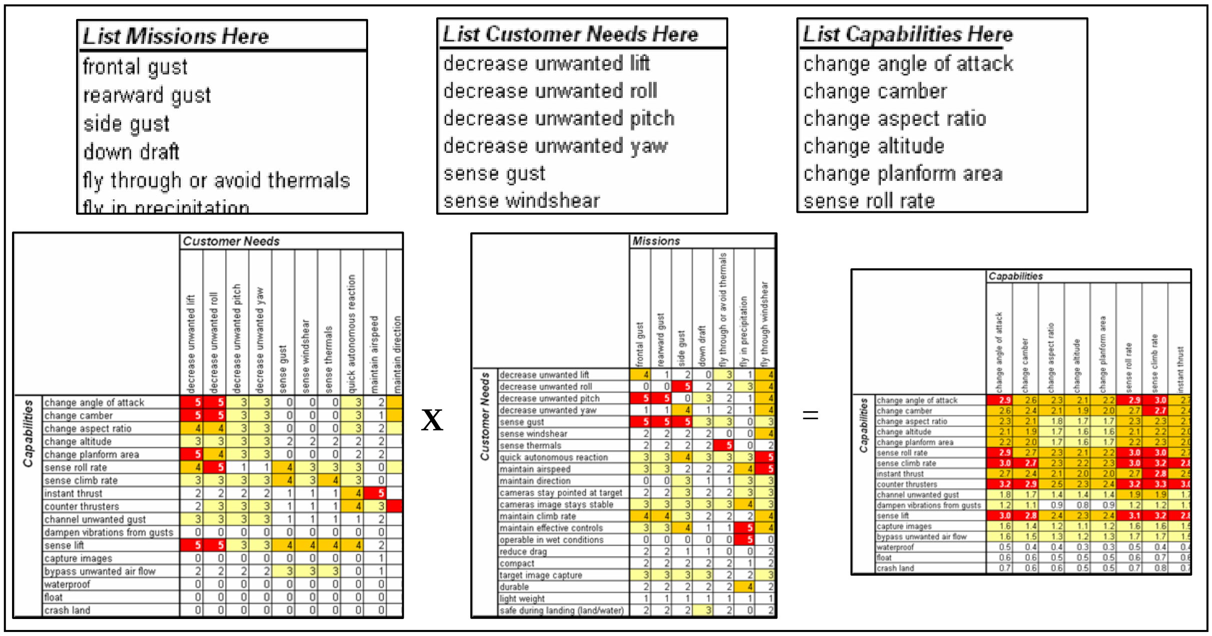

Figure 2. Transformation Methodology Software Input and Calculation

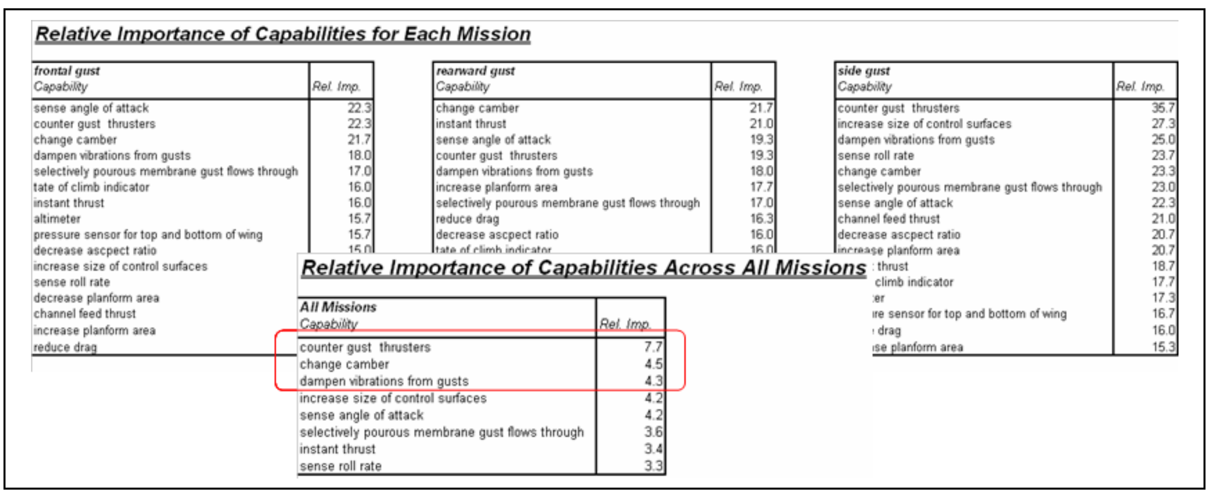

Figure 3. Software Result Listing Importance of Capabilities in Each Mission and Across All Missions

Overall 6 degrees of freedom control of the MAV was a distant second broad need. It was stated that GRW technologies should be implement able on the TACMAV (current MAV used by the Special Operations forces) but should be applicable to other MAVs as well. Capabilities, high order solutions which are not form specific, are then listed that cater to each customer need. The software creates a matrix for Customer Needs vs. Mission and Capabilities vs. Customer Needs which are given importance rating on a scale of 1 ~ 5; 1 being not important and 5 being highly important. The number of cells that need a subjective input from the engineer can be as high as 1700, depending on how many capabilities and needs were listed. Through a series of matrix math, a Mission vs. Mission matrix and Capabilities vs. Capabilities matrix is produced in an Excel spreadsheet. This information tells the engineer what capabilities are most important to each individual mission and all the missions combined. The three highest scoring capabilities (Fig. 3) were counter gust thrusters, changeable camber, and wing damping through increased dihedral. The Transformational Design Methodology software used in conjunction with Transformation Design Principle and Facilitators [6, 8] produced a wide variety of potential concepts for gust resistance. A subset of these concepts can be seen in Figure

4. Three of these concepts were determined to be of primary interest in this first iteration of GRW development. The three chosen concepts include a) Ports in the wings, b) Elastically hinged spoilers and c) Variable dihedral angels between the fuselage and wings.

- Trap Door Wing
  - Air brake (hole in wing)
- Window Blind Wing
  - Opens up wings to let gust through
- Hang Glider
  - Changes planform area
- Flying Thruster
- Piezoelectric Wings/Actuators
  - Change wing shape
    - Anhedral
    - Dihedral
- Ferromagnetic Veins in Wings
  - Flexible wings
  - Magnetic repulsion gets stronger
- “Batwing”
- Coupled wings
  - Springs attached
- Active camber
  - Wing spires
- Counter thrusters
  - Connect to control inputs to sense desired movement
- Hairy wing
  - Electric response polymers
  - Variable surface roughness
- Tail wing adds to planform area

Figure 4. Subset of Concepts Developed For GRW

2.3 Concepts for Gust Resistant Wing:

The following sections will detail the developments and preliminary results of “Ported Wing Concept”. In addition, the other two concepts (“Elastically Hinged Spoilers” and “Variable Dihedral”) will be briefly described as well. As the goal of the initial stage of the GRW project is to build a working prototype for the MAV competition held at Eglin, Florida in October, this initial concept selection process included preference for concepts that were determined to be implement able in a relatively short time frame. Carbon fiber has been used to manufacture concept wings and fuselage based on the needs of strength, stiffness and weight.

2.3.1. Ported Wing Concept:

The Ported Wing concept employs the design of wings with open sections (holes) in the airfoil. These ports are present to reduce the unwanted lift experienced by the wing due to wind gusts. This concept differs from slotted wing [9, 10] on the effect of its application. Slotted wings were first created and introduced in 1920s [10]. With flaps incorporated into the trailing edge of aircraft and the slotted wing design in the leading edge, aircraft were able to generate lift and laminar flows on the wing at a steep angle of attack (AoA). This also allowed for shorter landing and take off while not stalling at a high AoA for aircrafts flying at high speeds. Some aircraft, like the A-4 Skyhawk and Helio Currior have passive leading edge slats. The ports described in the concept have a function of reducing lift rather than increasing it and have a low speed application. Figure 5 shows a concept of the ported wing. The ports shown mitigate gusts that produce a large change in lift, where the gust is usually a change in vertical air velocity, resulting in a change in angle of attack (AoA) of the wing (vector sum of the gust from beneath the wing and the relative wind encountered by the wing). Ports can act somewhat as spoilers to create separated flow on the wing, thus reducing lift.

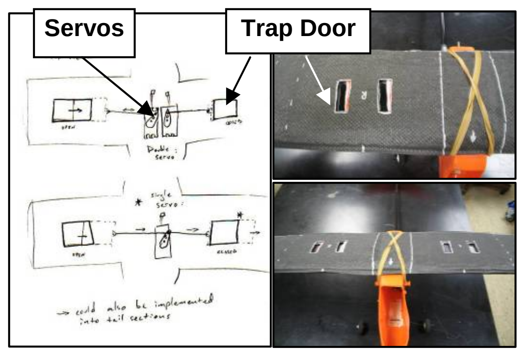

Figure 5. Ported Wing Concept

2.3.2. Elastically hinged spoilers:

In this concept 3-5 separate segments of the trailing edge spoiler are located along the length of the wing (Fig. 6). The segmented spoilers are approximately ¼ of the chord in width. This is implemented on a very thin carbon fiber wing (see the section on airfoil selection below). The purpose is the same as the “ported wing” concept, to dump the additional life that a vertical gust creates. This method takes advantage of the increase in hinge moment on a plain flap with an increase in angle of attack (or a vertical gust), and also the (small) increase in dynamic pressure increasing the hinge moment, deflecting the flap, and reducing the lift. In this concept the flaps should not deflect as speed changes at 1g, as the load and therefore the hinge moment is relatively constant versus speed at 1 g. This is facilitated by an elastic hinge tab mounted at the hinge point of the flap. The lift dumping characteristics of this concept are facilitated by two factors. First, when the dynamic pressure on the lower edge of the airfoil becomes great enough to overcome the force of the elastic hinge tab, the flap rotates which in effect "removes" that section of the airfoil depleting its lift generation. In addition, a small amount of the vertical gust can "pass through" in the slot location, mitigating the increase in lift in the same manner that the ports employ. This concept draws similarities to a concept that incorporated segmented control surfaces on the trailing edge of its wings [11] created at the University of Florida.

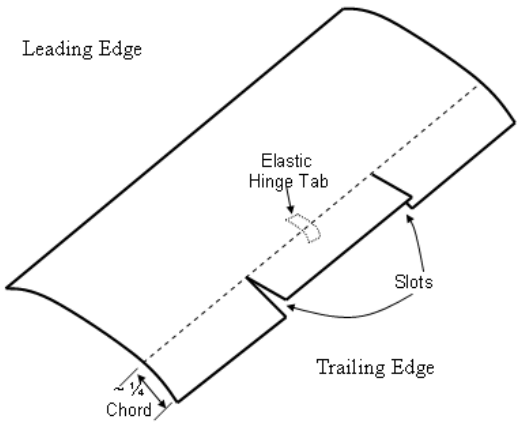

Figure 6. Elastically Hinged Spoiler Concept

2.3.3. Variable dihedral angels between the fuselage and wings:

This concept is being implemented in conjunction with the "ported wing" concept and "elastically hinged spoiler" concept. As a dihedral wing has a tendency to increase stability in many situations, the addition of small dihedral angles should increase the stability and therefore the effectiveness of the above two concepts. Here the root of the wing can either be flexible about the longitudinal axis or can be allowed to be preset for different fixed dihedral angels. This should help alleviate change in load factor due to gusts both in the positive and negative direction. We are in the process of verifying this hypothesis.

3. Experimental Approach:

The experimentation was basically a two pronged approach (Fig. 7) which consisted of: a) analytical modeling and wind tunnel and b) actual flight tests of the planes. The wind tunnel testing consists of two variations, 1) preliminary testing a scaled version of the thin airfoil (see the airfoil description in sections 3.1 and 3.2) extensive testing of a full chord, but reduced length section of the wing (see sections 3.2 and 3.3). Actual flight tests involved various iterations and modifications resulting from wind tunnel test data.

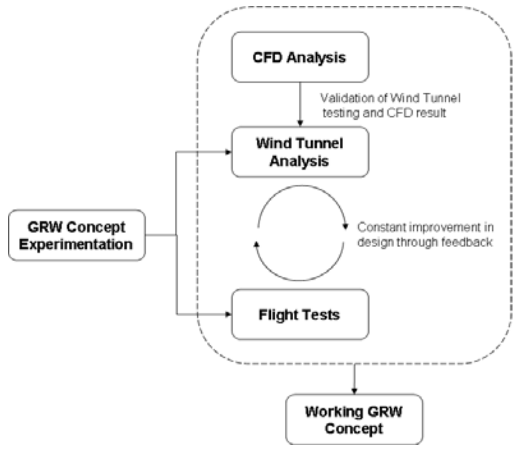

Figure 7. Two Pronged Experimentation Method

3.1 Thin Airfoil Lift Analysis, Similitude & Testing:

One of the first implementation tasks for the GRW project was selection of an airfoil. As is described below, two different airfoils have been used. The foam core foil used for the ported wing concept is described in the following sections. For the thin airfoil used to test the elastically hinged spoilers and the variable dihedral, the Goettingen 417A was chosen. The Goettingen 417A is known for being a superior low speed (low Reynolds number) airfoil for very small thicknesses. This is the airfoil currently being used on the TACMAV which is used by the Air Force Special Forces. Lift characteristics for this airfoil are readily available on the web. Figure 8 is a depiction of the airfoil shape.

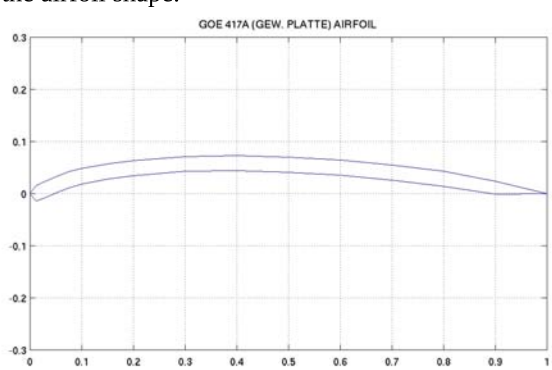

Figure 8. Goettingen 417A Airfoil

Using simple vector analysis we were able to determine the change in the angle of attack that the airfoil would experience for any given gust. This change in angle of attack directly correlates to a change in lift generated by the wing. Using the published lift characteristic data, it was possible to determine this change in lift. Using the equation:

$$L = \frac{1}{2}\rho V^2 C_O S \qquad \text{Eq. 1}$$

we were able to determine how much lift would be generated both in steady flight and when the aircraft experiences a gust. This difference in lift is the amount of lift we need to compensate for, in optimum gust resistant conditions.

In order to test whether the different modifications are actually capable of dumping the required lift, the airfoil is tested in an open test section wind tunnel. The recorded lift and drag data is used to determine the ideal modification solution for the airfoil. Because the wind tunnel will not allow an airfoil of greater than 12in., it was necessary to construct smaller wings that were fit to scale. In order for these smaller wings to provide an accurate model of actual wing performance it is necessary to maintain Reynolds number (Re) and wing aspect ratio (length/chord) similitude. Reynolds number is a parameter which describes the airflow over a wing. It follows the equation:

$$\mathrm{Re} = \frac{\rho V C}{\mu} \qquad \text{Eq. 2}$$

where ρ is the air's density, C is the chord length, V is velocity, and μ is the viscosity. Because the state of the air flowing over the airfoil is one of the most important factors in how much lift the wing generates, it is necessary to make sure the Reynolds number is the same in each condition. Since Reynolds number is a function of both the wing's cord length and air velocity, we needed to manipulate the conditions of our test to match the differing cord lengths and corresponding velocities so that the scaled wing and the full size wing experience the same flight conditions. As can be seen in the screen capture of the Excel sheet (Fig. 9), if the scaled wing has a length reduced from 21 inches to 12 inches (this is the max size for the wind tunnel) then the chord is reduced from 2.375 to 1.357 inches. With this new reduced chord, the scaled velocity must be increased from 33 ft/sec to 57.8 ft/sec.

	Full Scale						
	V=	33	ft/s	ρ	0.002377	slug/ft³	
				u	3.74E-07	slug/(ft*s)	
	L=	0.022414	lb		Length	21	in
	CL_0=	0.05	from Got 417a chart		Width	2.375	in
	q=	1.294277					
	S=	0.346354					
					Re=	4.15E+04	
	L=	0.627589	lb				
	CL_12=	1.4	from Got 417a chart				
	Delta_L	0.605175	lb				
	Scaled						
	V=	5.78E+01		ρ	0.002377	slug/ft³	
				u	3.74E-07	slug/(ft*s)	
L=	2.24E-02	lb					
CL_0=	0.05	from Got 417a chart					
q=	3.96E+00			Length	12	in	
S=	0.11309524			Width	1.357143	in	
L=	6.28E-01	lb					
CL_12=	1.4	from Got 417a chart					
Delta_L	6.05E-01						

Figure 9. Similitude Calculations to Keep Re & Aspect Ratio Consistency

Basic testing of the elastically hinged spoilers in the wind tunnel has provided sufficient confidence to continue the pursuit of this concept. In a 3-spoiler wing, engagement of the middle spoiler resulted in approximately 30% reduction in lift at approximately 10^0 AoA. Engagement of the other spoilers continued the lift dumping trend. In addition, the elastic hinge, while not optimized yet, shows promise in being able to maintain the airfoil profile for straight and level flight while engaging when significant vertical gusts occur. Figure 10 shows the open wind tunnel testing facility where the scaled versions of the elastically engaged spoilers and the variable dihedral are being tested. Figure 11 below shows the hinged region with the full spoiler engaged as it is set for wind tunnel testing.

Figure 10. Wind Tunnel Used for Testing Scaled Versions of the Spoiler & Dihedral Concepts

Figure 11. Scaled Wind Tunnel Tests with Full Spoiler Engagement

The testing process for the variable dihedral has just begun. We have created a fixture that will allow for attachment of wings at variable dihedral angels from 0 deg. ~ 10 deg. Although the justification for pursuit of this concept is purely theoretical at this point, we maintain sufficient confidence to continue the development of the MAV system for flight testing.

3.2 Wind Tunnel Testing and CFD for the Ported Wing Concept

The purpose of the experiment was to determine the effect on the lift and drag forces of a wing with various cut-out sections or ports within the wing. The wing used a full-scale chord, so the experiment and result obtained are valid for a 2 dimensional analysis [12]. An actual scaled down model would however have captured the effect of trailing vortices created by the wing and results obtained would have been closer to real flight conditions. This is a limitation of the wind tunnel experiment detailed in this section. Computational Fluid Dynamics software FlowWorks was used to generate lift and drag data and compute the coefficient of lift C_L for the airfoil used in the wind tunnel and validated the data from the wind tunnel testing. Five different orientations were tested: rectangular ports at the leading edge of the wing, rectangular ports at the trailing edge of the wing, rectangular ports along the chord of the wing, triangular ports with the base on the leading edge of the wing, and triangular ports with the base on the trailing edge of the wing, (shown in Figures 12(a) through Figure 12(e)). The hypothesis of the experiment was threefold - the ports along the leading edge would decrease the lift more than those at the trailing edge; drag would decrease with the addition of holes or ports in the wing; and turbulence would significantly increase due to air flow disruption by the ports. The results of these configurations were to be compared to the same 10in. section of wing without any holes

3.2.1 Experimental Set-Up and Procedure*:*

The wing test sections were constructed from OEM J-3 Cub wings manufactured by ParkZone which closely resemble the specifications of a standard NACA 8305-95 airfoil with a chord length of 5.6 inches. Each test section had a span of 10in. (full ½ span of the actual wing is about twice this). All of the various ports had the same area – 3.8in.^{2} (approximately 7% of the total wing area). Two ports, symmetric to the center of the wing, were cut with a scalpel

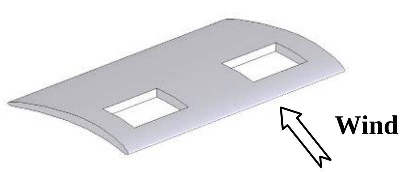

Figure 12(a). Rectangles Along Leading Edge

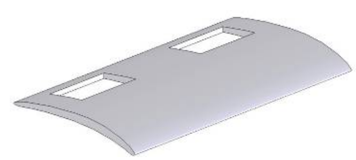

Figure 12(b). Rectangles Along Trailing Edge

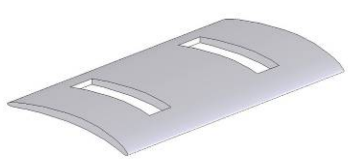

Figure 12(c). Rectangles Along Chord

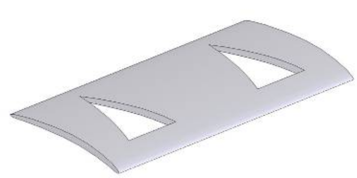

Figure 12(d). Triangle Base Along Leading Edge

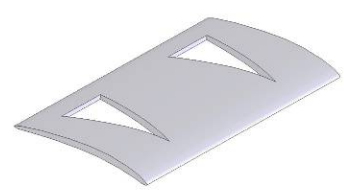

Figure 12(e). Triangle Base Along Trailing Edge

Figure 12. Different Configurations of Ports Cut Out for Wind Tunnel Testing

(removing 14% of the total wing area). In order to smooth the surface of the cut, clear adhesive tape was placed on the inner faces of the holes. Short lengths of white cotton twine were also affixed with adhesive tape along various locations of the wings to visualize the air flow along the wings.

The tests were conducted in a 12in. x 12in. wind tunnel. The wings were mounted to a force balance that contained two independent load cells to measure lift and drag forces. Modeled after anticipated flight characteristics of a modified ParkZone J-3 Cub, all of the trials were performed at a wind speed of 32mph. The force balance interfaced with a servo motor that allowed on-the-fly transitions for the angle of attack. Thus, measurements of lift and drag were obtained for angles of attack ranging from 0 to 25 degrees (in increments of 2.5 degrees) for each wing section. Photographs were taken at 0, 10, and 25 degrees to record the flow visualization produced by the cotton twine. The trials were randomized and replicated twice.

3.2.2 Wind Tunnel Test Results:

The unmodified full wing test section exhibited the highest lift trend; however, all but one of the wings with ports showed significant reductions in drag. Figures 13(a) and 13(b) show plots of the average values of lift and drag, respectively, for each wing relative to angle of attack. On these two graphs, the plot pertaining to the wing with rectangular ports at the leading edge (indicated by the magenta line) shows the most deviated trends of lift and drag. The reason for such drastic difference is most likely due to the turbulent flow caused by the ports. Figure 14 shows the full wing section at an angle of attack of 10 degrees. The white twine indicates that the flow is reasonably laminar. On the other hand, Figure 15(a) shows the wing section with rectangular ports on the leading edge also at a 10 degree angle of attack. The white twine is moving erratically; hence, the flow is more turbulent than in the pervious case. The fitful flow pattern is difficult to photograph; therefore red circles have been drawn around the twine to emphasize the location of the twine lengths.

The orientation with rectangular ports along the trailing edge of the wing demonstrated lift and drag trends most similar to the full wing. Referring to Figure 13a), the lift trend closely mimics the full wing, while the lift values are significantly lower. At an angle of attack of 10 degrees, which is approximately the level flight angle of attack for the plane, the lift is reduced by 30%. This is the lowest reduction in lift for the given port area.

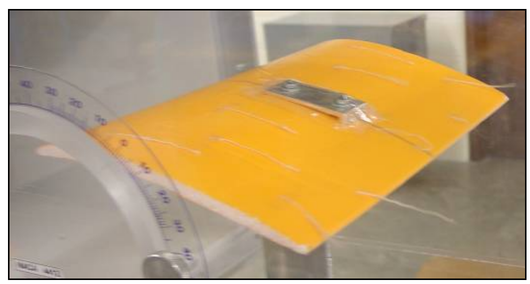

Figure 14. Full Wing Section at 10 deg AoA

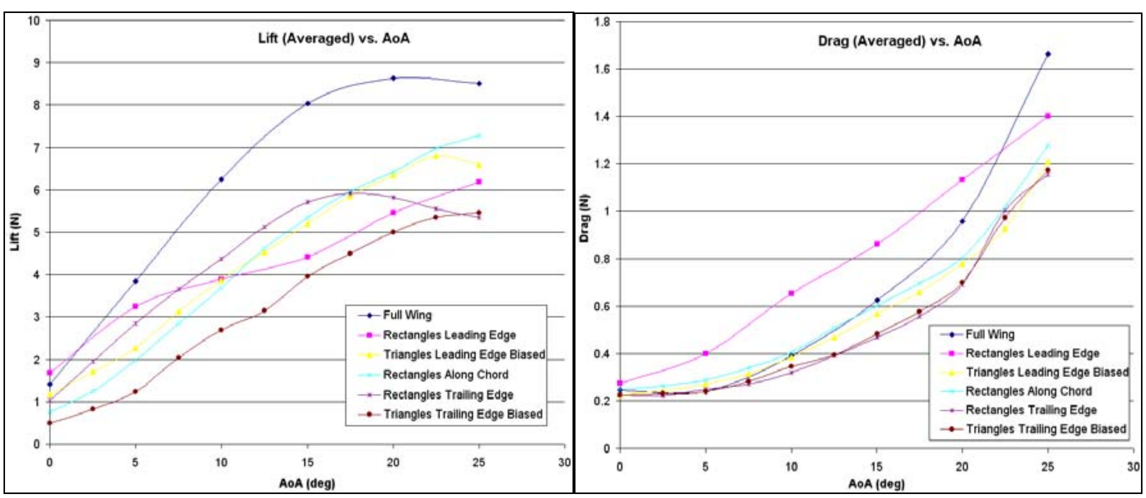

Figure 13. (a) Lift vs. AoA Curve (b) Drag vs. AoA curve for Various Ports

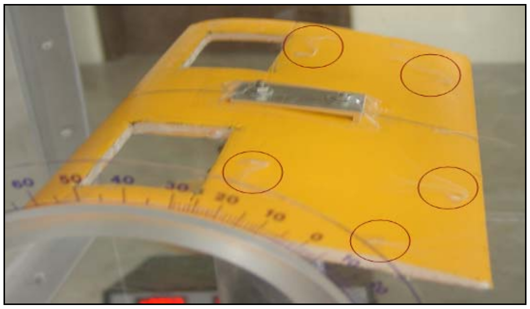

Figure 15(a). Rectangular Leading Edge at 10 deg AoA

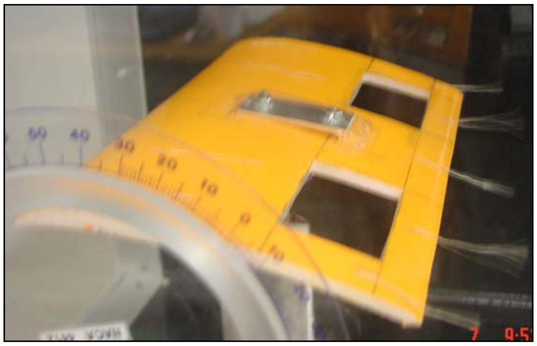

Figure 15(b). Rectangular Trailing Edge at 10 deg AoA

The main reason for the least reduction in lift relies on the principle that most of a wing's lift is generated toward the leading edge of the wing. Since this portion of the wing is left unchanged, less drastic lift characteristics are expected to be observed. The wing section with rectangular ports at the trailing edge also exhibited fairly laminar flow at a 10 degree angle of attack (Fig. 15(b)), which further supports why the least amount of lift was lost. Additionally, the trailing rectangle orientation provided the least amount of drag (at an angle of attack of 10 degrees) compared to all other test orientations (Fig. 13(b)). The combination of highest lift force and lowest drag force yields this orientation to be the most efficient when compared to the other ported wings. Figure 16 displays the efficiency curves for all the wings tested.

It is important to note that both triangular orientations, similar to the orientation with rectangular ports at the leading edge, reveal lift profiles quite different than the full wing at angles of attack between 0 deg and 15 deg. All three of these port layouts caused the wing section to vibrate highly and demonstrated instability on the force balance. While Figures 15(a) and 15(b) show the flow visualization of the wing with rectangular ports on the leading and trailing edge, Figures 17(a) and 17 (b) show the flow visualization of the wings having triangular ports with bias on the leading edge and trailing edge, respectively. The turbulent flow reduces lift drastically, but this type of flow also causes the lift to be highly varied.

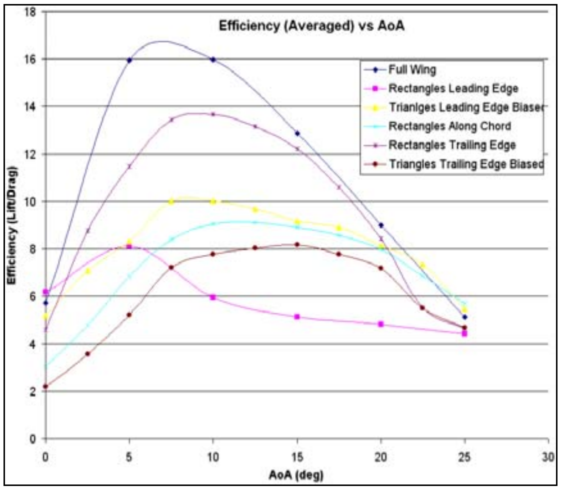

Figure 16. L/D Curves for Various Port Configurations

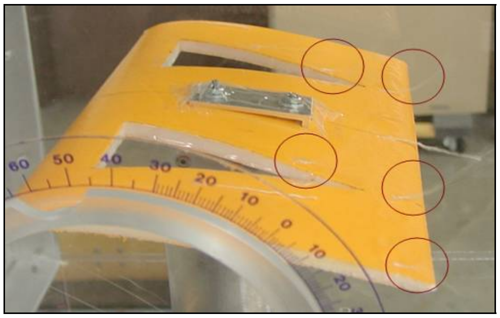

Figure 17(a). Triangular Leading Edge Biased at 10 deg AoA

Figure 17(b). Triangular Trailing Edge Biased at 10 deg AoA

The wing section with rectangular ports along the chord had aerodynamic characteristics falling in the median of the experimental data (Figures 13(a), 13(b) and 16). Flow visualization for this wing section, shown in Figure 18, was turbulent at the trailing edge. However, several of the lengths of twine illustrated highly laminar flow while the others were simultaneously turbulent. This variation in flow patterns most likely lead to the mid-ranged lift and drag values. Field tests demonstrate the possible effectiveness of this port layout; thus further experimentation is desired. Figure 13(a) illustrates how this particular orientation has a higher reduction in lift at 10 degrees compared to other orientations. If drastic reductions in lift are needed for gust mitigation, this orientation would be a viable candidate.

Figure 18. Chord Spanning Port at 10 deg AoA

Assume that the MAV weighs about 400 grams. The minimum lift required to be generated for straight and level flight would be approximately 3.9 N. From the lift graph in Figure 13(a) we can compare the lift characteristics of the "Full Wing" (Fig. 14) and the "Rectangular Trailing Edge Port Wing" (Fig. 15(b)). Table 1 and 2, shown below, give us some interesting results. The effect of gust (coming vertically from under the wing) can be modeled as a vector sum with the relative wind

Table 1. Effect of Varying AoA on "Full Wing" and "Ported Wing"

Gust Vector on the Wing Effectively Increasing the AoA

	At Min. AoA to Sustain Flight	+5 deg AoA	+10 deg AoA	+15 deg AoA
Lift of "Full Wing"	3.9 N	6.3 N	8 N	8.6 N
	(5 deg AoA)	(10 deg AoA)	(15 deg AoA)	(20 deg AoA)
Lift of "Rectangular Trailing Edge Port Wing"	3.9 N	5.3 N	5.9 N	5.5 N
	(8 deg AoA)	(13 deg AoA)	(18 deg AoA)	(23 deg AoA)

Table 2. % Change in Lift Comparison of Two Wing at Different AoA's

	% Change in Lfit for "Full Wing"	% Change in Lift for "Rectangular Trailing Edge Port Wing"
Gust causing + 5 deg increase in AoA	61.5	35.9
Gust causing + 10 deg increase in AoA	105.1	51.3
Gust causing + 15 deg increase in AoA	120.5	41

acting on the wing by increasing the AoA experienced by the wing. The "Full Wing" can be assumed to be flying at 5 deg AoA and the "Rectangular Trailing Edge Port Wing" at 8 deg AoA, where both wings maintain at least 3.9 N of lift for sustained flight. The AoA shown in Table 1 are in increments of 5 degrees. Table 2 shows us the % increase of both the wings at varying AoA's. It can be clearly seen that the "Rectangular Trailing Edge Port Wing" analyzed here shows significant lift reduction compared to the "Full Wing". For example at +10 deg of AoA there is a 105 % increase in lift generated by the "Full Wing" compared to 51% lift generated by the ported wing. Also the % increase in lift of the ported wing is lower than the full wing, while maintain lower drag (Figure 13(b)) indicating potential for decreasing lift more steadily compared to a normal wing. This configuration of rectangular ports on the trailing edge appears to have tremendous potential as a GRW.

3.3 Field Flight Test of Ported Wing:

The field tests of the ported wing concept were carried out concurrently with the wind tunnel tests. Some results of wind tunnel testing were explored during the field tests and subsequent results of the field tests will be carried out in the wind tunnel such as changing the area of ports.

3.3.1 Manufacture of Ported Wings:

The ported wings were manufactured through Vacuum Bagging (Fig. 19(a)) using foam core wings, available commercially, which were wrapped with one ply of uni-directional carbon fiber (fibers running along the wingspan). The addition of carbon fiber gives more flexibility in the creation of the ports along the wingspan as the carbon fiber provided strength to the wing. The wing was then marked with a 1in. x 1in. grid (Fig. 19(b)) for port size and location. The port shapes tested were "Chord Spanning Ports" (Fig. 20). Each port represented

2% of the total wing area. A total of 8 ports (yellow) were cut into the wing, 4 on each side of the wing at increments of 2in. from the center of the wing.

Figure 19(a). Vacuum Bagging Lay Up

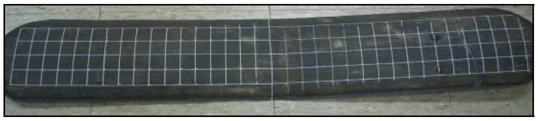

Figure 19(b). Grid Marked on Carbon Fiber Wing for Port Size and Location

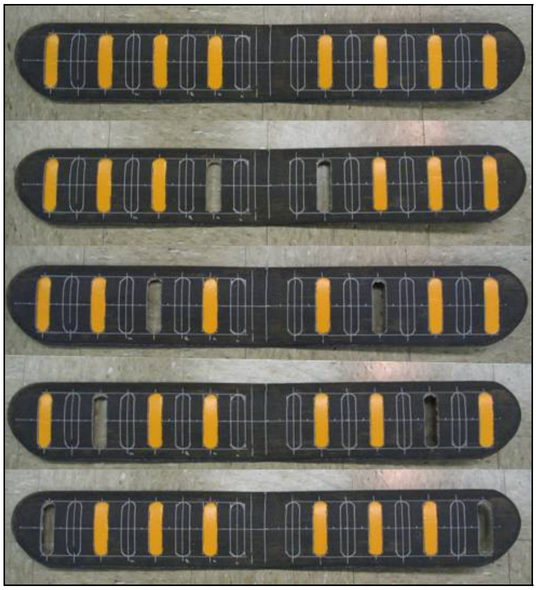

Figure 20. Chord Spanning Ports Along the Wingspan

3.3.2 Field Test Results:

From the field tests (Fig. 21) it was seen that as the ports went inward i.e. towards the fuselage the plane would experience less lift and would tend to have a rolling moment and oscillate during turns. The plane was stable and didn’t loose as much lift (comparatively) when the ports were towards the wing tips. There are two main reasons to this occurrence:

a) The lift generated across the wingspan is the greatest near the fuselage. This distribution is well know and is approximately elliptical. Therefore, the plane generates more lift when the ports are at the tips compared to when the ports are near the fuselage.
b) The rolling moment experienced is more when the ports are near the fuselage because the moment generated is from the lift at the wing tips, which is now more pronounced. When the ports are towards the wing tips, the lift at the tips is lower and hence low rolling moment is experienced.

Figure 21. Field Test Video Images

These preliminary field tests have given us valuable insights on the design and location of these ports. Subsequent field test iterations will include testing of the “rectangular trailing edge” ports which seemed a promising port shape and location from the wind tunnel test. Work on making wings with semi-active ports is also being concurrently carried out to test the actuation of ports during flight (Fig. 22). The wings are being made of carbon fiber and have a servo embedded at the center that actuates ports on either side. The semi-active wing will be tested on new plane platform shown in Figure 23; the body of which is made of carbon fiber to make it light weight and more robust.

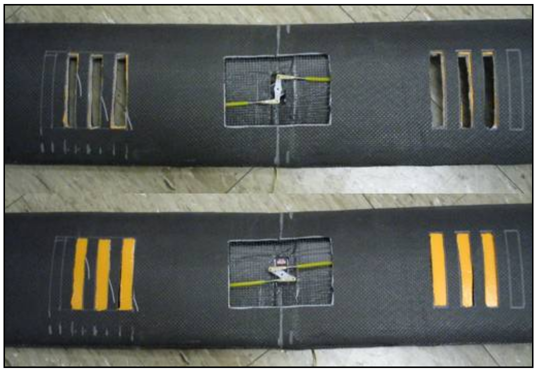

Figure 22. Semi-Active Port Actuation

4. Conclusion:

MAVs are low-weight, small wing span RC aircraft. Both civilian and military customers use these MAVs for surveillance. As this surveillance is accomplished through the use of on-aircraft video cameras, the stability of the aircraft is critical to obtaining quality video images. Windy environments often make this video virtually un-usable. In light of this scenario, the development of wing technology that can resist wind gusts is critical.

Figure 23. New Testing Platform

A newly developed Transformational Design Methodology (used to design systems that change state in order to facilitate new functionality) has been implemented to produce concepts intended to mitigate gusts. Three concepts in particular have been identified for continued testing. These concepts are 1) Ported Wings, 2) Elastically Hinged Spoilers and 3) Variable Dihedral. Each of these concepts has been investigated both in wind tunnel testing and through the use of actual flight tests. In particular, the ported wing concept has been extensively tested resulting in confidence that this concept is implementable and effective at mitigating the effects of gusts. For example, rectangular ports located close to t he trailing edge of he airfoil have been shown to reduce the lift associated with vertical gusts (modeled as increasing AoA) by as much as 50% while actually reducing drag. The concept of elastically hinged spoilers also appears to have promise in the ability to “dump lift” in the presence of vertical gusts.

4.1 Future Work:

Future experiments will be done with various port areas. These experiments will focus on the orientation with rectangular ports along the trailing edge and the rectangular ports along the wing chord. This will be carried out in the wind tunnel as well as in actual flight tests. The motivation this is that the trailing edge rectangles performed well in the previous experiments, while field test have proven that rectangular ports along the chord fly well. The experimental data on these ports show even more reduction in lift at 10 deg angle of attack with only moderate turbulent flow across the wing surface. The next phase of experimentation will provide optimal port orientations and areas, validated through successful implementation of this concept and test flight to demonstrate vertical gust mitigation of MAVs.

Experiments on the elastically hinged spoilers are also continuing. Different numbers of spoilers as well as different hinge stiffness are among the critical variables. Both wind tunnel and flight testing is in progress for this concept. Similarly, the testing for the variable dihedral is also continuing. The variable dihedral concept is scheduled to be implemented in conjunction with the other two concepts to determine if it will produce the hypothesized increase in stability.

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