Virginia Tech Aerospace Engineering
Fall Semester Final Report
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1. Introduction

1.1. Introduction to Flight

In December 17, 1903 almost precisely 100 years ago the world's first heavier-than-air, controllable machine-powered aircraft leapt into the air in Kitty Hawk, North Carolina. The first 100 years of flight have since passed and human air vehicles are faster, safer and more efficient than ever. With all the progress that has come about in the past Century, human flying machines still cannot come close to the adaptability and efficiency of nature's own elegant designs. The next step in aviation is to come closer to the elegance and simplicity of avian creatures and to expand the envelope of flight as we know it today.

In order to maximize the efficiency of flight, human-built flying machines will have to become less rigid. A definition of morphing from Virginia Tech's Morphing Project 2002 is "to cause to change shape". In terms of the wing's geometry, morphing is a smooth change in an aircraft's physical characteristics. The third Virginia Tech Morphing Wing Design Team aims to design and build an airplane model that will incorporate variable camber and incidence for demonstrating morphing technology.

1.1.1. Morphing

NASA began its Morphing Project as an approach of researching ways in which advanced technologies could be incorporated into air and space vehicles. A morphing wing has the potential of surviving tradeoffs against conventional design. However, due to the early status of this technology it has not yet been refined. It is Virginia Tech's goal to eliminate the need for control surfaces and allow efficient flight in multiple flight regimes.

The trade-off between high-efficiency and high-maneuverability and the restriction of efficient flight to a single regime will no longer apply. This design paradox intrigues and fuels the goals of Virginia Tech's Morphing Wing Design Project. This year's Morphing Project hopes to accomplish two morphing schemes: mission morphing and control morphing. The difference between the two lies in the primary purpose. Control morphing eliminates the need for conventional control surfaces such as ailerons and elevons. This type of morphing involves small changes to improve efficiency or serve as the control mechanism. Mission morphing is larger in scale; it involves more pronounced shape changes and is meant to change the vehicle's flight properties to account for the appropriate flight regime.

An example of mission morphing was the variable sweep F-14 Tomcat. The slightly swept wing position of the F-14 Tomcat was advantageous for short takeoff and landing, low-speeds, and fuel efficient flight, whereas the fully swept wing position was ideal for supersonic flight and maneuvering. However, the increased weight and complexity of the variable sweep mechanism caused increased maintenance costs and lowered the aircraft's overall fuel efficiency.

1.2. HECS

The Hyper Elliptic Cambered Wing Span (HECS) was conceived as part of the biomimetics division which was added to NASA's Morphing Project in 2002. The NASA Langley study researched advances in flight technology inspired by biological systems. The endeavor centers on learning from nature by applying and understanding how biological flight systems work. By following nature's examples of very elegant and efficient multi-functional component designs NASA hopes to lead development of the next generation of airfoils.

The HECS wing is an airfoil inspired by shore birds in flight. The variable dihedral in its fully deflected state is given by the equation

$$z(y) = \kappa\left[1 - y^n\right]^{1/n} - \kappa \qquad (1.1)$$

where $0 \le y \le 1$, _ scales the z-axis, and n defines the super-ellipse. This variable dihedral airfoil shape was analyzed using the Tornado Vortex-Lattice Method (VLM) written by Tomas Melin at the Royal Institute of Technology (KTH)[1]. Because the work done on the HECS concept was never concrete, only approximations were made using Tornado.

Figure 1-1 and Figure 1-2 were used to approximate the shape of the variable dihedral wing in Tornado. Because the Tornado VLM program does not accept variable dihedral, several partitions with different dihedral were used to approximate the continuous geometry. Below are two figures which show the initial crude approximation used for the aerodynamic analysis of the HECS wing.

This first crude analysis of the HECS wing was done by approximating the elliptical camber by three partitions with varying dihedral and sweep. The HECS wing airfoil NASA had chosen to retrofit to the original HECS design was the SD7032 airfoil. This airfoil is a low Reynolds number airfoil designed by M. S. Selig and J. F. Donovan.

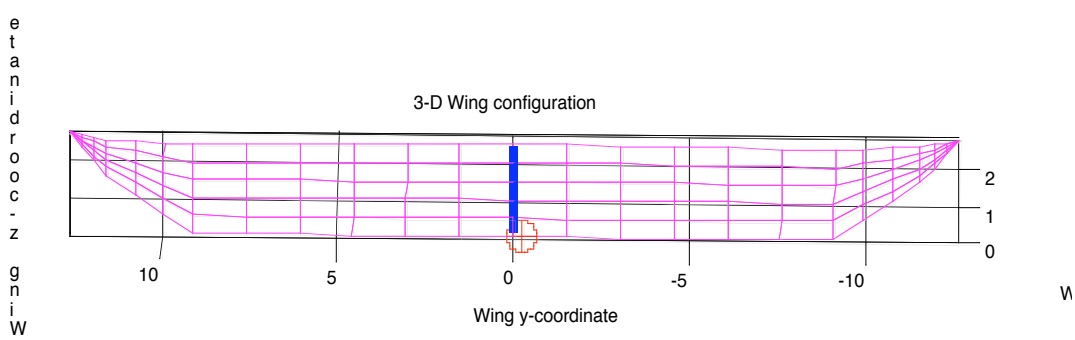

Figure 1-1: Top view of approximated HECS geometry used by Tornado

[1] Melin, Thomas. "Tornado Vortex Lattice Method." Avail. http://www.flyg.kth.se/divisions/aero/software/tornado/

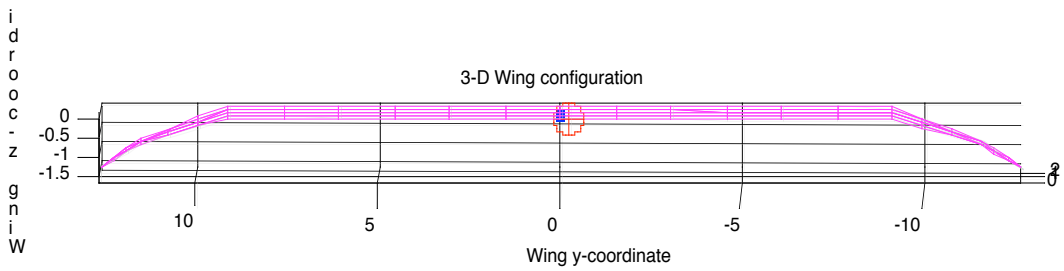

Figure 1-2: Front view of approximated HECS geometry used by Tornado

Unexpectedly whilst working on the HECS design, NASA decided to cancel the project and laid doubts on the aerodynamic benefits of this configuration. Chris Johnston, a Virginia Tech aerospace graduate student, demonstrated a lack of benefits to having variable dihedral capability with linear theory[2].

Virginia Tech's Morphing Project was to incorporate the HECS wing to test for wing tip morphing as a form of control. The project had been temporarily designated "MOTH" (Morphing Tip-control HECS) before its cancellation. The HECS wing for Virginia Tech was to be scaled to equal the size of NASA's initial analysis.

1.3. Wing In Ground Effect

Wing in Ground Effect (WIG) aircraft are a hybrid of boat and aircraft intended to take advantage of added lift and reduced drag encountered when flying close to the ground. WIG vehicle concepts have been around since the 1940's. However, it was not until two decades later that the first serious WIGs were developed by Russia to explore the possibility of tactical

[2] "An Aerodynamic Analysis of NASA's HECS Wing", Chris Johnston

military use. Over time, the objective for WIGs has shifted to a commercial and military use of freight transport.

Most WIG aircraft today fly efficiently in ground effect but have a low absolute ceiling or are not as efficient at altitude where the configuration for ground effect is not efficient. The Morphing Wing Design Project was looking at designing and building a vehicle that could take advantage of ground effect and fly efficiently at altitude by morphing, thereby achieving multiple flight regimes.

In researching WIG technology, the question of controlling a radio-controlled (R/C) airplane in ground effect became an issue. For a small scale aircraft, the aircraft would have to fly 3-6" off the ground. However, tests during July 2003 concluded that the pilot could not maintain control of the aircraft without assistance from an automated flight control system.

Products from UAV Flight Systems were researched as autopilots to control the aircraft close to the ground. However when searching, price became a large factor as no system under $4000 could be found to maintain altitude within ± 10 ft. All findings of the automated flight control systems and practicality for small scale WIG applications can be found in the Appendix.

1.4. Summary of two Semesters

1.4.1. Fall Semester

The Morphing Wing Design Team began the semester by studying multiple concepts simultaneously in order to determine the request for proposals (RFP). Initially, last year's BetaMax was modified to use wing extension for roll control. Two conceptual design configurations were investigated: the first was the biologically inspired Hyper Elliptic Cambered Span (HECS) wing and the second was a variation of current WIG designs. The concept for the

WIG was to eliminate the inefficient flight of an aircraft designed for flight in ground effect at higher altitudes. Increasing the low absolute ceiling of a conventional WIG transport was the mission driver for the morphing WIG concept.

Several problems were encountered when modifying last year's BetaMax. The most prominent problem was a weight and stability issue. The strategy for modifying the BetaMax was to first ensure that the new extension mechanisms satisfied the roll rate required. The longitudinal stability also had to be tailored to the current project. The longitudinal static stability was increased by shifting the center of gravity (*cg*) forward. Finally, the wing loading was compared to the original BetaMax configuration to ensure similar results. In order to reduce added weight, new wings were fabricated for the BetaMax. These wings were manufactured using balsa wood, bass wood and two plastic rods. By using lighter materials, the airplane recovered its lost stability and was then successfully flight tested. An account of the flight test and all data is depicted in Section 2.8.

1.4.2. Spring Semester

Spring semester, the Morphing Wing Design Project will continue to incorporate more morphing technology on R/C airplanes. Conceptual designs of variable planform area, variable incidence, and variable camber wing morphing aircraft were generated. Focus was placed on variable camber and wing incidence in order to maximize efficiency at takeoff, landing and cruise. This also allowed for removal of conventional control surfaces. The final design will exhibit both mission morphing and control morphing. The established goals are:

- Investigate and compare inflatable airfoils and embedded airfoils for achieving camber change
- Investigate and compare wing tendons and a rotating spar for flight control
- Examine the use of flexible materials for covering the wings

The majority of spring semester will be spent modifying the preliminary morphing design. Research will be conducted to determine the optimal configuration for reduced landing and takeoff speed and improved maneuverability. The team will work with the Center of Intelligent Material Systems and Structures (CIMSS) at Virginia Tech to study flexible skins and methods of implementing variable twist and camber. The semester will conclude with collection of flight data from a new aircraft with a 48”-60” wing span that will roll only by wing twist and change chamber in flight.

1.5. Group Organization

The Morphing Wing Design Project is a partnership between the aerospace and mechanical engineering departments. The associated division of the mechanical engineering department involved with the Morphing Wing Design Project is the CIMSS. CIMSS focuses on the use and development of smart materials including device design and modeling.

Several concepts were initially studied in the fall semester. Due to the diverse nature of the concepts, members of the Morphing Team were assigned tasks according to individual interests. The breakdown of tasks is shown in Table 1-1.

Table 1-1: Concept distribution

	Telescoping Wing	WIG	HECS
Beverly Beasley	✓		
Kevin Birocco			
David Pfeffer	✓	✓	
Daniel Pedraza			✓
James Pembridge	✓		✓
Adam Barker	✓		
Justin Farmer	✓		
Jonathan Inman	✓		
Peyton Martin	✓		
Matthew McCarty	✓		✓
Christopher Minton	✓		
Josiah Oliver	✓	✓	✓

Upon deciding to modify the BetaMax for roll control, all attention was diverted towards the telescoping mechanism. At this point, the group reconvened on a single concept.

2. BetaMax Modification

2.1. Request for Proposal

The 2003-2004 Morphing Team focused on modifying the 2002-2003 Morphing Team's delta wing for the duration of fall semester. Last year's delta wing R/C aircraft, BetaMax, utilized two wing tip extensions, caged together, to change the wing span and wing area of the aircraft. The wing extensions extended simultaneously to increase the aspect ratio for better loiter capabilities, then retracted for cruise.

The 2003-2004 Morphing Team focused on modifying the BetaMax to allow independent extension of each wing tip to permit roll control. Upon completion, the BetaMax was to use only wing extension for roll control, rendering the elevons useful only for pitch control.

2.2. Project Goals

To complete the RFP, the design team set out to fabricate a gear-extension system to independently extend each wing tip. The goal was to extend the wings at a fast enough rate such that the aircraft bank angle performance met MIL STD 1797, which demands 60º bank in 1.3 seconds for lightweight aircraft. The extension mechanism had to be light-weight, efficient, and require minimum power to operate. BetaMax's *cg* had to be shifted such that the aircraft maintained stability for retracted-wing flight, as opposed to extended-wing flight in 2002-2003.

The modified BetaMax was to be test flown using a roll rate sensor to complete the project's final goals: to fly the modified BetaMax using wing extension for roll control and compare flight data to engineering predictions and previous flight data.

2.3. Mission Drivers

The project was driven by new technology and the desire to defy convention, proving ailerons and elevons were not the only method for roll control.

Various types of motors, batteries, gears, and bearings were researched to implement the most efficient system. New piezo-electric motor technology was compared and weighed against conventional electric motor performance, while Nickel-cadmium (NiCd), Nickel-metal Hydride (NiMH), and Lithium Polymer batteries' voltage, endurance, weight, and cost were compared.

Time restraints drove the team to make quick, well-informed decisions in order to flight test the aircraft by the end of November. The team was driven to complete the BetaMax modification project by the end of fall semester in order to dedicate spring semester to a new morphing concept.

2.4. Roll Control

Roll control is traditionally achieved by deflecting ailerons or spoilers in opposite directions. The deflections modify the spanwise lift distribution, resulting in a moment about the longitudinal axis. The use of telescoping wings for roll control is based on the same principle, except the lift distribution is modified and roll moment is created by extending only one wing.

Implementation of telescoping wings for roll control required several modifications to the BetaMax. The rack and pinion telescoping mechanism which controlled both wings simultaneously had to be replaced with two telescoping motors to control the wings independently. Rack and pinion, piezo-electric, car antenna, and high rpm electric motors were investigated as viable options. The piezo-electric motor was eliminated from further investigation due to its weight, difficulty of integration, and availability. Only one-piezo electric

motor was available and two would be needed to independently extend the wings. Further eliminations were made on the basis of weight and wing extension rates. The weight and extension rates of the remaining three options are listed in Table 2-1.

Table 2-1: Telescoping Motor Data

Motor	Extension Rate (in/sec)	Motor Weight (oz.)
HItech servos combined rack and pinion	1.6	5.6
Car antenna	4.2	50
Radio Shack high rpm electric motors	12	12.2

Since the Radio Shack motors exhibited the fastest extension rate, the effectiveness of the telescoping wings with these electric motors was analyzed using two mathematical models.

Initial predictions of the BetaMax telescoping roll capability were analyzed with the MATLAB vortex paneling code Tornado. A model of the original BetaMax was input, the reference flight condition was set as 45 mph at 4º angle of attack, and stability derivatives and roll moments were calculated. An asymmetric model of the BetaMax with the right wing fully extended was also input. A comparison of the two models is presented in Table 2-2.

Table 2-2: Retracted and right wing extended BetaMax models

	Retracted	Right Wing Extended
Root chord, c_r (in)	37	37
Taper ratio, _	0.48	0.48
Inboard aileron location, y_1 (in)	7.25	7.25
Outboard aileron location, y_2 (in)	21.75	21.75
Wing area, S (in^2)	1367	1467
Wingspan, b (in)	54	64
Maximum $\_a$	25°	25°
Roll moment of inertia, I_{xx} (sl ft^2)	0.5149	0.5149
Lift curve slope, $C_{L\_}$	3.3811	4.2553
Aileron effectiveness, C_{L_a}	0.10935	0.13693
Roll damping, C_{lp}	-0.31241	-0.64309
Steady state roll rate at max. $\_a$, P_{ss} (deg/sec)	256.682	131.747
Roll moment (Nm)	7.3752 (Max. $\_a$)	4.9493 ($\_a$ = 0)

To determine the maximum roll capability of the modified BetaMax, the reference roll rate input was increased until the roll moment of the original BetaMax matched the roll rate of the asymmetric model. The roll moment was matched at 170 deg/sec, giving an equivalent aileron deflection of 18.7º and roll moment of 4.95 Nm. The original BetaMax had a maximum aileron deflection of ±25º and a maximum roll rate of ±250 deg/sec. The prediction assumed instantaneous wing extension, one degree of freedom, and constant moment of inertia based on the retracted BetaMax geometry. Thus, the modified BetaMax can optimally produce just over half as much roll control using telescoping wings compared to traditional ailerons. If the telescoping wings were to malfunction during flight, then the ailerons would have enough control authority to counteract roll moments caused by the asymmetric geometry, allowing for a safe landing.

The roll rates and bank angles based on this prediction method are plotted against time in Figure 2-1 and Figure 2-2 for various extension rates. The governing equations for these plots are based on Equation 2.1, which is then solved for roll rate and bank angle in Equations 2.2 and 2.3.

$$\sum L = I_{xx}\dot{p} \tag{2.1}$$

$$p(t) = \frac{-L_{\delta a}\left(\frac{d\delta_a}{dt}\right)_{\max}}{L_p^2}\left[(1+L_p t) - e^{L_p t}\right] \tag{2.2}$$

$$\phi = \frac{-L_{\delta a}\left(\frac{d\delta a}{dt}\right)_{\max}}{L_p^2}\left[\frac{1}{L_p}(1-e^{L_p t}) + t + \frac{L_p}{2}t^2\right] \tag{2.3}$$

In these equations, p is the roll rate, L is the roll moment, $\dot{p}$ is the angular roll acceleration, I_{xx} is the roll moment of inertia, $\_{a}$ is the aileron deflection, L_p is the roll damping, L_{a} is the aileron effectiveness, and _ is the bank angle. The bank angle was used as a performance requirement based on MIL STD 1797. The bank angle requirements to meet the criteria are indicated as stars on the graph for the indicated class and category of aircraft.

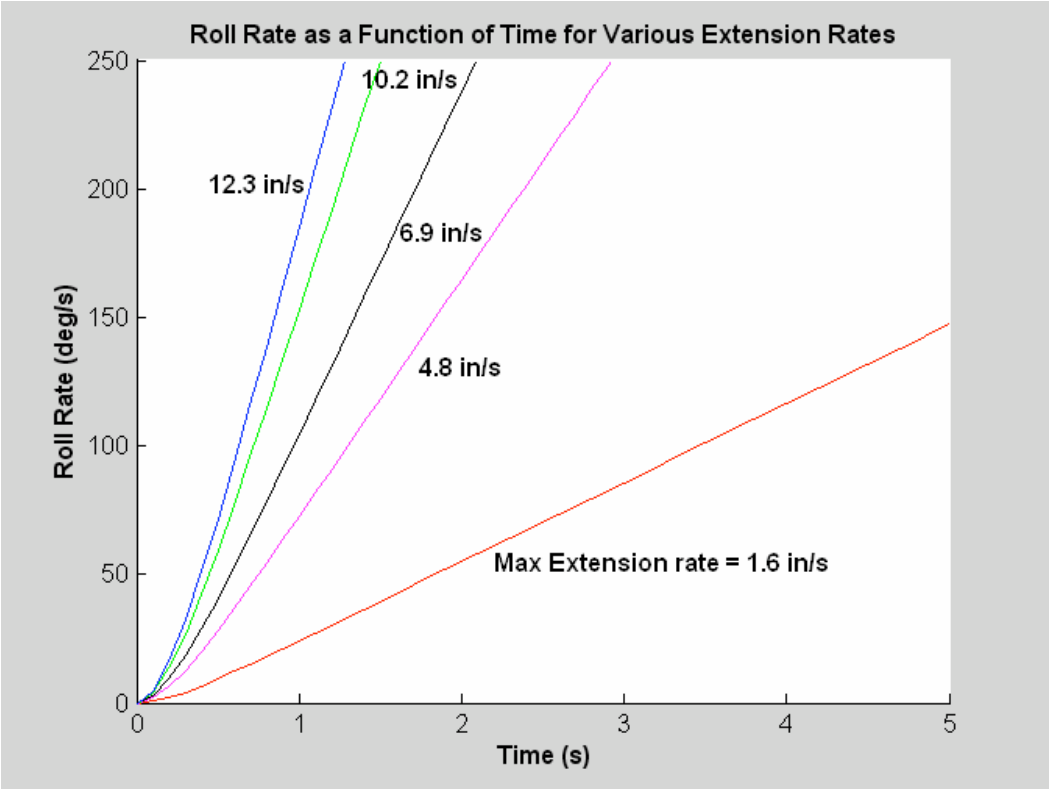

Figure 2-1: Roll rates for various extension rates (red line is the original BetaMax configuration)

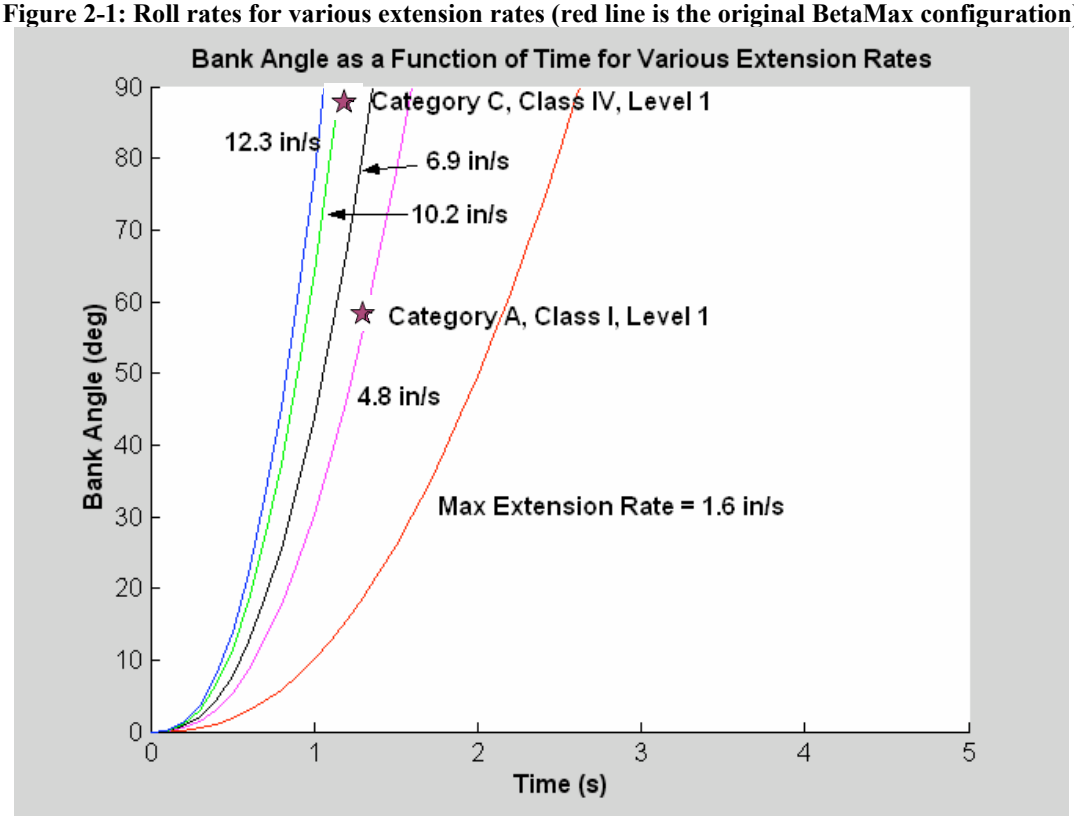

Figure 2-2: Bank angle for various extension rates and criteria requirements

Figure 2-2 shows that an extension rate of 4.8 in/sec would meet the bank angle requirements for a lightweight Category A, Class I, Level 1 aircraft. The extension rate of the worm gear motor exceeded 12 in/sec, allowing the aircraft to reach Category C, Class IV, Level 1 criteria of highly maneuverable aircraft. However, the assumptions stated to derive these plots limited accuracy. A better prediction method was derived based on changing moment of inertia.

Equation 2.1 was modified to reflect changes in the moment of inertia.

$$\sum p = I_{xx}\dot{p} + p\dot{I}_{xx} \tag{2.4}$$

Traditionally the sum of the rolling moments is defined as $L_{\_a\_}a + L_p p$; however, since no ailerons were to be used, the $L_{\_a\_}a$ term was replaced with an asymmetric extension term, _L(t). The other terms that became functions of time due to the telescoping wing extensions were $I_{xx}(t)$ and $L_p(t)$. Changes in I_{xx} were derived from Equation 2.5.

$$I_{xx} = \iint \rho r^2 dA \tag{2.5}$$

_ was the density in sl/ft^2 and r was the perpendicular distance from the x-axis. The BetaMax was approximated by a flat plate, with the density measured by an estimated weight of 13.1 lb and S_{ref} of 9.493 ft^2. The changes in roll damping and roll moment were approximated by Equations 2.6 and 2.7.

$$L_p = \frac{QSb^2 C_{lp}}{2I_{xx}V} \tag{2.6}$$

$$\Delta L = 4.1943t \tag{2.7}$$

C_{lp} was approximated to vary linearly with time between the two values calculated in Tornado (Table 2-1). The constant 4.1943 in Equation 2.7 was determined by the projected roll moment

calculated in Tornado. The resulting first order ordinary differential equation describing the system is:

$$\dot{p} + \left(\frac{\dot{I}_{xx}}{I_{xx}} - \frac{L_p}{I_{xx}} \right) p = \frac{\Delta L}{I_{xx}} \tag{2.8}$$

The roll rate and bank angle solutions were determined numerically in MATLAB, plotted in Figure 2-3 and Figure 2-4, and compared to the previous results. The solutions assumed an extension rate of 12 in/sec based on the Radio Shack electric motor output. Again, the bank angle criteria for various aircraft classes and categories are indicated by stars on the graph.

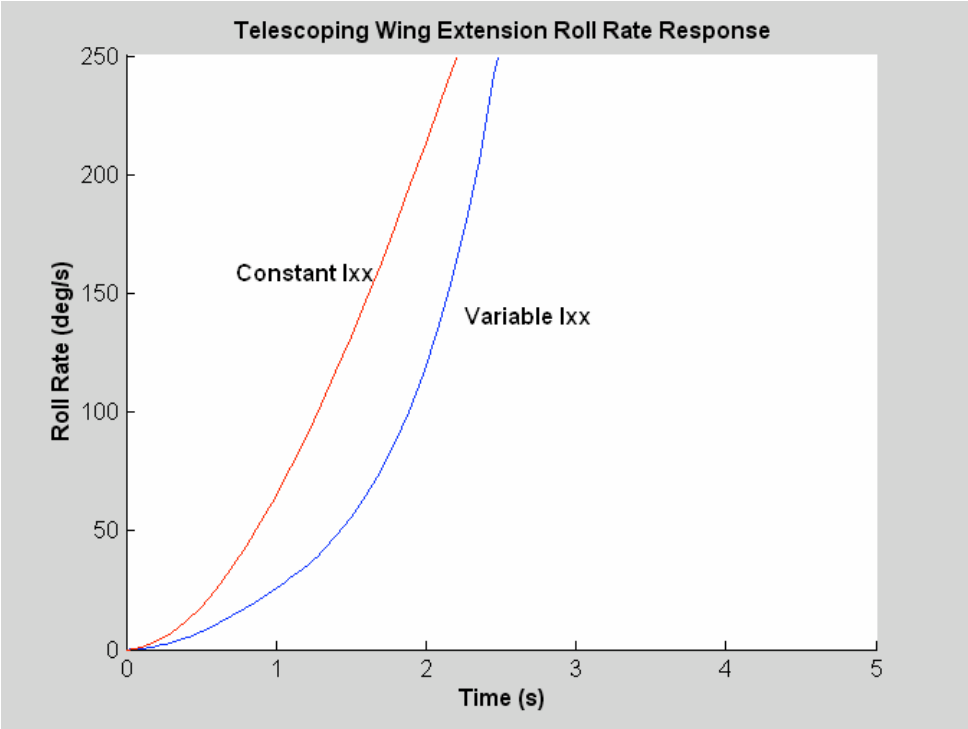

Figure 2-3: Roll rate comparison for constant and variable roll moment of inertia, wing extension rate: 12 in/sec

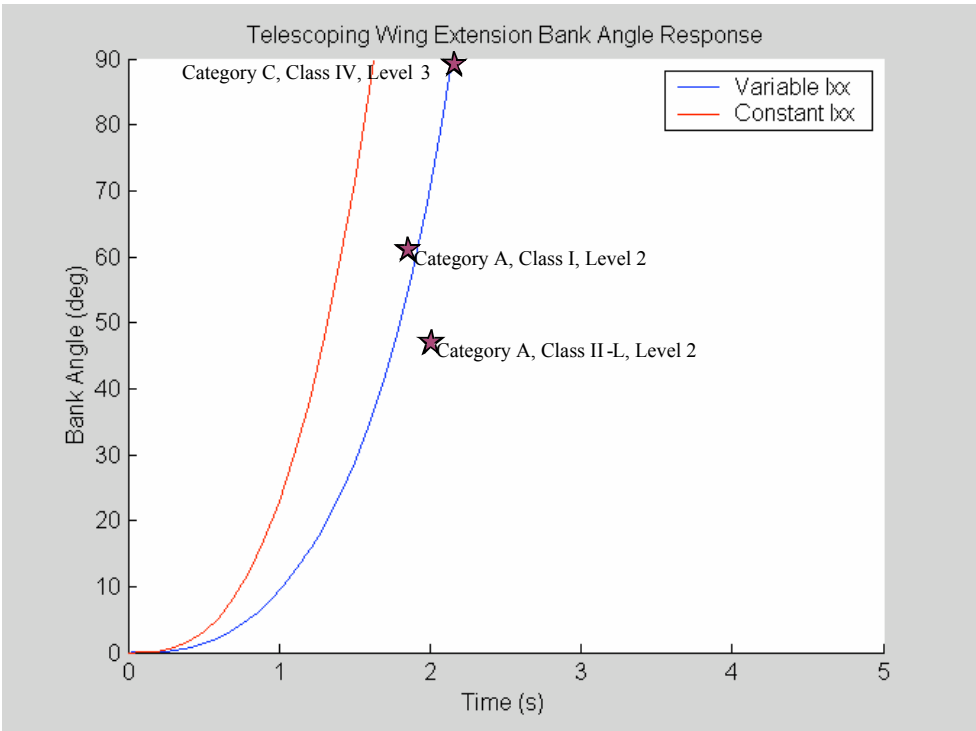

Figure 2-4: Bank angle comparison for constant and variable roll moment of inertia, wing extension rate: 12 in/sec

The effects of changing I_{xx} prevent the BetaMax from meeting the same time to bank angle requirements. The extension rate of 4.8 in/sec met Category A, Class I, Level 1 requirements with the original mathematical model, but an extension rate of 12 in/sec with the new mathematical model did not meet Category A, Class I, Level 2 or Category C, Class IV, Level 3 bank angle requirements. With the new model, the BetaMax met Category A, Class II-L, Level 2 requirements. Though the modified BetaMax cannot meet the criteria as hoped for, it should still produce a roll moment sufficient for causing rolling motion.

2.5. Wing Extension System Designs

2.5.1. Motors

Numerous electric motors were researched to find the optimum combination of extension rate and weight that would best adapt to the aircraft.

Piezo-electric motors are small motors composed of lead zirconate titanate (PZT) ceramics that are capable of precise actuation through closed loop control. Two PZT actuators were considered to drive a rack and pinion system to extend the wings to exact positions. The actuator, shown in Figure 2-5, extended the wing at a rate less than 2 in/sec. The PZT motor required a digital servo-controller that determined the voltage to send the motor based on comparing a reference position to the motor's actual position. Although permitting a great deal of accuracy, the necessary controller increased the total weight of the system.

Figure 2-5: Piezo-electric motor[3]

HItech servos are small electric motors commonly used in remote controlled vehicles to move control surfaces, throttles, and wheels. Two HItech servos were considered to extend the two wing tips using a rack and pinion method shown in Figure 2-6. The servos weighed 2.3 oz combined and could extend the wings at 1.6 in/sec when supplied with 6V.

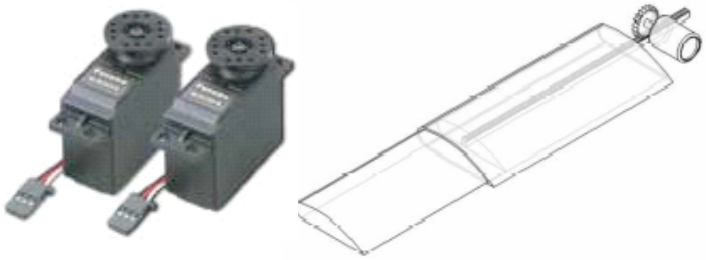

Figure 2-6: Rack and pinion system using HItech servos[4]

An Auto Works model 728048 telescoping car antenna uses an electric motor to drive a geared plastic line through an aluminum antenna to extend the antenna on command. The type of system shown in Figure 2-7 was considered to extend and retract the BetaMax wing tip extensions. A system was purchased from *Advanced Auto Parts* for research of its practical use. The system consisted of an enclosed electric motor with attached antenna that would extend at a rate of 4.2 in/sec when supplied with 12V power. The system weighted 50 oz and would be sufficient to extend only one wing.

[3] Piezo electric motor avail. http://www.physikinstrumente.de
[4] http://www.fuabarc.com/radios/futm89c-2.jpg and [4]

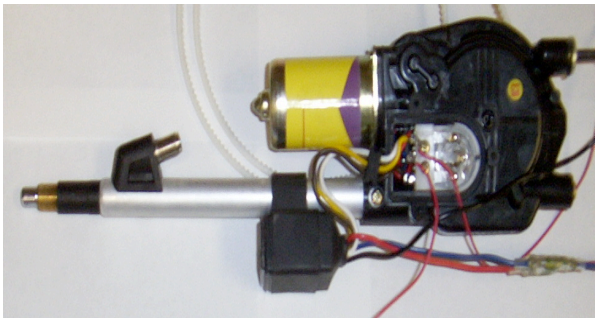

Figure 2-7: Auto works model 728048 car antenna extension system

Another rack and pinion extension system considered for the design was fabricated by the mechanical engineering team. The system was similar in design to the HItech servo system but used larger electric motors rated at 20,000 rpm to yield an extension rate of 12 in/sec. The system weighed 12.2 oz and required 18V to operate.

2.5.2. Batteries

Multiple types of batteries were considered in order to find an affordable unit with adequate endurance and high power to weight ratio. Research focused on NiCd, NiMH, and Lithium Polymer batteries.

NiCd and NiMH batteries are two cell types commonly used in remote-controlled vehicles and portable electronics. NiCd cells have good high and low temperature performance and are resistant to shocks and vibrations that occur in flight. NiMH cells have good low temperature and high power performance. NiCd batteries are rated at 1.25 V/cell, while NiMH have slightly more power at 1.50 V/cell. Both cells have a high initial cost, but can be recharged for repeated used.

Lithium Polymer batteries perform poorly at extreme temperatures, but have an energy density more than twice that of the NiCd or NiMH cells. Lithium Polymer cells produce 3.7

V/cell, giving it a high power to weight ratio. However, Lithium Polymer cells are fragile, have a shorter lifetime, and can leak if not carefully handled. The cells can be recharged like the NiCd and NiMH cells, but a special charger rated only for Lithium Polymer cells must be used.

2.6. BetaMax Performance Considerations

2.6.1. Wing Loading

The addition of the wing extension system for roll control triggered problems with maximum gross weight. The maximum gross weight was quantified by the wing loading of the aircraft. Higher wing loadings equated to a longer takeoff roll and higher landing speed. To ensure enough takeoff distance and safe landing speed, the additional wing loading was kept to a minimum.

The BetaMax was first constructed by the 2002-2003 design team from a Delta Vortex delta wing kit, manufactured by Bruce Thorpe Engineering. The aircraft boasted a 9.424 ft^2 wing area and 1.082 lb/ft wing loading. Last year's BetaMax increased the wing loading 31.4% from the Delta Vortex kit. Flight tests proved the aircraft's high thrust to weight ratio permitted the aircraft to takeoff in 100 ft and land at a safe airspeed.

The addition of the wing extension system added additional weight, and increased the wing loading even more. Table 2-3 compares the weight and predicted wing loading for the proposed wing-extension systems. The weight estimates of the proposed methods did not include the weight of the batteries necessary to power the systems.

Table 2-3: Weight and wing loading comparisons for proposed wing extension systems

	Delta Vortex	BetaMax 2002-2003 wings retracted	BetaMax Car antenna Extension system	BetaMax ME fabricated rack and pinion system	BetaMax HItech rack and pinion system
Weight, lb	10.2	13.5	15.963	14.223	13.42
Planform area ft^2	9.424	9.424	9.424	9.424	9.424
Wing loading lb/ft^2	1.0823	1.433	1.694	1.509	1.424
Wing loading increase from Delta Vortex	-	32.4%	56.5%	39.4%	31.6 %
Wing loading increase from 2002-2003 BetaMax	-	-	18.2%	5.3%	-0.63 %

If the car antenna extension system were implemented, the BetaMax would weigh 15.963 lb, increasing the wing loading 56.5% from the Delta Vortex kit. The mechanical engineering fabricated rack and pinion system would increase the wing loading 39.4% from the original aircraft, while the HItech rack and pinion system would increase the total weight to 13.42 lb and increased the wing loading 31.6 %.

2.6.2. Longitudinal Static Stability

All proposed systems added additional weight aft of the aircraft's center of gravity (*cg*), causing a disruption in the aircrafts longitudinal static stability. The longitudinal static stability of an aircraft can be quantified by the static margin, K_n, where

$$K_n = h_n - h_{cg} \tag{2.9}$$

Here, h_n and h_{cg} are the neutral point and *cg* respectively, normalized with respect to the mean aerodynamic chord. For an aircraft to be stable, the static margin must be greater than zero.

There is a difference however between defined stability and relative stability. Last years BetaMax flew at a static margin of 10.9% (K_n=0.109) with the wings extended. The static margin dropped to 5.5% when the wing-extensions were retracted for cruise. The pilot reported the aircraft was stable and easy to control with the wings extended. However, flying the BetaMax with the wings retracted was very demanding. The pilot was not confident a safe landing could be made with the wings retracted due to the decreased stability of the aircraft. As a result of the pilot's remarks, a 10% static margin was deemed necessary for the modified BetaMax. Last year's BetaMax properties with the wings in the retracted configuration were the basis for roll control modifications. Table 2-4 shows the neutral point, *cg*, mean aerodynamic chord, and static margin of last years BetaMax with the wing-extensions retracted. To achieve a static margin of 10%, the *cg* had to be shifted approximately 1.26 inches forward of its previous location at 16.25 inches aft of the wing apex.

Table 2-4: 2002-2003 BetaMax reference conditions

Parameter	BetaMax 2002-2003 (wings retracted)
Neutral point, h_n (in)	17.7
Specified *cg*, inches aft of wing apex	16.25
Mean aerodynamic chord, in	27.1
Static Margin, K_n	0.055

2.7. *Final Design*

2.7.1. Motor

Two key restraints drove the motor choice decision: extension rate and weight. The HItech rack and pinion system was the lightest of the proposed systems, while the telescoping car antenna system was the heaviest. Only the ME-fabricated rack and pinion system provided an extension rate to meet the 4.8 in/sec extension rate required by MIL STD 1797. The car antenna extension system fell short by only 0.6 in/sec, but was far heavier than the fabricated rack and pinion system. The HItech servo rack and pinion system was much lighter than any of the proposed systems, but did not meet the required extension rate. As a result, the team-fabricated rack and pinion system utilizing two electric motors rated at 20,000 rpm was used to extend the wings. The system was mounted in the BetaMax as shown in Figure 2-8.

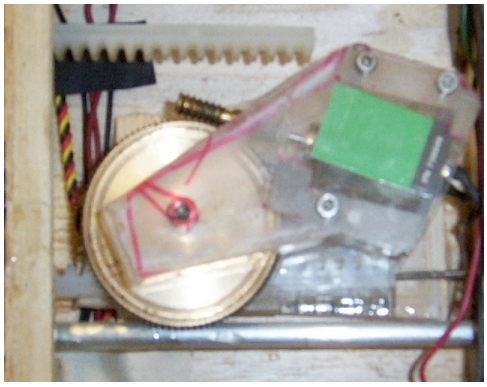

Figure 2-8: BetaMax team-fabricated wing extension system

2.7.2. System Power

The decision for the system's power source was based on weight, endurance, and the 18 Volts power requirement of the rack and pinion system. All three cell types considered (NiCd, NiMH, and Lithium Polymer) could supply 18V to power the system; however, the Lithium

Polymer cells added the least weight. Since the batteries would power the system for only a short time, the shorter lifespan of the Lithium Polymer cells was not a significant factor in the decision. Five 3.7V Lithium Polymer cells were wired in series to provide 18.5V to the two motors. The five cells were encased in protective padding to reduce the risk of damage. Although the batteries cost more than the NiCd or NiMH, the five cells only added 10.2 oz to the aircraft.

2.7.3. Aircraft Balancing

The BetaMax was weighed to determine the new *cg* location after installation of the rack and pinion system. Two OHAUS Navigator scales accurate to ±0.05 lb were used to weigh the aircraft. To determine the *cg* in the longitudinal direction, one scale was placed under the front landing gear while the main gear was placed on the second scale. The *cg* was determined from,

$$\overline{Xc} = \frac{\sum_{i}^{N} Xc_i \bullet W_i}{\sum_{i}^{N} W_i}$$

where $\overline{Xc}$ is the *cg* location from a given reference point, X_c is the distance of a given weight from the same reference point, and W is the measured weight at distance X_c from the reference point.

The *cg* of the BetaMax was determined using the same assumptions for conventional aircraft: the mass was assumed constant along the longitudinal axis and the weight was assumed to act only at the wheel location. Continuing convention from the 2002-2003 Morphing Team, the aircrafts *cg* was referenced in inches aft of the wing apex.

The empty weight (no fuel or batteries) after installation of the wing extension system was 13.10 lb. The additional weight aft of the previous *cg* shifted the new *cg* from 16.25 inches

to 17.37 inches aft of the wing apex. To generate a static margin of 10%, it was necessary that the *cg* act at 15 inches.

The data recorder, all batteries, and both receivers were relocated to the nose of the aircraft to aid in shifting the *cg* forward. After all movable devices were shifted forward, addition of a 0.2 lb weight acting 2.5 inches aft of the apex and 1.5 inches left of the aircraft centerline was necessary to shift the *cg* farther forward and laterally balance the aircraft.

The resulting *cg* acted at 14.81 inches aft of the apex with full fuel. The *cg* was farthest aft at 15.29 inches when the fuel was fully depleted. The result was a longitudinally and laterally stable aircraft with static margin greater than 10% for most of the flight.

2.7.4. Wing Loading

The final takeoff weight (full fuel) was 14.25 lb, giving the aircraft a 1.51 lb/ft^2 wing loading. The additional 0.2 lb weight did not have a significant effect on the wing loading. The BetaMax, modified for roll control, displayed a wing loading 39.7% greater than the original Delta Vortex, only 5.5% larger than the 2002-2003 BetaMax.

2.8. Flight Testing

2.8.1. Summary of flights

On November 20, 2003, the BetaMax successfully completed a flight test at the Salem Remote Control Club in Salem, Virginia. The winds during the flight were relatively calm with gusts around 5 MPH. Data was recorded continuously through the flight.

Figure 2-9: BetaMax rolling with wing extensions in flight

2.8.2. Preparation for Flight

Upon arriving at the Salem RC airfield, the BetaMax was prepared for the flight and all necessary equipment was installed. The preflight preparations began with the instillation of the five Lithium Polymer batteries.

Prior to arriving at the airfield, a dual remote control system was setup to control the BetaMax during flight. The primary remote control of this system was used to control the amount of throttle supplied and the deflection of both the elevons and rudders. The second remote was used to control the extension of the telescoping wings. The secondary remote was setup in such a way that as the joystick of the remote control was deflected in the direction of the roll wanting to be achieved, the corresponding wing would then be extended. The wing would continue to extend until either a switch was triggered to signal the maximum extension of the wing or until the pilot released the joystick. If the wing reaches its maximum extension and the joystick of the secondary remote was still deflected, then the wing would remain at maximum extension until the joystick was released. At anytime when the joystick was released and allowed to return to its neutral position, the wings would continue in similar manner and return

to their neutral retracted position. Once at the airfield, the wings were tested to ensure proper operation.

The remainder of the preflight preparation consisted of minor repairs being made, the fueling of the BetaMax, and the initialization of the data logger.

2.8.3. Preflight Problems

During the testing of the wings it was noticed that as the telescoping wings were extended the rudders and elevons would erratically deflect throughout the extension. The cause of the deflections was due to the interference between the primary and secondary receivers. This complication posed a large problem due to the fact that the interference could prohibit the telescoping wings from making a clean roll and adding large amounts of error to any of the data collected. If left untreated, full control could have been lost in flight.

To remedy the problem, the receivers were moved to the nose of the BetaMax, placing each of the receivers on either side of the aircraft. Any easily accessible wiring was reorganized so that wires to each receiver were not crossing. To prevent the interference, the antennas for the two receivers were secured on opposite sides of the aircraft's belly.

These improvements resolved most of the interference problems, although some lingering effects were evident. When the remote controls were placed relatively far apart, the interference continued to decrease.

Another problem that arose during the testing of the wing was that the right wing extended at a slower rate than the left wing. The right wing was sluggish and seemed to be getting caught up while extending, prohibiting the telescoping wing from making a clean extension. Since this problem could not be easily repaired, the majority of the testing was conducted using the extension of the left wing.

2.8.4. Instrumentation

Since the main purpose of the test flight was to acquire real time data during a roll maneuver utilizing the telescoping wings, the BetaMax was fitted with instruments that would allow for accurate readings during the flight such as a pitot-static system, potentiometer, gyros, and an accelerometer. The majority of the instruments were installed by the 2002–2003 Virginia Tech Morphing Wing Team.

A Dwyer standard model 1/8 pitot-static system was used to read the free stream dynamic pressure. Knowing the free stream dynamic pressure allowed the airspeed of the BetaMax to be calculated throughout the flight. According to the 2002–2003 Morphing Wing Team, the airspeed had an error of 2.3%.

The two most important pieces of equipment used to acquire data were the potentiometers and the roll axis gyro. The potentiometers were connected to servos and used to measure the deflection in the left and right elevons and Analog Devices ADXRS150EB/300EB single axis angular rate sensor was used to measure the roll rate of the BetaMax. The sensor was capable of recording roll rates up to 300 deg/sec.

All measurements read by the instruments were recorded by a Crossbow AD200 Data Logger. The data logger was capable of receiving and recording up to 8 different signals simultaneously.

2.8.5. Flight

At approximately 4:00 pm on November 20, 2003, the data logger was turned on and the first test flight of the modified BetaMax began. The flight path consisted of a standard aircraft traffic pattern seen in Figure 2-10.

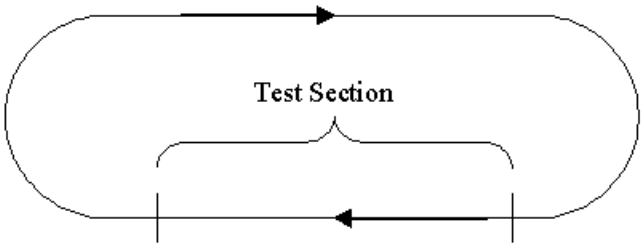

Figure 2-10: General flight path of the modified BetaMax during first test fight

All maneuvers using the telescoping wings were performed in the test section. By performing all rolls in this section clean video and pictures were taken and an accurate time of the maneuvers were recorded to compare to the times in the data logger.

During the initial laps of the test flight it was noted that aircraft was adequately stable with the wings retracted and easy to control during normal flight. Once the pilot was comfortable with the control of the BetaMax testing of the telescoping wings proceeded.

Since the main focus of the flight was on the testing of the left wing, the first four wing extensions were performed extending the left wing to produce a roll to the right. These maneuvers were followed up by an extension of the right wing to produce a roll to the left. Although the initial analysis of the wings proved that the right wing was not as productive as the left, it was tested to compare the wings roll effectiveness. The final maneuver performed before landing was an extension of the left wing while deflecting the elevons to prove the elevons could nerate a sufficient roll moment to counter the roll moment produced by the telescoping wing if failure in the telescoping mechanism occurred.

During all of the wing extension maneuvers an average airspeed of 57 MPH was maintained, while the maximum airspeed achieved during the flight was 74.6 MPH. The entire

flight from take off to landing lasted a total of 8 minutes and 48 seconds. Due to a successful flight and clean data being acquired, a second test flight was not conducted.

2.9. Roll control during flight

The data logger was successful in recording all the data throughout the length of the flight. This data was analyzed using the bmdata.m MATLAB file to reduce the data and convert the values recorded into their respective units. During the flight a log of the times were kept to help locate the maneuvers along the data plot. Using this timeline and the video, three portions of the flight were analyzed to determine the amount of roll supplied by the telescoping wing extensions.

2.9.1. Left Wing Extension Data

By comparing the data and the video, the last left wing extension produced the cleanest and most accurate data. During this particular maneuver there was no interference from the deflection of the elevons.

As seen in Figure 2-11, the maximum roll rate during the maneuver was 68.7 deg/sec causing the BetaMax to roll to a maximum bank angle of 137.8 degrees (Figure 2-12). By observing the data and video of the flight it was determined that the wing took approximately 1.25 seconds to fully extend.

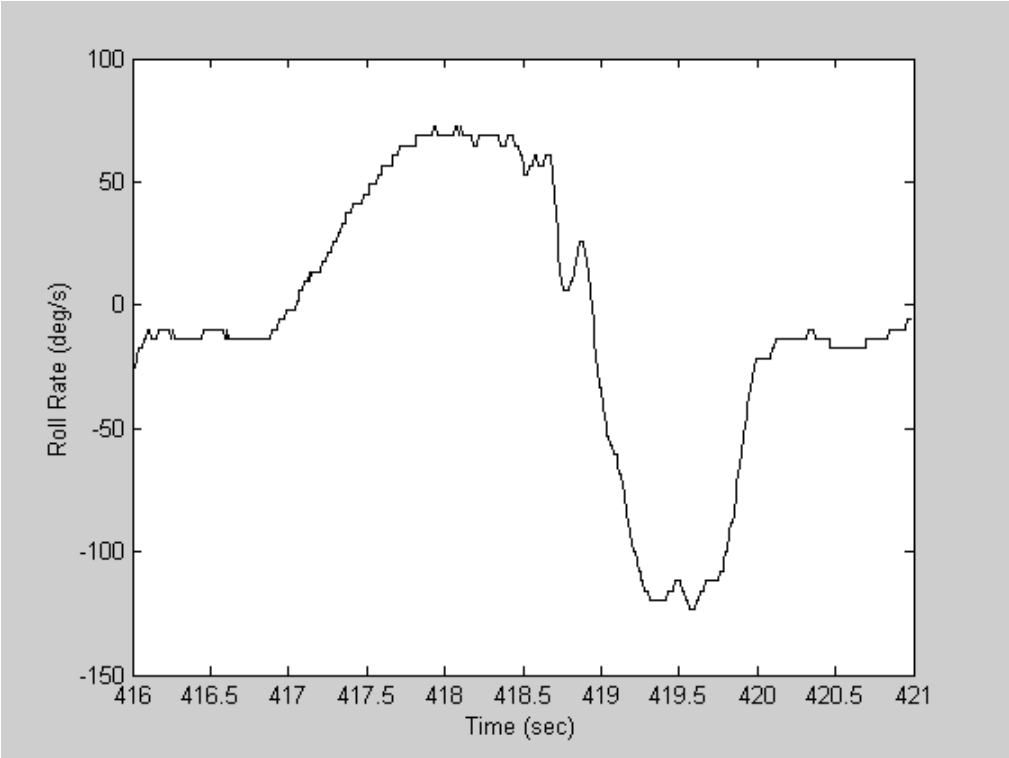

Figure 2-11: Roll rate of the BetaMax during a left wing extension

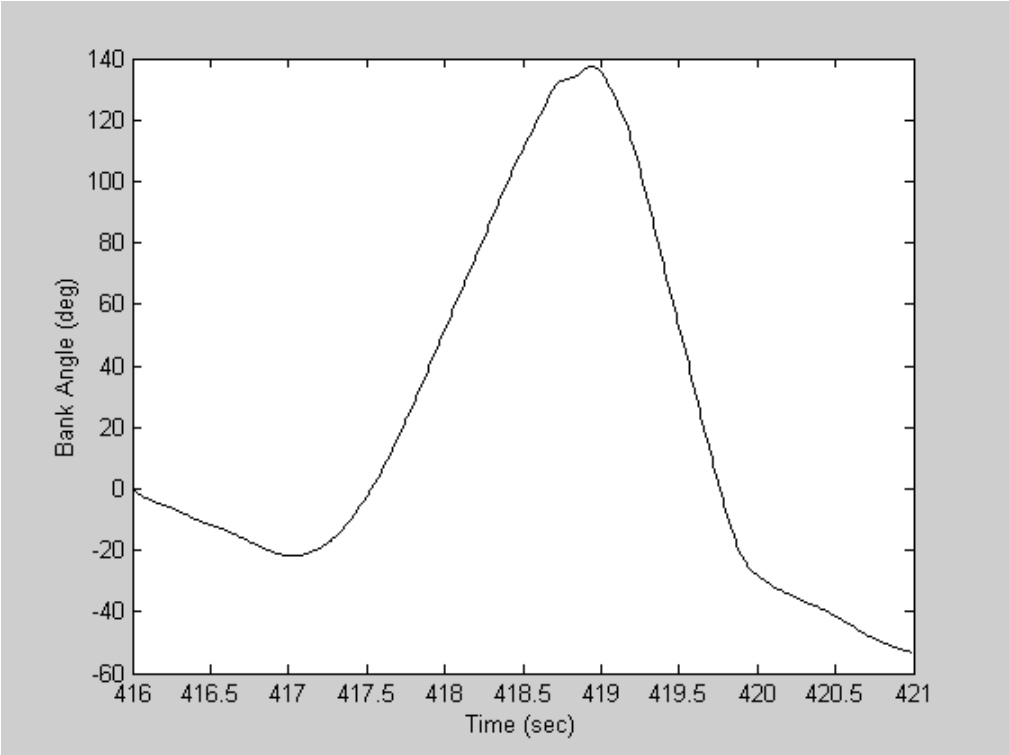

Figure 2-12: Bank angle of the BetaMax during a left wing extension

By observing Figure 2-13, the effects of the extension of the left telescoping wing was seen by a gradual increase in the roll rate between 417 sec and 418.5 sec. Immediately following the increase in roll rate was a rapid decrease between 418.5 sec and 419.5 sec. This decrease was due to the deflection of the elevons that corrected for the roll induced by the left wing extension and returned the BetaMax to level flight.

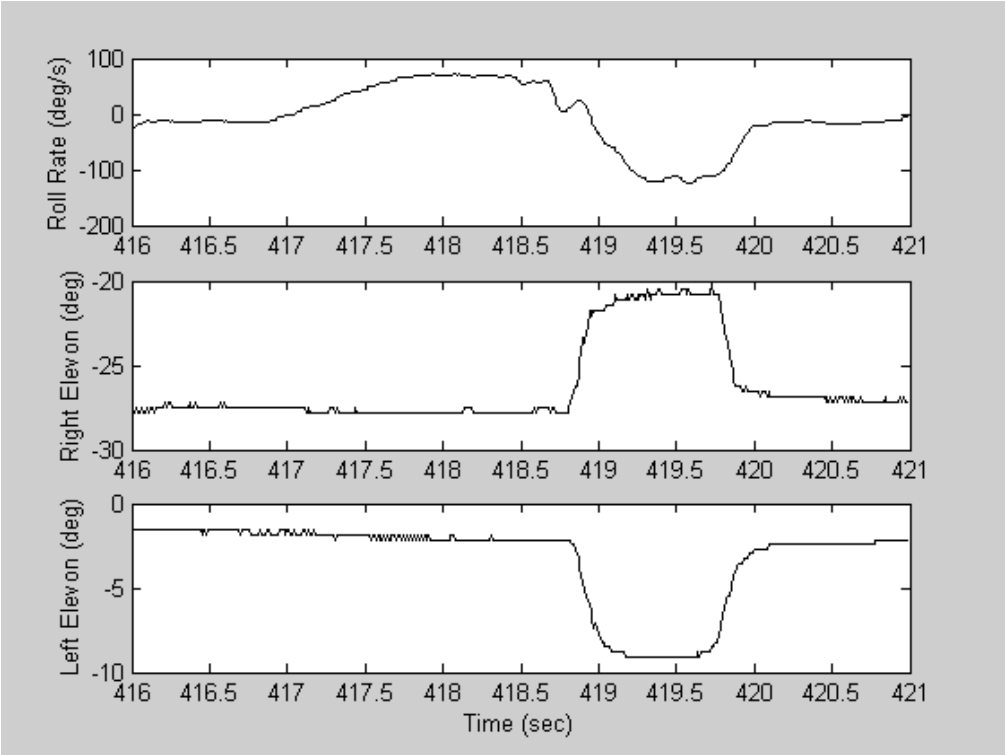

Figure 2-13: Roll rate of the BetaMax during a left wing extension compared to the deflection of the left and right elevon

2.9.2. Right Wing Extension Data

During the extension of the right telescoping wing, it was seen that once again the right wing did not perform as well as the left telescoping wing, taking approximately 2 seconds to become fully extended. Figure 2-14 shows that, compared to the roll rate of the left telescoping wing extension in Figure 2-11, the roll rate changes at a slower rate but achieves a maximum roll

rate of 64.7 deg/sec. This value is comparable to the maximum roll rate of the left wing extension. The maximum bank angle achieved during the maneuver can be seen in Figure 6.6 as -110.6 deg. Due to the slower extension rate, this was slightly less than that achieved by the left wing extension.

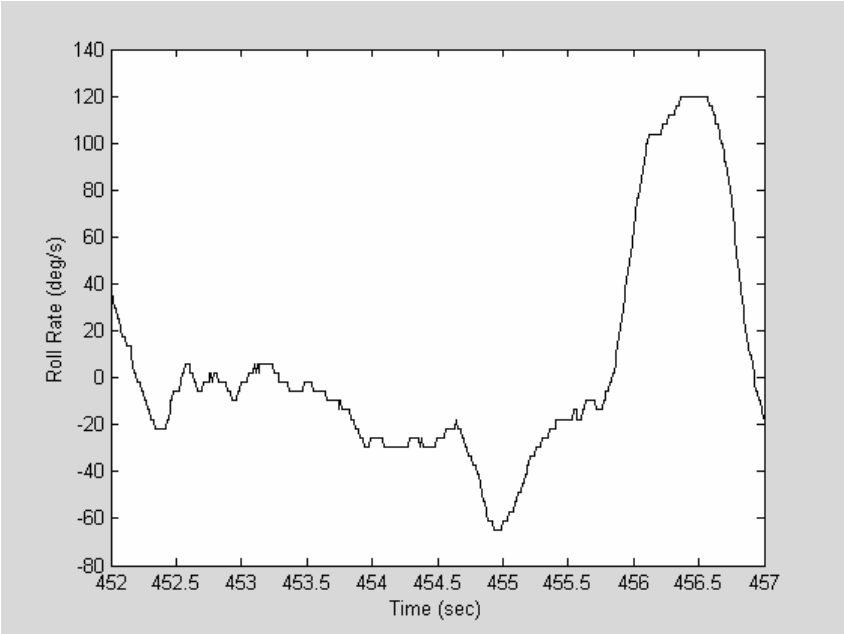

Figure 2-14: Roll rate of the BetaMax during a right wing extension

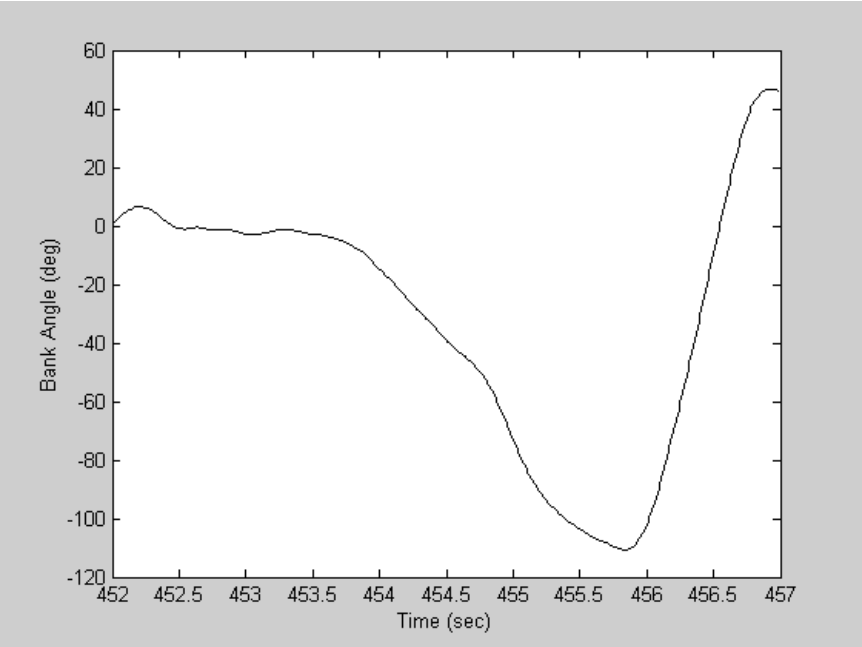

Figure 2-15: Bank angle of the BetaMax during a right wing extension

The extension of the right wing was observed to occur at approximately 453 seconds in Figure 2-14. At this point it can be seen that the wing encountered some problems extending until it reached 454.5 sec. At this point, the roll rate sharply decreased to its maximum absolute extension rate value. Immediately following the point of maximum roll rate, the effects of the elevons returning the BetaMax to level flight was seen at 455.75 sec in Figure 2-16.

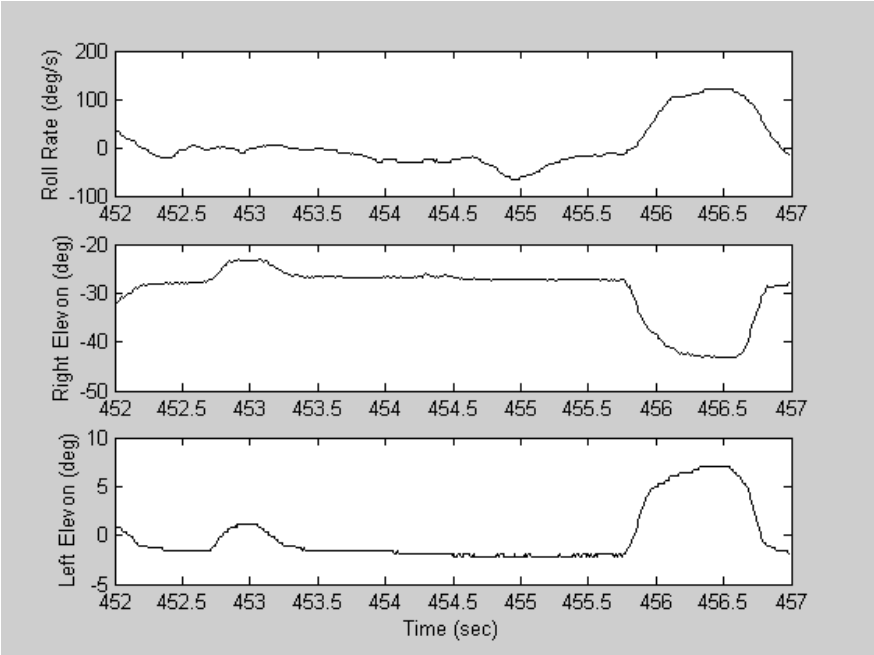

Figure 2-16: Roll rate of the BetaMax during a right wing extension compared to the deflection of the left and right elevon

2.9.3. Left wing extension with elevon deflection

The final maneuver performed before landing was to test the amount of elevon deflection required to counter the roll moment induced by the extension of the left telescoping wing. During this maneuver the left wing was fully extended for 6 seconds while deflecting the left and right elevons. The elevons were never fully deflected during the maneuver.

Figure 2-17 shows the amount of elevon deflection used to counter the roll induced by the wing extension. Initially, the roll rate began to increase steadily at 528 seconds but as time

increased, the roll rate dropped down to approximately zero. The initial roll rate occurred due to incorrect timing between the primary and secondary remote controls. The left wing was extended one second before the elevons were deflected causing the BetaMax to roll to the right. At the time the elevons were deflected, the roll rate decreased causing the BetaMax to maintain its current bank angle momentarily then return to level flight.

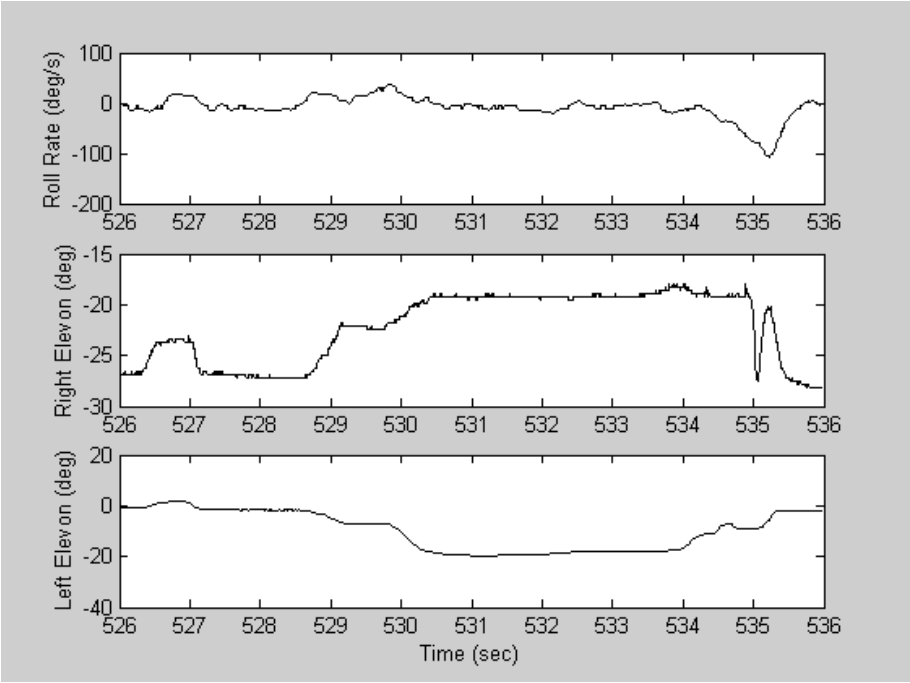

Figure 2-17: Roll rate and deflection of the left and right elevons of the BetaMax during a left wing extension with elevon deflection to counter the rolling moment.

2.10. Roll comparison

A valuable part of flight testing is comparing the data obtained to a comparator aircraft or to previous calculations to determine if the desired effects of roll control were achieved. Since the BetaMax is a modified version of the 2002–2003 Morphing Team's BetaMax, the original BetaMax provided for an accurate comparison. The flight data obtained may also be compared to the calculation run through Tornado and on roll control.

2.10.1. Comparison to 2002–2003 BetaMax

During 2002-2003, the Virginia Tech Morphing Wing Team modified the Delta Vortex to have both wings extend simultaneously. During the flight test of the original BetaMax a roll maneuver was conducted utilizing the elevons with the simultaneously telescoping wings retracted. The maneuver was performed at an airspeed of 55 mph.

Figure 2-18 displays the data that was acquired during that flight test. At approximately 2.5 seconds, the roll maneuver was executed providing a maximum roll rate of 150 deg/sec. This is more than twice the maximum roll rate achieved by the extension of the left telescoping wing from the modified BetaMax.

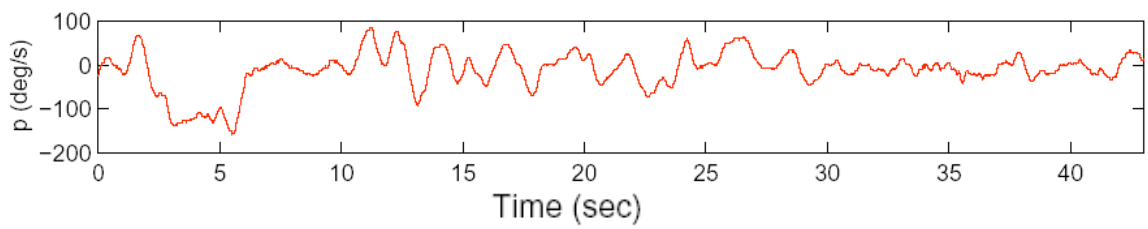

Figure 2-18: Roll rate, p, of the original BetaMax during the flight test conducted by the 2002–2003 Morphing Wing Team.

2.10.2. Comparison to Tornado roll calculation

The roll rate data from the left telescoping wing extension (section 6.2.1) was integrated to produce Figure 2-19. The extension of the wing begins at zero seconds, the bank angle response was examined for 5 seconds, and compared to the calculations done earlier. The results correspond with the response from a motor with a 12 in/sec extension rate, like the fabricated rack and pinion motor used in the BetaMax.

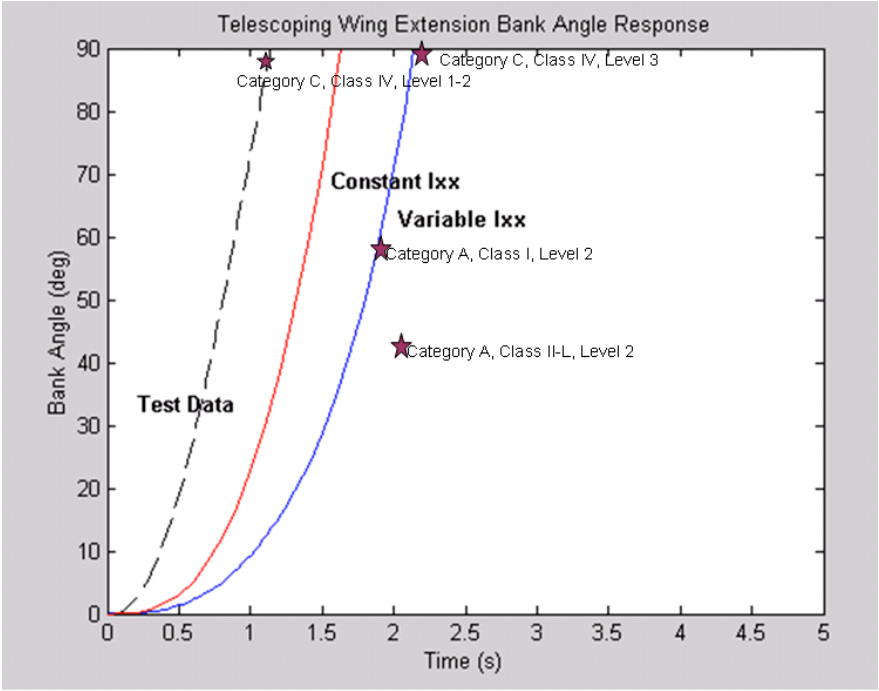

Figure 2-19: Plot of bank angle response to the telescoping wing extension

The extension rate of the wing, according to MIL STD 1797, qualifies the modified BetaMax to be classified as a Category C, Class IV, Level 1-2 aircraft: a highly maneuverable aircraft that can produce gradual maneuvers with accurate flight path control, similar to that of a fighter aircraft. It also has the ability to be controlled with little or no pilot work load during the mission flight phase.

Although conventional aircraft with control surfaces have the ability to be highly maneuverable, an aircraft with individual telescoping wings will provide enough roll control to be classified as highly maneuverable as long as the extension rates are great enough.

3. Spring Semester RFP

The RFP of the Morphing Wing Team is to design, build, and test a unique morphing aircraft or wind tunnel model for comparison against traditional concepts. The key mission, as decided by the team, is to design an R/C aircraft with no traditional control surfaces, capable of both mission morphing and control morphing. This could be accomplished by the use of variable incidence, camber, planform area, or a combination of the three.

3.1. Design Concepts

Variable twist is a means of control morphing. Variable twist was investigated to produce rolling motion by twisting the wings in opposing directions. Twist would mimic the role of ailerons, but use a smooth, continuous surface instead. Twist is generally implemented in aircraft to prevent the wing tip from stalling first, and is common on general aviation aircraft. If an aircraft with variable twist control did stall, then the use of twist alone may increase the difficulty of recovering. Variable twist could be actuated with a flexible spar or wing tendons.

Variable camber was researched for transitioning between high speed and low speed flight. Camber increases the lift coefficient of airfoils; a cambered airfoil is particularly desirable for takeoff and landing, whereas an airfoil with less camber can achieve higher speeds. The use of variable camber is best suited for mission morphing. Variable camber could be implemented with inflatable airfoils, embedded airfoils, or flexible ribs. Depending on the method of varying the camber, the devices could be heavy, inaccurate at reshaping the airfoil, or rely on flexible skin technology.

Variable planform area is another means of mission morphing. Several aircraft, such as the F-14 Tomcat, B-1B Lancer, and F-117 implemented a form of variable planform area

through the use of swing wings. The telescoping wings of the BetaMax also exhibited variable planform. The wing area can be increased or modified to produce more lift or transition between high speed and low speed flight. Variable planform designs would be difficult to build and probably add more weight to the aircraft than other types of morphing. Transition between the two planform designs might also cause instability during flight.

A concept matrix comparing variable incidence, camber, and planform is presented in Table 3-1.

Table 3-1: Concept Matrix

	Weight	**Effectiveness**	**Stability**	**Construction**	**Total**
Importance Factor	***5***	***4***	***4***	***5***	***90***
Variable Incidence	4	4	4	4	72
Variable Camber	3	5	3	3	62
Variable Planform	2	4	2	3	49

The team decided to focus on both variable camber and wing incidence in order to eliminate the need for control surfaces and maximize efficiency at takeoff, landing, and cruise. The combination of variable incidence and camber would allow both mission and control morphing, as neither alone could achieve both.

Goals for next semester include:

- Investigate and compare inflatable airfoils and embedded airfoils for achieving camber change
- Investigate and compare wing tendons and a rotating spar for flight control
- Examine the use of flexible materials for covering the wings

- Complete conceptual, preliminary, and detailed design of one or more R/C aircraft that implement the chosen method of variable camber and incidence
- Construct and fly the aircraft
- Collect and analyze flight data
- Compare morphing aircraft data to conventional aircraft data

A. Appendix

A.1 Timeline

Figure A-1: Project Timeline

The Schedule above is the proposed timeline and plan of action for the upcoming semester. The shaded region in Figure A-1 comprises Virginia Tech's Winter Break. Upon returning, Dr. Rudy Yurkovich from Boeing will visit and give some advice before moving on. The preliminary design phase should be finished within a month of the new semester. Detailed design will follow and construction of the aircraft will begin given favorable weather conditions, multiple flight tests will be performed at the Salem R/C airfield. The collected data will be analyzed and compared to conventional aircraft data.

The schedule is an expected plan of action. Barring any large obstacles the design team should be able to keep with the schedule as promised in the spring semester and complete multiple flight tests.

A.2 Cost Analysis

Item	Price
Wood Supplies	$ 150.00
Carbon Fiber Tubes	$ 150.00
Aluminum Tubes	$ 10.00
Multiple Engine s	$ 2000.00
Top Flite MonoKote	$ 47.00
Servo Motors	$ 120.00
Flight Control	$ 400.00
Landing Gear	$ 20.00
Tires	$ 12.50
Tower Hobbies 6 -Minute Epo xy 9 oz	$ 7.99
Tower Hobbies 30 -Minute Epoxy 9 oz Epoxy	$ 7.99
CA Glue	$ 2.99
Fiberglass	$ 90.00
Composites for Fuselage	$ 1200.00
Pneumatic motors for inflating	$ 20.00
Fuel (Approximately 4 Gallons)	$ 57.00
Dwyer Pitot tube (x2) and pressure trans ducer	$ 215.00
Analog Devices angular rate sensors (x2)	$ 120.00
Crossbow Data Logger	$ 960.00
Electrical Supplies	$ 200.00
Miscellaneous	$ 200.00
Total Cost	**$ 6000.00**

Figure A-2: Cost Analysis

The above budget contains the approximate cost considerations that may be incurred during the spring semester. These costs were determined by expanding upon the 2002–2003 Morphing Wing Team's budget. A portion of the budget was also reserved for composites. The budget will allow for the fabrication of multiple aircraft that will be used for testing and comparison purposes.

A.3 Autonomous Vehicle Autopilot Comparison

UAV AUTOPILOT MANUFACTURES

Two main companies dominate in building advanced autopilots for autonomous vehicles: *UAV Flight Systems, Inc* of Wheat Ridge, Colorado and *MicroPilot* in Canada. Both companies worked under two co-owners for a few years under the name *UAV Flight Systems*, then split to form two separate entities in 2001. As a result, the products offered by both companies are very similar. Both companies sell their autopilots worldwide to academic, military, and private research institutions, as well as to UAV manufacturers.

AUTOPILOT SYSTEMS

Two autopilots were considered for use on a wing-in-ground-effect (WIG) aircraft, the AP40 and MP2000. The AP40 is the mid-grade autopilot offered by *UAV Flight Systems* for $1500.00. The MP2000 is *MicroPilot's* mid-grade system offered for $5000.00 (US dollars).

The AP40 is in the middle of its class of three GPS-enabled flight control systems that incorporate navigation, mission, stability control, and data logging. The system utilizes a two-axis sensor module with pitch and roll gyros as well as six-state user-defined control laws for stability. Navigation is preformed by an onboard GPS, while altitude and airspeed are maintained by a barometric altimeter and pitot static tube. Wireless communication with a base station will even allow a pilot to manually control the UAV using software that emulates a flight simulator. The autopilot weights only 30grams (1.1 oz) and is 2.85"x1.6"x1.1" (UAV Flight Systems).

The MP2000 is one of three autopilots offered by MicroPilot. The system can be used to control small simple UAVs to high speed, high functionality military autonomous aircraft.

The MP2000 is capable of complete autonomous operation, including takeoff and landing. The system is driven by a 32 bit processor and includes all gyros necessary to stabilize the aircraft as well as the GPS that is used to guide the vehicle. The autopilot supports flaps, flaperons, elevons, v-tail, split rudders, and flap/aileron mixing and has the capability for extensive data logging. As in the AP40, the autopilot uses a pitot-static system to monitor airspeed. Instead of using a barometric altimeter for altitude control, the MP2000 uses GPS, then switches over to an optional ultrasonic transducer when in close proximity to the ground. The ultrasonic transducer is a necessity for autonomous takeoffs and landings. It can be purchased for $750. The MP2000 system comes standard with *Horizon* software that allows one to operate and monitor the aircraft from a computer. Radio modems necessary to provide a link from the PC to the aircraft must also be purchased separately for $2000 (includes 2 modems). The unit weights 28 grams (1.01 oz) and is 3.94”x1.57”x0.59” (MicroPilot).

PRACTICAL USE FOR WIG AIRCRAFT

The autopilot systems were researched to determine whether or not such a system could effectively control a WIG aircraft 4-6 inches off the surface. Neither company could guarantee their system could keep control of the aircraft that low to the surface. *UAV Flight Systems* used a barometric altimeter in their system that was only accurate to ±10 ft, making it impossible to maintain an altitude error of only a couple inches. The possibility of replacing the barometric altimeter with an ultrasonic transducer in the AP40 was explored because the AP40 was priced significantly less than the MP2000. Research concluded however that such a modification could not be made. Voltage conversions used to interpret the analog output of the barometric altimeter were preprogrammed into the AP40 during manufacturing and could not be altered.

The MP2000 with optional ultrasonic transducer could reduce the error in altitude to ±0.5 inches for takeoff and landing. In theory, the autopilot could maintain any altitude (within close proximity to the ground) to ±0.5 inches and would correct for any attitude changes at a rate of 30Hz. Therefore, theoretically, the MP2000 could control a WIG aircraft close to the surface. *MicroPilot* however had never tested their system for such performance and, as a result, could not guarantee prolonged flight at inches above ground level could be handled safely by their product.

PRODUCT ASSESMENTS

The *MicroPilot* MP2000 is clearly superior in performance to the AP40. It is capable of maintaining control of inherently unstable aircraft, can handle a wider variety of control system variations, and has the capability to control more mission servos. Its ground control system has been field tested by many and is comparable to those used by the military.

Though the *UAV Flight Systems* AP40 does not have all the bells and whistles of the MP2000, it is capable of handling nearly any aircraft and recoding data from multiple channels for an hour. The base station to compete with *MicroPilots* "Horizons" is well on its way and is far cheaper. For anything other than a WIG aircraft, the AP40 is the unit of choice. The system can accomplish nearly everything the MP2000 can (autonomous takeoffs and landing being the big exception) for a quarter of the price. In addition, *UAV Flight Systems* is willing to reduce their prices for Virginia Tech now that a connection has been established with Lee Reep. 900MGZ radio modems (Part No. DK09-EDU) to link the AP40 to a ground station, if desired, can be purchase by the university for 50% off through *MaxStream Inc* (http://www.maxstream.net).

Additional information on both autopilot manufactures as well as a list of their products and prices can be found at their corresponding websites.

UAV Flight Systems: www.uavflight.com (contact: Lee Reep)

MicroPilot: www.micropilot.com

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