CONTROL OF MICRO AIR VEHICLES USING WING MORPHING

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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CONTROL OF MICRO AIR VEHICLES USING WING MORPHING

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A micro air vehicle (MAV) is typically defined to have a wingspan of 6 *in* and operates with airspeeds of less than 25 *mph*. Recent attention has been devoted to MAVs because there is a variety of applications for which they can be used. Specifically, they are useful in missions within urban environments. These missions require MAVs to be very small and highly agile. These characteristics are achieved with the use of light materials such as carbon fiber airframes and plastic membrane wings; however, this design also causes these vehicles to be difficult to operate. This construction makes them strong with good aerodynamic properties; however, hinges for conventional control surfaces are not easily implemented on flexible wings. Therefore, these vehicles are strong and light but have limited control authority. A different control effector is then necessary in order to provide control authority. This thesis will consider using wing morphing as a control effector. Simple techniques are used to change the shape of the wings during flight such as twisting the wings of a 24 *in* MAV and curling the wings of a 12 *in* MAV. Flight tests are then performed and show that morphing is an effective way to induce roll motion. The data are then analyzed to consider linear modeling techniques as well as control design. The use of morphing

results in a more effective roll motion than the use of the rudder and improves the maneuverability of the vehicles.

CHAPTER 1
INTRODUCTION

Recent advances in technology have made the use of smart vehicles in a variety of applications possible. These advances have led to the development of small unmanned air vehicles (UAV) as well as micro air vehicles (MAV) which have mission capabilities. These vehicles can range in size according to their specific application. Small UAVs and MAVs can be designed to operate within urban environments. Their design typically depends on the mission in which they will be used and can range from civilian to military applications.

For example, these vehicles might be assigned to military missions such as bomb damage assessment, which would involve transmitting video after a bomb has been dropped at a specific location. These vehicles could also be used in warfare as a means to have live video of what is occuring ahead before ground troops are sent into the battlefield. There are also some civilian applications to MAVs, such as transmitting video for traffic/news coverage, and to look in specific places for search and rescue missions.

Other scenarios where MAVs would be useful include assessing the damage caused by chemical spills, in search and aiding in rescue missions and even in traffic/news coverage. Some of these applications might require MAVs to work in collaboration with other MAVs in order to cover a large area of surveillance.

Another application where a MAV would be useful is if for example, there is a biological agent released into a public area. A biohazard team would have to suit up and prepare before being able to enter the area for testing and clearing of the biological agent. Instead, a MAV can be released from a nearby station which can have sensors on board, and be able to detect the extent of the contamination and the type of biological agent which was released before any humans have arrived at the scene.

The recent concern for terrorism being planned in urban environments such as small apartments leads to specific situations where MAVs could be useful. Current technology cannot keep track and observe these small suspected areas. A MAV would be useful in this situation because it could fly up to windows or even indoors and send live video and audio of the suspect activities.

In order to accomplish the evolving missions for which MAVs can be used, their designs have to be considered accordingly. For most military missions, the requirements typically demand that these vehicles be very small and highly agile. They are constructed of very light materials, such as carbon fiber airframes and flexible membrane sheeting for wings. However, this vehicle design does not allow for conventional control surfaces due to the complexity of implementing hinges along the flexible membrane wings.

The lack of conventional control surfaces makes these vehicles difficult to fly. Several benefits can be achieved by the use of additional control effectors. The implementation of wing morphing as an additional control effector is considered to increase controllability. Simple techniques are considered to study the benefits of using morphing as compared to the current control effectors which are used on MAVs.

This thesis will consider morphing as a control effector for a pair of micro air vehicles with different dimensions. The vehicles shown in Figure 1–1 with a 24 *in* wingspan and a 12 *in* wingspan will be used to demonstrate morphing for control. These vehicles will be referred to as MAVs, though their wings are larger than the definition implies, due to the similarities in design and construction.

The MAV is an ideal platform for morphing because the power required is very small due to the flexibility of the wings, and there are several benefits including increased controllability.

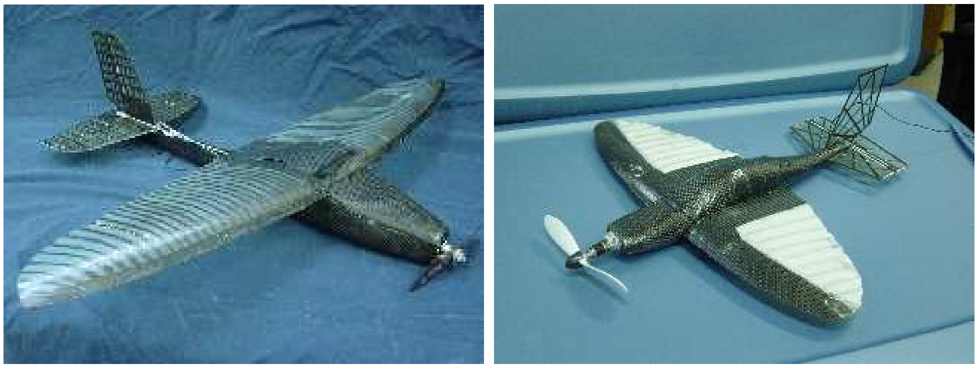

Figure 1–1: MAVs with 24 *in*(left) and 12 *in*(right) Wingspan

Wing morphing on the 12 *in* MAV is actuated by connecting a strand of Kevlar to a servo inside the fuselage and then to a location on the wing. This initial design only allowed for morphing at a single location, which was the wing outboard. Further testing led to the consideration of more dramatic morphing. The morphing of the wing was made more dramatic by then adjusting an extra Kevlar strand to the servos. This allows for morphing about the span and the trailing edge at the same time.

The morphing is actuated on the 24 *in* MAV by use of torque rods which are connected from the fuselage to the wing outboard. These torque rods are connected to the wings by being sewn along the plastic sheeting of the wing. These rods are then actuated and in turn change the shape of the wings.

Data is then collected with a data acquisition system which provides information with 3 accelerometers and 3 gyros along an orthogonal coordinate system of the vehicle. This data is then processed to consider the response of the aircraft to the input commands. A linear model approximation is then done using the roll rate and yaw rate responses. The approximation is done using an ARX technique in Matlab using the responses.

The approximation results in a good correlation of the coefficients when compared to the data which was collected. The linear model for the 24 *in* MAV can then be approximated but the model of the 12 *in* MAV requires further research. This is due to the fact that the 24 *in* MAV is being morphed symmetrically so that a linear approximation can be made, but the 12 *in* MAV is morphed asymmetrically which requires a nonlinear study to be done.

CHAPTER 2
MICRO AIR VEHICLES

Micro Air Vehicles(MAVs) are typically defined as vehicles with a wingspan of less than 6 *in* and which operate with airspeeds of less than 25 *mph*. The idea for a MAV is to have a platform which is small, inexpensive and that can be used in situations which are not suitable for larger vehicles [14].

The first succesfull design of a micro air vehicle was achieved by AeroVironment. They designed the Black Widow MAV with funding from DARPA. The Black Widow is a MAV with a 6 *in* wingspan, airspeed of about 30 *mph* and weighs under 100 *grams* [13]. This vehicle also has the capability of carrying a video camera which transmits live video to the ground and has an endurance of 30 minutes. It is also equipped with an autopilot, which is capable of performing altitude, airspeed, and heading holds as well as a yaw damper. The transmitter and actuators are some of the smallest and lightest systems available. This design led to further interest and research in the field of MAVs from several countries and universities.

The University of Florida has been very active in the design and testing of micro air vehicles. Dr. Peter Ifju has led a successful research team at the University of Florida in the area of MAVs. They have been able to win various aspects of the annual MAV competition, which is sponsored by the International Society of Structural and Multidisciplinary Optimization. The MAV team at the University of Florida has succeeded in this competition each year from 1999 to 2003 with the various designs that have been tested and have won the overall first place award. The annual MAV competition typically includes entries from several universities around the world. The 2003 competition consisted of entries from 15 universities.

Current MAV designs are based on a flexible wing design used at the University of Florida [14]. The most common design is an airframe constructed entirely of composite carbon fiber. The fuselage is typically a two-piece monocoque structure designed to house flight components and instrumentation. The flight components include servos and connectors, and some of the instrumentation used in flight includes orientation systems. A conventional empennage is affixed to the fuselage with elevators and rudders hinged to the horizontal and vertical stabilizers.

The MAVs are equipped with sensors for measurement consisting of 3-axis gyros and 3-axis accelerometers along with the servo command. The sensing and actuation data is recorded on an on board data acquisition board which weighs 7 *grams* and was developed by NASA Langley Research Center specifically for MAV applications [1]. This micro data acquisition board is capable of recording 27 analog channels which is sufficient for the current sensor package. The data is then available at 50 to 100 Hz and is resolved using a 12-bit analog-digital converter. The data is recorded in a 4 MB flash chip on board the data acquisition board and is then downloaded to a PC at the end of each flight.

The vehicles use an electric motor for propulsion and the duration of flights depend on the amount of batteries which can be carried and the throttle setting on the motor. On average, flights ranging from 10-15 minutes are easily achieved for the 24 *in* and 12 *in* MAVs which are considered.

Structures used in flight, both in biological and aircraft applications, are flexible by a certain amount. For aircraft to be able to withstand the large forces obtained during flight; however, the wings have to be strong enough.

Flight of birds also consists of flexible wings which can adapt to the changing environments they fly in. Birds have many layers of feathers which can be moved around in order to adjust to the specific maneuver they need to perform [22]. The use of flapping for flight, such as done by birds, has not been extensively studied. This has not been done due to the complexity of the flight mechanics which includes changing geometry, flexible surfaces and unsteady aerodynamics.

The flexible membrane wings together with the size constraints of MAVs make analysis and design of these vehicles very challenging. Specifically, the aerodynamics of a MAV are complicated by low Reynolds number flight, largely deforming structures, the effects of viscosity and flow separation at high angles of attack [22]. The fact that the MAVs are challenging to design provides a good platform for research in the areas of dynamics and control, aeroservoelasticity, structures, microelectronics, small actuation and data acquisition systems, and other fields.

The research and development of these vehicles has progressed rapidly due to the availability of smaller electronics as well as the advances in lighter materials. Several of these vehicles are shown in Figure 2–1.

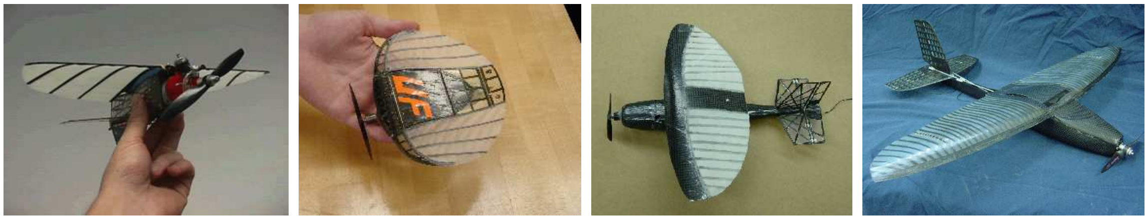

Figure 2–1: Members of MAV Fleet at University of Florida

Advances in miniature digital electronics, communications and computer technologies have made sensing capabilities on micro air vehicles possible. A typical application of these miniature electronics is in a reconaissance mission where a small MAV would be preferred to a larger vehicle in order to remain stealthy.

The use of innovative control effectors is an area being explored as an enabling technology for designing a stability augmentation system. The current generation of MAVs uses traditional effectors, specifically an elevator and rudder, whose positions are commanded by the remote pilot. The elevator presents adequate effectiveness for longitudinal control but the rudder presents some difficulty for lateral-directional control.

The rudder mainly excites the dutch roll mode so steering and gust rejection are really accomplished using the coupled roll and yaw motion resulting from dutch roll dynamics. Such an approach is obviously not optimal but traditional ailerons are not feasible on this type of aircraft.

Actuation of the MAV control surfaces is accomplished with two control effectors or servos mounted inside the fuselage. These devices actuate the control surfaces by rotating an arm and pushing or pulling a pushrod when a deflection is commanded.

Research in the design and testing of these vehicles has been done in several countries and universities. Research of micro air vehicles has also been done extensively at NASA. Specifically, NASA has considered a control assesment and simulation of a micro air vehicle with aeroelastic wings which adapt to the disturbances during flight [23]. This was done using aerodynamic data which was obtained in previous testing of a MAV [24].

CHAPTER 3
MORPHING

The concept of morphing is not an idea which has been strictly defined. A morphing aircraft is generally defined to be an aircraft whose shape changes during flight to optimize performance. Types of shape changes include span, chord, camber, area, thickness, aspect ratio and planform. The morphing can also be applied to a control surface in order to eliminate hinges.

Morphing can be used as a control effector by changing the shape of the aircraft in order to alter the flight dynamics. The concept of morphing has been looked at by DARPA and NASA to show the aerodynamic benefits; however, the use of morphing for control design has not been studied extensively. The wing morphing techniques for the MAVs in this project consider using servos which are attached to the wings.

Aircraft have previously used techniques for adapting their shape depending on the specific flight characteristics desired. The use of morphing as a control effector was used initially on the Wright Flyer, where the pilot used cables to twist the wings in order to achieve the desired motion. Wing warping did not become a common technique; however, due to the power which is required from actuators to change the shape of the wings [21].

Morphing is also used on the F-14 which has a variable sweep on the wing, therefore changing the shape of the wing during flight. The wings are swept in order to balance the range and speed by slowing down the increase in drag which develops as velocity increases [21].

There are different ways that an aircraft can be morphed which are appropriate for control. The current research will focus on morphing of the wings in order to consider primarily control issues. The flight characteristics of birds will be considered as a guide since they also change the shape of their wings to achieve certain maneuvers.

Many mechanisms which consider morphing have been designed but have not been tested in flight vehicles. NASA has designed a wing which changes the camber of the wing [6]. One of the wings considered is referred to as a Hyper-Elliptic Cambered Span (HECS) because the curvature along the span is continuously changing. This provides a larger area which allows for greater lift. This vehicle uses a hinge-less panel along the trailing edge of the wing as a form of a control surface for pitch and roll. The simulations demonstrated the aerodynamic benefits but also show this vehicle has unstable lateral-directional dynamics.

The use of smart materials such as shape memory alloys and piezos have been considered in the design of morphing wings but there is still a limit in that not enough force can be produced in order to twist large wings using these mechanisms. However, smart spars have been built which provide different types of morphing but have not been tested on flight vehicles [2].

Another mechanism for morphing which has been studied considers changing the sweep of the wings of a small unmanned air vehicle (UAV) [7]. The morphing on this UAV is done in order to meet changing mission requirements. Actuation of the morphing is done by using inflatable actuators which are powered with compressed air. One of the benefits of this project is that the actuation mechanism used is much lighter than the typical hydraulic systems that are used on full scale aircraft. The effects of the sweep are then studied considering the change of aspect ratio, lift and drag.

Similarly, a study has been done considering an inflatable telescopic spar which can be morphed spanwise [4]. This design allows for changes in the aspect ratio while still providing enough support from the spars for the airloads which are being applied. This is achieved because the telescopic spar is pressurized and the telescopic skins maintain the geometry of the airfoil as well as provide effective storing and deployment of the mechanism.

Also for the purpose of considering improved maneuverability and performance, roll maneuvers have been studied using a flexible wing [16]. Numerical studies were used to consider the aerodynamic loads on a flexible wing at high speeds. Wing twist is also considered in order to recover the rolling moment lost but has not been tested in flight. This is due to the challenges involved in implementing a functioning mechanism for wing twist on a full scale aircraft.

Research has also been done considering the material aspects of shape changing with a finite element model of a wing [17]. This considered roll maneuvers using a piezoelectric material as an actuation mechanism with aerodynamic loads being applied. Piezoelectric sensors and actuators are useful for this application because they are light, have a small volume and can achieve various shapes. This technique has not been tested; however, due to the large deflections that are needed from such small actuators.

Numerical studies have considered structural and aerodynamic modeling for shape changing wings [12]. These considered a generic lambda wing such as used in unmanned combat air vehicles (UCAV). The different mode shapes were studied to consider structural modeling. This model was then used to study the roll performance of the morphing wing. It was shown that this wing with hinge-less control surfaces shows improved roll performance because of the aerodynamic and structural benefits.

As mentioned previously, there are several benefits such as improved performance due to the use of wing morphing. Also, morphing is easily achieved on MAVs because the wings are constructed of flexible membrane material. The flexible wings can be grossly deformed via mechanical actuation yet are capable of withstanding flight loads. The flexible nature of the wing also gives rise to the mechanism of adaptive washout which permits small changes in wing shape in response to gusty wind conditions.

For this project, morphing is limited to changing the shape of the wings, not of the entire airframe. This type of morphing can be studied with the use of biologically inspired techniques. The different ways that birds change the shape of their wings during flight is studied and compared with morphing techniques. Consider, for example, the birds in Figure 3–1. These birds typically change the shape of their wings depending on the types of maneuvers that they need to perform.

Figure 3–1: A Gull (left) and Snowy Owl (right) in Flight

Certain techniques of morphing for aircraft can be designed by studying these birds. There are several morphing techniques which are used by these birds that demonstrate how their flight maneuvers can be changed, such as loitering, diving and take-off.

The wings of birds are shaped similarly to airfoils and have the same basic function [8]. Certain birds use their wings more often than others who just fly for short periods of time. Also, the environment the birds are in can affect the aerodynamics of the flight, therefore birds have different shapes of wings.

The aspect ratio of the wings of birds is measured as the square of the span of the wing divided by the area of the wing. This ratio can vary depending on the specific technique for flying of each bird. For example, long wings provide a smoother gliding motion but it takes more energy to flap them quickly, therefore they are not useful for increasing speed. Therefore, birds with longer wings tend to use gliding as their primary method of flight. Wing loading can also affect how a bird flies since the energy required to flap their wings also depends on how heavy they are.

Consider, for example, Figure 3–2 which shows the wing design for four different birds [8]. The lower aspect ratio wings, such as for a pheasant, typically allow for quick take off and slow flights, but are not useful for gliding. The slightly larger aspect ratio wings, such as for eagles, are typically longer and have feathers which are adjusted as a type of control surface for more precise maneuvering.

The wings for waders, with a typical aspect ratio of 12.5, are useful for faster speeds and gliding but do not allow for fast take off. This limit on a fast take off is because a lot of energy is required to flap these longer wings. The higher aspect ratio wings, as for gulls, are typically useful for gliding close to surfaces such as sea and land and take advantage of the winds in order to conserve energy. These are only a few of the many different designs of wings which vary depending on the migration patterns of each bird.

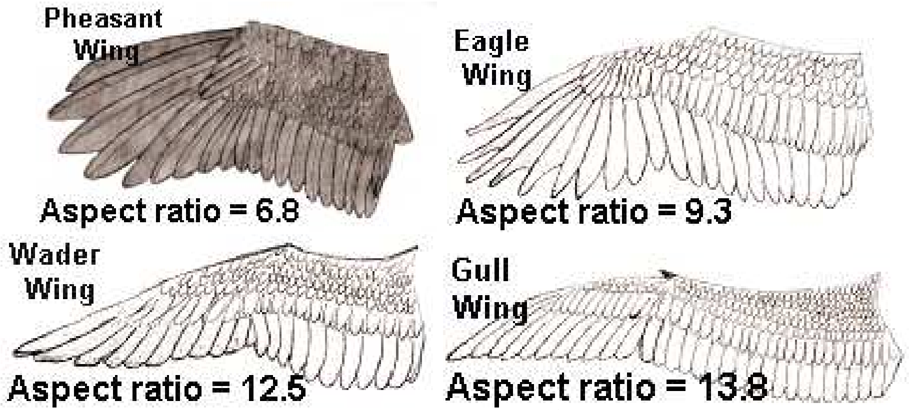

Figure 3–2: Aspect Ratio of Bird Wings

Some biologically inspired techniques can be applied to MAVs. The span of the wings, the horizontal distance from the tip of a wing to the tip of the other, can be altered to create a shorter wing for example. Birds and bats are also capable of changing the span of their wings to decrease the area, therefore increasing the forward velocity and reducing drag. The chord, which is the distance from the leading edge to the trailing edge, can also be altered. The wing can also be morphed by twisting or rotating parts of the wing in order to affect aerodynamic performance.

Another type of morphing is sweeping the wing either at an elbow joint on the wing or at the root of the wing. This provides a type of wing sweep which takes a similar shape change as seen in birds. The area of the wing can also be changed by extending the length or trailing edge as some birds do. The aspect ratio is also affected by the morphing and can be used to consider lift and drag for aerodynamics.

A simple form of morphing is a wing twist. This is currently being used for control on the Active Aeroelastic Wing (AAW) as well as the vehicles in this project. The morphing on the AAW causes the wings to be twisted in response to the moments induced by the control surfaces. Birds and bats also do this in order to obtain the required lift or thrust during flight.

Morphing on the MAVs is accomplished by actuation of control effectors located inside the fuselage. These servos are connected to the wings by either use of a torque rod or Kevlar strand. The wing morphing is actuated by moving the arm which rotates the tube or pulls the strand and changes the shape of the wing.

Certain maneuvers are of interest when considering the effects of wing morphing on a MAV. The flight test maneuver of interest is a control doublet for both rudder and wing shaping controls. The rudder doublet is being applied only to the 24 *in* MAV since the 12 *in* MAV consists of only elevator and wing morphing control effectors. These maneuvers are performed by commanding a constant left deflection for a certain time period followed immediately by a right deflection for the same time period and finally returning to the neutral position. Aircraft response characteristics to the control input are then determined by analysis of the servo position and rate responses.

Wing-shaping control doublets induce a different behavior of the MAV. The response of the airplane to wing shaping is similar in nature to responses from ailerons. Essentially, the aircraft response to the morphing is predominantly roll motion with little yaw or pitch coupling. Thus, the doublets are performed without considerable directional or altitude deviation.

Following the completion of the maneuver, which resembles rocking the wings, the airplane is in a banked attitude. Recovery from the wing shaping doublet is considerably easier than that of the rudder doublet. Such a response indicates the wing shaping excites the roll convergence mode.

Clearly, the MAV requires a stability augmentation system to facilitate operation and greatly expand its mission capability. In general, lateral maneuvers are particularly difficult because the MAV is so responsive. The introduction of a controller would lessen pilot workload for trajectory tracking.

The design of a controller is the next step in the research of facilitating the ability to operate these MAVs with the aid of active wing morphing. Future research will also enable development of a vision-based autopilot system currently being studied [9].

Open-loop flight tests were performed using wing morphing as an actuation mechanism. These flight tests demonstrate the value of morphing for consideration of a stability augmentation system. The rudder can be used to generate lateral maneuvers but the tight coupling of roll and yaw complicates the control needed for trajectory tracking. Conversely, the morphing produces almost pure roll so an associated controller for tracking roll commands will be the first to be implemented.

CHAPTER 4
MODELING

A model of a system can be described by comparing the relationship between the signals which are observed [19]. A model can be developed with the use of data which is collected in experiments. System identification considers the development of the model of a system with the use of observed data. For this purpose the signals typically considered are the output signals, which are measured, as well as the input signals, which consider the effect the observer has on the response of a system. Other signals which can be considered are outside disturbances, which are signals that are produced from outside sources such as noise, wind gusts and sensor drift.

A model is therefore a mathematical description of a system considering several aspects but is not an exact description of the physical system [19]. System identification is performed by first collecting data which emphasizes the parameters that are to be considered in the model estimation. Therefore, the input and output signals as well as specific maneuvers are selected prior to the data collection.

For some systems it is useful to describe the models using graphical interpretations. More specifically, they can be described using impulse, step and frequency responses. Certain systems can also be described using mathematical models. These can include continuous-time and discrete-time systems as well as linear and nonlinear systems.

A set of models can then be selected according to the specific application or dynamic system. A model which uses a black box approach is used for this project. This approach considers the input and output signals of the system in order to perform a fit to the data without providing physical meaning to the values. This model is then compared with the values obtained in the experiment in order to determine whether it is a good estimation of the system response.

The black box model structure which considers input and output signals can be expressed as the linear equation shown in 4.1 where *e(t)* is the noise error term.

$$y(t)+a_1y(t-1)+\ldots+a_{n_a}y(t-n_a)=b_1u(t-1)+\ldots+b_{n_b}u(t-n_b)+e(t) \qquad (4.1)$$

Then this equation can be expressed in terms of the initial output signal as shown in 4.2.

$$y(t)=-a_1y(t-1)-\ldots-a_{n_a}y(t-n_a)+b_1u(t-1)+\ldots+b_{n_b}u(t-n_b)+e(t) \qquad (4.2)$$

This is typically referred to as an ARX model, which defines the autoregressive part to be the output terms in 4.2, and the input terms in 4.2 as the extra input.

So the initial output values as well as the input and output terms on the right hand side of 4.2 are collected in matrix form for each time interval. This makes it possible to solve for the regression coefficients since the initial output and the input values are known.

The initial output values for each time interval can be expressed as in 4.3 in terms of the input and output values as well .

$$\begin{bmatrix} y^t \\ y^{t-1} \\ \ldots \\ y^{t-n} \end{bmatrix} = \begin{bmatrix} -y_1^t & -y_{n_a}^t & u_1^t & u_{n_b}^t \\ -y_1^{t-1} & -y_{n_a}^{t-1} & u_1^{t-1} & u_{n_b}^{t-1} \\ \ldots & \ldots & \ldots & \ldots \\ -y_1^{t-n} & -y_{n_a}^{t-n} & u_1^{t-n} & u_{n_b}^{t-n} \end{bmatrix} \begin{bmatrix} a_1 \\ a_{n_a} \\ \ldots \\ b_{n_b} \end{bmatrix} \qquad (4.3)$$

Then the regression coefficients are obtained by using the matrix equation 4.4 and solving for the matrix of coefficients X as shown in 4.5.

$$B = AX \tag{4.4}$$

$$A^{-1}B = X \tag{4.5}$$

A transformation as shown in 4.6 is then applied to equation 4.1 in order to obtain a transfer function as shown in 4.7. In this transfer function the B term contains all the input coefficients from equation 4.6 and the A terms consists of all the coefficients in the output terms.

$$y(t) + a_1 z^{-1} y(t) + \ldots + a_{n_a} z^{-n_a} y(t) = b_1 z^{-1} u(t) + \ldots + b_{n_b} z^{-n_b} u(t) + e(t) \tag{4.6}$$

$$yu^{-1} = BA^{-1} \tag{4.7}$$

A Tustin transformation is then done using Matlab in order to create a continuous time version of the discrete time system. This is done using a standard bilinear transformation such as shown in 4.8.

$$z = 1 + 2(sT/2) + 2(sT/2)^2 + 2(sT/2)^3 + \ldots \tag{4.8}$$

The ARX model approximation is just one of several types of model structures which can be used for system identification. An ARMAX model structure can similarly be used but was not used in this project because an initial simple estimation was desired. The ARMAX model considers the basic properties that the ARX model uses but also includes a moving average term, which considers the noise in its coefficient calculations.

Another modeling technique considers recursive identification methods. This considers calculating a model simultaneous to obtaining data. However, this is not a requirement for this specific project but can be useful in different applications. Certain applications include having an up to date model in order to consider these parameters when making decisions about what the system is to do next. This is typically referred to as an adaptive modeling technique because the input and output signals are calculated in order to be used as they become available.

An example of a recursive model which can be used for system identification in Matlab is the RARMAX model. This uses a recursive technique of an ARMAX model which considers the noise in its calculations. However, this technique only provides models for single-input, single-output systems. Similarly, another technique is the RARX model which estimates parameters recursively of a single-output system.

Therefore, for this project an initial linear approximation was done using an ARX technique. The initial step was to design an experiment which consisted of specified maneuvers such as doublets to the morphing and rudder servos. These were done in order to consider the roll and yaw rate responses of the system.

The data is then collected and processed before considering it for modeling. The data processing included using an algorithm which plotted, filtered and removed the bias in the data. The filtering was done using a low pass Butterworth filter on all the parameters and the bias was removed from the parameters by subtracting the mean.

This processed data is then used in the ARX modeling approximation. The roll rate and yaw rate responses are then compared to the simulation responses. This is done for both the morphing and rudder servos. The orders and delays are selected for the parameter estimation.

The orders of the approximation are the orders of the polynomials A and B in equation 4.7. Therefore, they are the orders of the polynomials in equation 4.9 and equation 4.10.

$$A(z) = 1 + a_1 z^{-1} + \ldots + a_{n_a} z^{-n_a} \tag{4.9}$$

$$B(z) = b_1 + b_2 z^{-1} + \ldots + b_{n_b} z^{-n_b+1} \tag{4.10}$$

The delays which are referred to as *nk* are selected as the number of delays from input to output as shown in equation 4.11.

$$A(z)y(t) = B(z)u(t - nk) + e(t) \tag{4.11}$$

In multi-output systems, the orders of the polynomials have as many rows as outputs. This is then used to create the simulation and it is then converted to a continuous time system from a discrete time system. The roll rate and yaw rate responses are then compared and for this project show a good correlation between the estimated and the actual data for the doublet maneuvers.

The following step in system identification would be to validate the model which was chosen as the best approximation to the data. This is done by considering whether the model is a good enough approximation for what it will be used for. In other words, whether the model can be trusted to reproduce the collected data. A model is typically not accepted as describing the actual true system, but simply as a good description of specific parts of the system which are of interest.

The first model obtained using these techniques typically has to be revised because it may not describe a system considering several different aspects. Particularly, for this project the models were obtained by considering the inputs and outputs of the system and then reproducing that data. However, the model obtained does not describe physical parameters which can be used for purposes of further control design.

A model which would be useful for control design would include approximations of certain aerodynamic parameters and time constants. These parameters can then be used to design a controller as well as considering the modes. Once the system is represented in physical parameters, controllers such as roll and yaw dampers can be designed by feeding back the appropriate angles. This can be done by using a simple proportional gain in the closed loop system.

CHAPTER 5
24 *in* MICRO AIR VEHICLE

5.1 Vehicle Description

One of the vehicles considered is the micro air vehicle with a 24 *in* wingspan shown in Figure 5–1.

Figure 5–1: Overhead View of the 24 *in* MAV

The 24 *in* MAV consists of a carbon composite frame with a mylar membrane skin wing. The leading edge of the wings consist of carbon-fiber weave with battens of unidirectional carbon attached to the underside and extending to the trailing edge. These battens provide the strength needed to support the airloads which are being applied while the membrane provides the lifting surface. The original control effectors for this MAV are the rudder and elevator. The rudder and elevator each have a single servo for actuation.

The control surfaces, the elevator and rudder, are connected to the servos using a spring steel pushrod. The approximate range of motion for each is given in Table 5–1.

Table 5–1: Range of control effectors

Effector	Range of Motion
elevator	-15^o to $+20^o$
rudder	-25^o to $+25^o$

The basic properties of the 24 *in* MAV are given in Table 5–2.

Table 5–2: Properties of the 24 *in* MAV

Property	Value
Wingspan	24”
Wing Area	100 in^2
Wing Loading	20.32 oz/ft^2
Aspect Ratio	5.76
Powerplant	Electric motor w/ 4.75” propeller
Total Weight	400 g

5.2 Morphing

Wing morphing is used as an additional control effector. A simple technique is used to morph the wings of the 24 *in* MAV. The morphing is actuated by two servos, one for each wing. The technique used for morphing on this vehicle consists of the use of a torque rod which produces the deflection that is commanded. This torque rod lies along each wing connected to the servos inside the fuselage as shown in Figure 5–2.

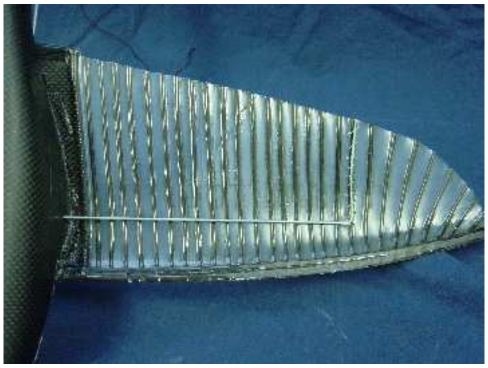

Figure 5–2: Wing with Torque Rod

The rods are sewn into the leading edge of the membrane therefore causing movement of the membrane if the rods are actuated. The effect of the morphing is seen to act as a simple form of wing warping. The wing deflection due to the morphing actuators for the 24 *in* MAV is shown in Figure 5–3.

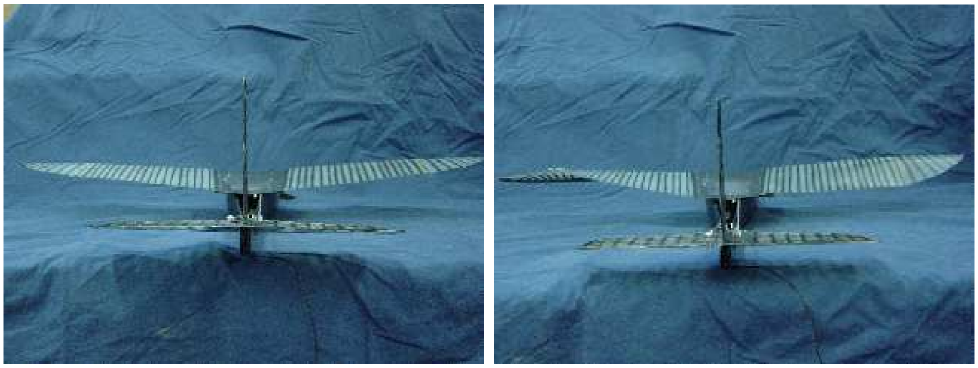

Figure 5–3: Rear View of the 24 *in* MAV with Undeflected (left) and Morphed (right) Wing

5.3 Flight Testing

Flight testing of the active wing-shaping 24 *in* MAV is performed in the open area of a radio controlled (R/C) model field during which wind conditions range from calm to 7 knots throughout the flights. Once the flight control and instrumentation systems are powered and initialized, the MAV is hand-launched into the wind. This launch is an effective method to quickly and reliably allow the MAV to reach flying speed and begin a climb to altitude.

This airplane is controlled by a pilot on the ground who maneuvers the airplane visually by operating an R/C transmitter. There is a data acquisition system on board which begins recording as soon as the motor is powered. This DAQ system records accelerations and rates about the coordinate system which is centered on the MAV.

This aircraft design allows either rudder or wing shaping to be used as the primary lateral control for standard maneuvering. The airplane is controlled in this manner through turns, climbs, and level flight until a suitable altitude is reached. At altitude, the airplane is trimmed for straight and level flight. This trim establishes a neutral reference point for all the control surfaces and facilitates performing flight test maneuvers.

Open-loop data is taken to indicate the flight characteristics of the MAV. Specifically, the roll and yaw rates and accelerations about a body fixed axis are measured in response to doublets commanded separately to the servos. Several sets of doublets are commanded ranging in magnitude and duration to obtain a diverse set of flight data.

The dynamics of the MAV in response to rudder commands is investigated to indicate the performance of the traditional configuration for this MAV. A representative doublet command is shown in Figure 5–4. The roll rate and yaw rate measured in response to this command are shown in Figure 5–5. The roll rate is large and indicates the rudder is able to provide lateral-directional authority; however, the yaw rate is clearly larger than the minimal amount which can be expected. Actually, the yaw rate is close in magnitude to the roll rate so the lateral-directional dynamics are very tightly coupled. The effect of the rudder in exciting the dutch roll dynamics is clearly seen in this response.

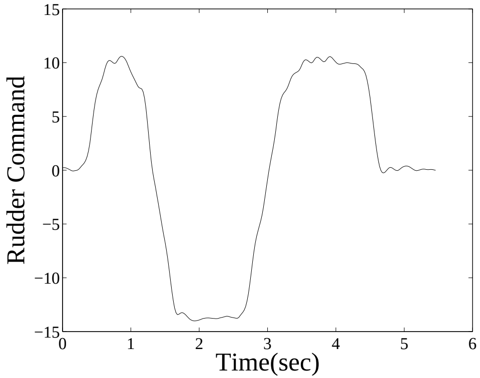

Figure 5–4: Doublet Command to Rudder Servo

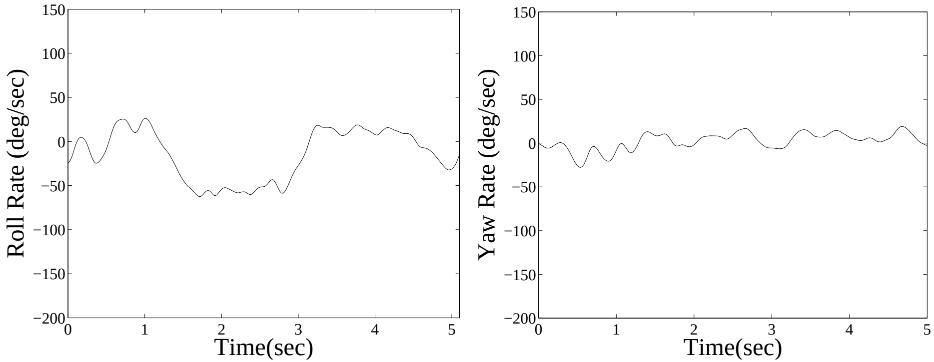

Figure 5–5: Response to Rudder Doublet for Roll Rate(left) and Yaw Rate(right)

Another doublet is commanded to the rudder in order to consider its response. The rudder is commanded with a slightly larger magnitude and longer duratio doublet which is shown in Figure 5–6. The response to this doublet command is shown in Figure 5–7.

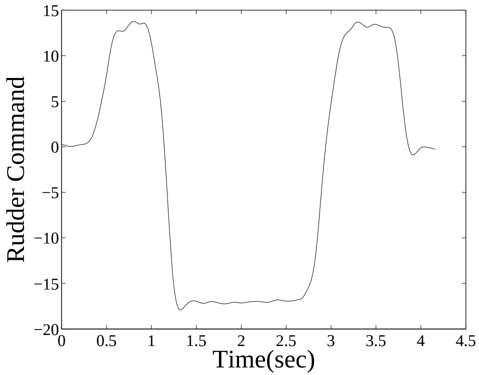

Figure 5–6: Second Doublet Command to Rudder Servo

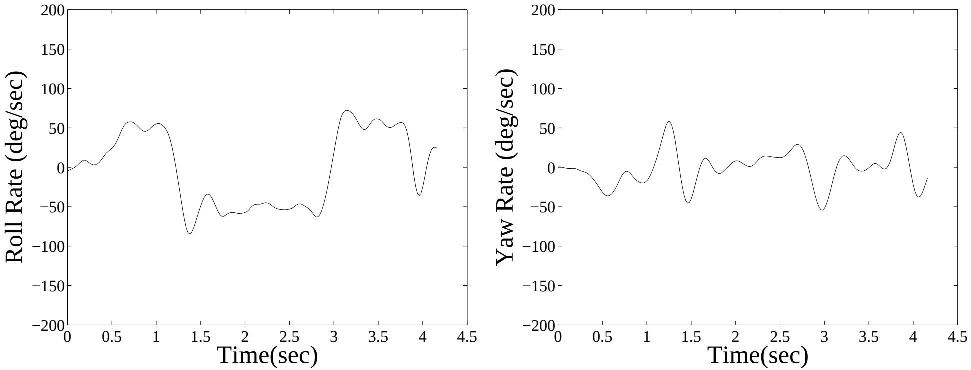

Figure 5–7: Response to Second Rudder Doublet for Roll(left) and Yaw Rate(right)

This shows a similar response as with the first doublet to the rudder servo. It shows a roll rate response of similar magnitude as the yaw rate. This then describes a dutch roll motion instead of a pure roll motion even with a slightly larger command to the rudder. Also, since the doublet was of larger magnitude and longer duration, this would indicate that the vehicle could be deviating farther from trim than in the previous maneuver which would result in greater nonlinearities such as increased yaw motion.

Doublet commands such as shown in Figure 5–8 are used in order to actuate the morphing servo. This maneuver is done without any input from the rudder in order to consider strictly commands to the morphing actuators. The amount of deflection of the morphing; however, is difficult to interpret because it is a deflection of the material and it is not expressed in a physical dimension such as degrees.

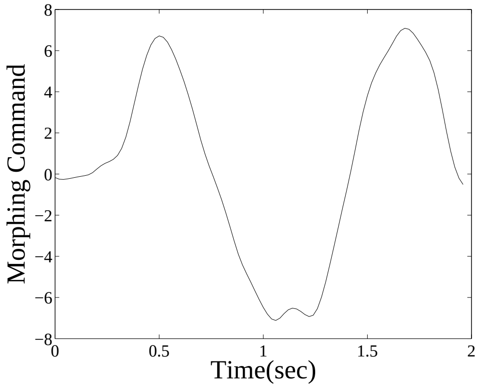

Figure 5–8: Doublet Command to Morphing Servo

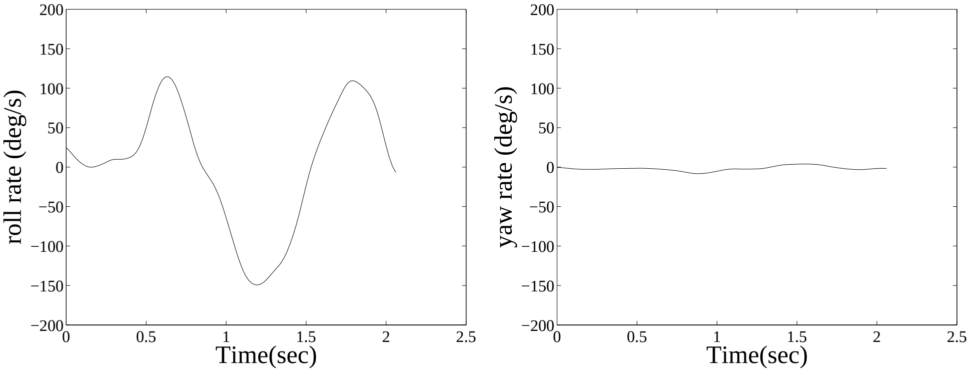

Figure 5–9: Response to Morphing Doublet for Roll(left) and Yaw Rate(right)

The roll rate and yaw rate in Figure 5–9 are measured in response to the doublet commanded to the morphing servo. These measurements indicate the roll rate is considerably higher than the yaw rate. Thus, the morphing is clearly an attractive approach for roll control because of the nearly-pure roll motion measured in response to the morphing commands.

A separate morphing doublet is commanded at a different time as shown in Figure 5–10 in order to consider the modeling for a different maneuver. Similarly, this maneuver consists of strictly morphing actuation and no rudder input.

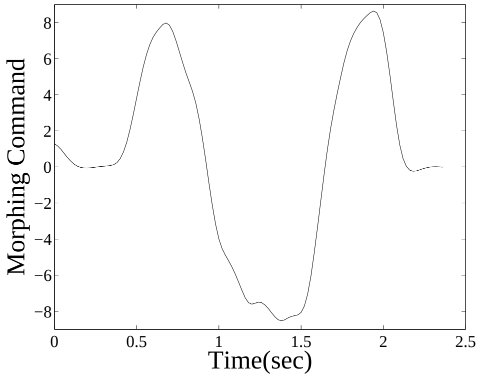

Figure 5–10: Second Doublet Command to Morphing Servo

The roll rate and yaw rate responses to the second morphing doublet are shown in Figure 5–11. It can be seen that the morphing doublet commanded in the second maneuver was of a slightly larger magnitude than the first maneuver. This results in a larger roll rate response due to a larger morphing deflection.

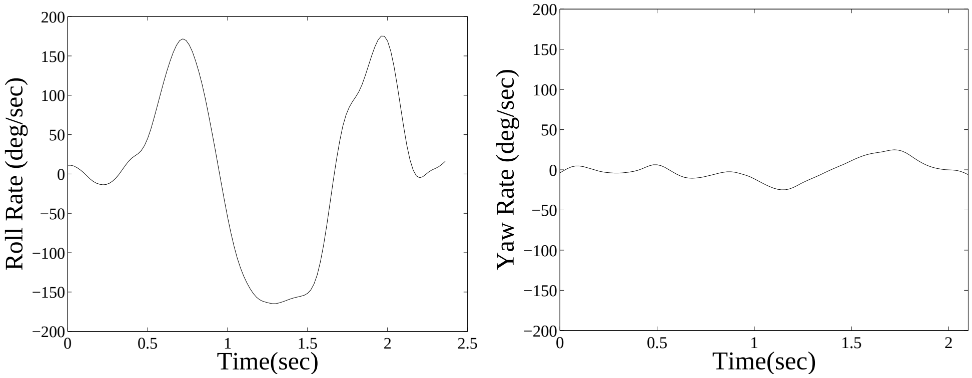

Figure 5–11: Response to Second Morphing Doublet Command for Roll Rate(left) and Yaw Rate(right)

It is also seen that there is a minimal yaw rate response from the actuation of a larger morphing deflection. Therefore, it similarly resulted in an almost pure roll motion with a slightly faster roll rate response than with the previous maneuver.

5.4 Modeling

The data from open-loop flights is then used to approximate a linear time-domain model using an ARX approximation [18]. This model is generated by computing optimal coefficients to match properties observed in the data.

The maneuvers of interest are doublets ranging in magnitude and centered around a trim condition. Therefore, the assumption of linearity is reasonable since the maneuvers are about trim. For the approximation, the rates which are considered are roll and yaw rate because they are of most interest for maneuvers such as doublets. The accelerometers were considered but the data was very noisy, therefore, not allowing for accurate approximations to be made.

The simulated and measured values of roll rate and yaw rate are shown in Figure 5–12.

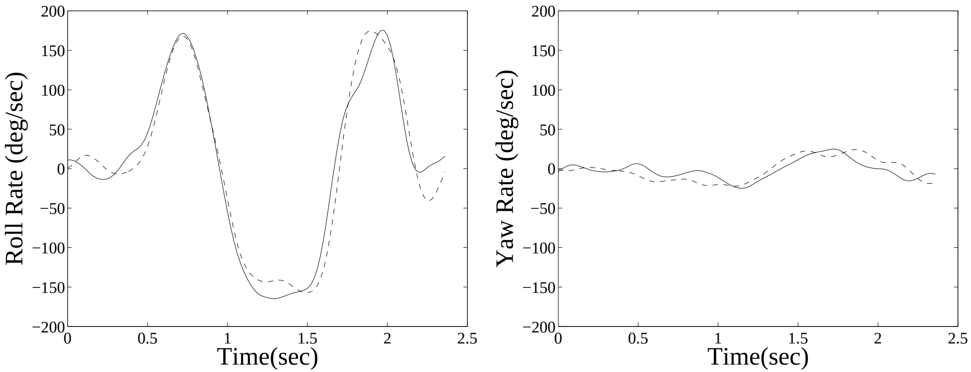

Figure 5–12: Simulated (- - -) and Actual (—) Roll Rate(left) and Yaw Rate(right) Responses to Morphing Doublet

The simulated responses show good correlation with the actual data. The model is thus considered a reasonable representation of the aircraft dynamics as it is excited by the doublet. The existence of such a model is important for future design of autopilot controllers but it is also valuable for interpreting the morphing.

When using the ARX simulation in Matlab, a linear approximation could not be made on the maneuvers which were not centered around trim. Therefore, not only are maneuvers around trim desired for a linear approximation, but they are also necessary in order for the simulation to be done.

The model which will be used was chosen because it produced the closest match to the maneuver as compared to four other doublets. The maneuvers compared were from the same data set, but the one that was chosen resulted in a closer match due to the aircraft being closer to trim. The resulting model consists of six states and poles as shown in Table 5–3. The roll mode is clearly shown and the dutch roll mode indicates the slight oscillations which are present in the combined roll and yaw motion as shown in Figure 5–12.

Table 5–3: Poles of a linear model of the 24 *in* MAV

Poles	Value
Dutch Roll	-3.75 ± 13.84
Roll	-4.03

In order to study whether this model is a good enough linear approximation of the dynamics of the 24 *in* MAV, different inputs are considered for the same model. These inputs are doublet morphing commands at different times throughout the same set of data. The simulated and measured values of roll rate and yaw rate are shown in Figure 5–13 for several inputs.

It is clearly shown that the simulated and actual roll rate and yaw rate responses demonstrate good correlation. The simulations shown in Figure 5–13 show that the model which was obtained from a doublet maneuver responds well to different inputs. The first input was a small morphing doublet commanded from a separate data set. The following two inputs were from a medium and large morphing doublet, respectively from the data set that was used for obtaining the model.

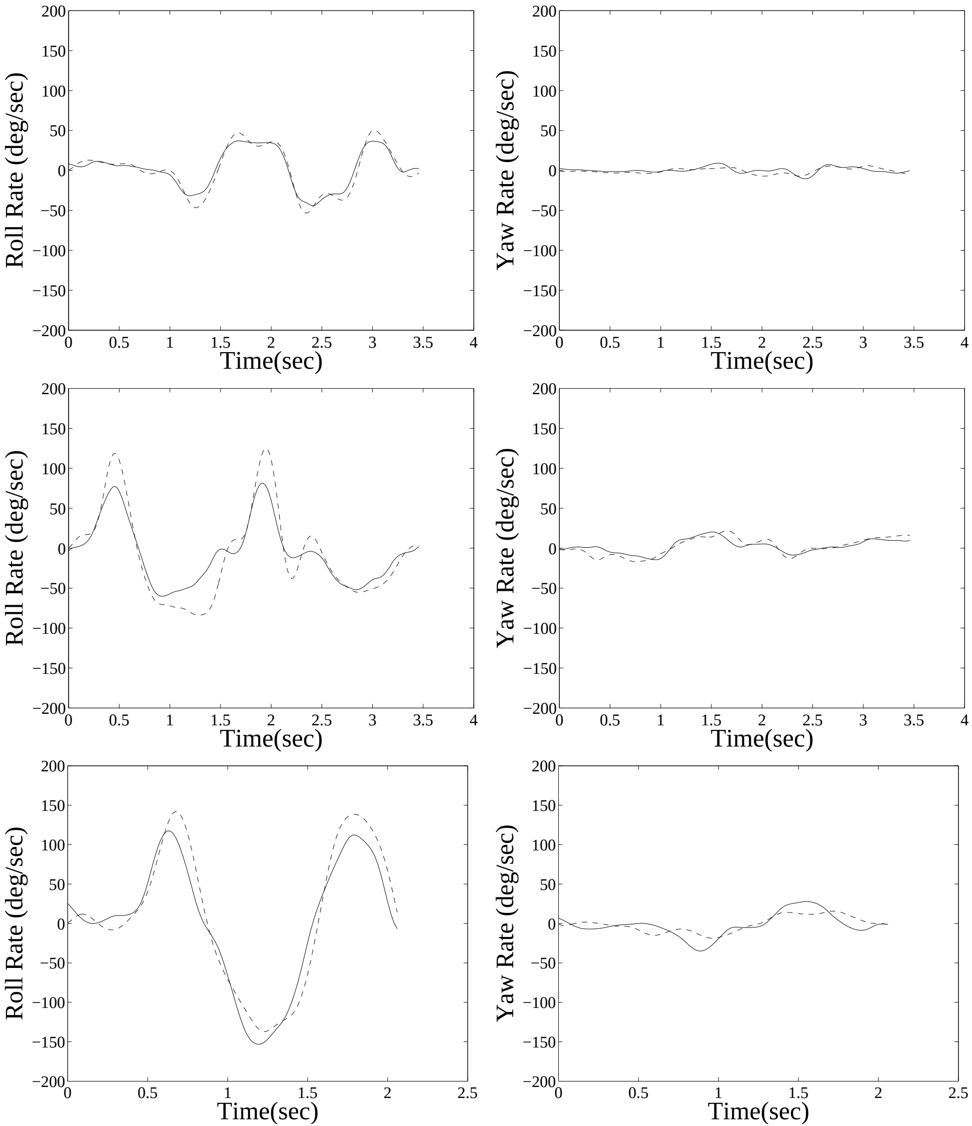

Figure 5–13: Simulated (– – –) and Actual (—) Roll Rate(left) and Yaw Rate(right) Responses to Morphing Doublets

5.5 Evaluation

If this MAV is to be used in surveillance missions, the use of only rudder and elevator could provide sufficient control during turns. However, the resulting dutch roll motion creates difficulties if this MAV is to be used for a more demanding mission and also requires more pilot control. Therefore, this vehicle requires further control in order to be used in situations such as in urban environments where more controlled turns are required.

Using wing twisting as an additional control effector for roll improves the performance and controllability of the aircraft. Using wing twist additionally, as compared to the traditional rudder and elevator results in improved flight path tracking, especially when considering gusty weather environments.

The flight characteristics of the 24*in* vehicle are actually quite impressive to view. The measurements of roll rate and yaw rate indicate the mathematical nature of the characteristics; however, a qualitative evaluation is also useful. Such an evaluation is best achieved in association with step commands given to each servo.

The step to the rudder causes the airplane to roll but the coupled yaw results in a flight path similar to a corkscrew spiral. Conversely, the step to the morphing causes the airplane to roll with a minimum of yaw so the flight path is nearly a straight line. In other words, the morphing induces almost pure roll and allows much more accurate tracking of desired flight paths.

Also, the morphing results in considerably higher roll rates than the rudder. This result is quite interesting given that the rudder deflection is quite large but the morphing, as shown in Figure 5–10, is not overly commanded to deflect. Thus, a small amount of morphing is sufficient to cause a dramatic response from the aircraft.

CHAPTER 6
12 *in* MICRO AIR VEHICLE

6.1 Vehicle Description

A different micro air vehicle is also considered. This vehicle has a wingspan of 12 *in* and is shown in Figure 6–1.

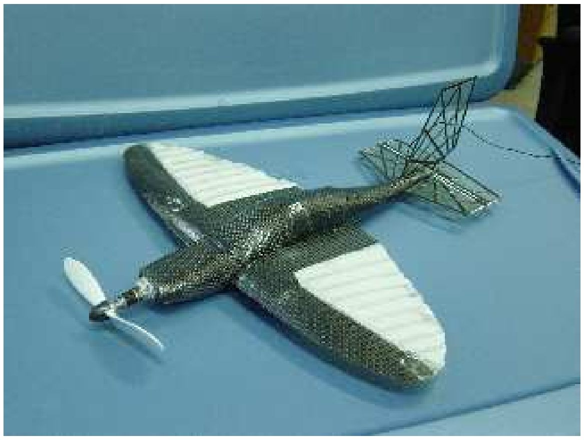

Figure 6–1: View of the 12 *in* MAV

The basic properties of this vehicle are given in Table 6–1.

Table 6–1: Properties of the 12 *in* MAV

Property	Value
Wingspan	12”
Wing Area	$44in^2$
Wing Loading	$14.19\ oz/ft^2$
Aspect Ratio	3.27
Powerplant	Electric motor w/ 2.25” propeller
Total Weight	123g

The 12 *in* MAV is designed to have an elevator as its control effector. The elevator is actuated by using a single servo. Therefore, this vehicle does not include a rudder and an additional control effector will be added.

This vehicle is constructed using the similar designs which are used at the University of Florida which consist of carbon fiber airframes and flexible membrane wings. The composite wing on the 12 *in* MAV skeleton is covered with an extensible membrane skin of latex rubber. The latex material used in the 12*in* MAV is considerably more flexible than the mylar sheeting which is used in the 24 *in* MAV.

6.2 Morphing

The 12 *in* MAV is designed with morphing as an additional control effector. The morphing is implemented by actuating a single servo which is connected to each wing. The use of a more flexible material for the wing surface of this vehicle was chosen on purpose in order to consider more dramatic shape changes of the wings. This is also done on a smaller airframe without a rudder to consider strictly the effects of morphing.

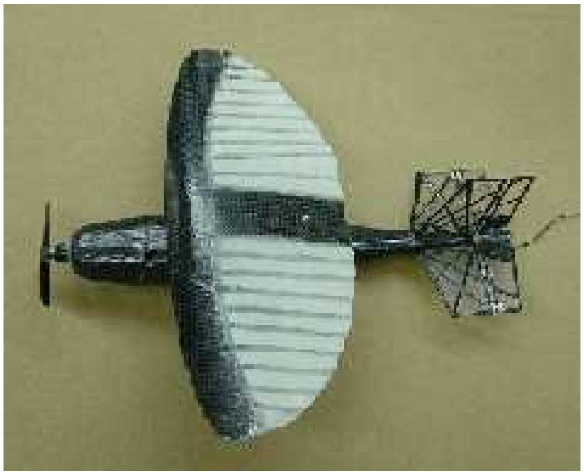

Figure 6–2: View of the 10 *in* MAV

The initial implementation of this morphing strategy was originally attempted on a MAV with 10 *in* wingspan as shown in Figure 6–2. The 10 *in* MAV is designed with a similar carbon fiber airframe and flexible membrane wings. The fact that this aircraft is smaller than the 12 *in* MAV allows for a smaller wing area and shorter, more closely aligned wing battons. This vehicle, like the current vehicle, has latex covering on the wings so was very easy to morph in flight. The 10 *in* MAV was chosen for the initial study because it was already constructed and could be readily adapted for the new study. The flights of that vehicle were quite promising and clearly indicated that the morphing provided an effective form of control authority.

This MAV responded well to the wing morphing commands, however, is restricted in the amount of flight testing which can currently be done due to its payload limitations. This led to the design of the 12 *in* MAV with the requirement of a larger aircraft in order to carry the required instrumentation to perform open-loop and closed-loop flight testing.

The design of the 12 *in* MAV initially followed closely the design of the 10 *in* MAV with a similar airframe and wing design. The open-loop flights are similarly performed with a data acquisition board and the closed-loop flights will be done with a memory board.

The 12 *in* vehicle was essentially a scaled version of the original vehicle except for the wing construction. The original version had a single structure for the wings that mounted atop the fuselage. The new version had separate wings that attached to posts on each side of the fuselage. This separation of the wings allowed for more flexibility due to the removal of the carbon fiber structure.

The leading edge of the 12 *in* MAV was initially built with a single layer of carbon fiber. This proved to be faulty during the first attempts at flight when the leading edge would fold over when wing loads were applied. Therefore another layer of carbon fiber was applied to the wing making it stiffer and better capable of withstanding the wing loads.

Another issue with the wing design was using the same flexible latex material on this 12 *in* as on the 10 *in* MAV with the larger airframe requiring a larger wing area. The wing battons are not as closely aligned on the larger frame and the larger sheet of latex is weaker with larger loads. Therefore not allowing for wing morphing as dramatic on the 12 *in* as on the 10 *in* MAV.

Further flight testing of the 12 *in* MAV indicated a problem with the thread connection. The morphing of the 10 *in* MAV used only a single thread attached to the outboard of the trailing edge and this style was used for the 12 *in* MAV. Unfortunately the battens on the larger MAV were spaced farther apart than on the smaller MAV so the wing was weaker. The leading edge on the 12 *in* MAV would now remain properly shaped but the trailing edge would collapse when loaded. This problem was addressed by attaching a second thread to the trailing edge of the wing and allowing the morphing actuation to provide strength to support the loads.

The 12 *in* MAV is designed to allow for a more complicated type of morphing than is used for the 24 *in* MAV. The wings of this smaller vehicle are constructed from latex sheeting whereas the wings of the larger vehicle are made of mylar sheeting. Consequently, the wings of the 12 *in* vehicle are considerably more flexible, and thus easier to morph, than the wings of the 24 *in* vehicle. This flexibility allows simple mechanisms to again be appropriate for generating morphing and allow control issues to be investigated.

The high flexibility of the wings for this MAV allow consideration of morphing beyond basic warping. More specifically, this vehicle is used to consider morphing that affects the twist and span of the wings. A torque rod, as used for the 24 *in* MAV, would clearly not be appropriate for such a morphing. Instead, the rod was replaced with threads.

The morphing strategy for this MAV is shown in Figure 6–3. Kevlar threads are strung between a servo in the fuselage and points near the outboard of the wings. These threads are incredibly strong and the minor stress received during flight is not sufficient to cause any stretching.

The morphing achieved by this strategy is directly dependent upon the attachment points of the threads. The attachment of the threads to the fuselage is near the leading edge of the wings. The corresponding attachment to the wings is actually at separate

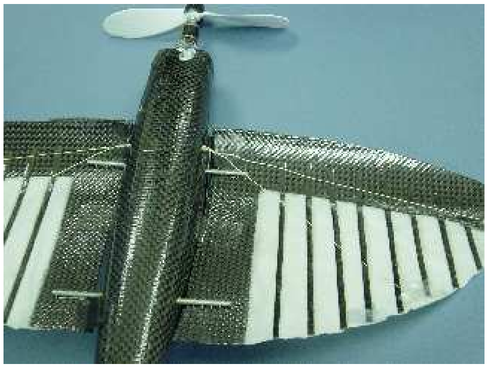

Figure 6–3: Wing with Kevlar Threads

points. One attachment point is near the mid-chord point at the wing-tip outboard. Another attachment point is the trailing edge near the two-thirds span location.

The morphing that results by actuating the servo is shown in Figure 6–4. The servo rotates and causes the threads to pull against the attachments on the wing. The morphing resulting from this strategy is clearly beyond simple warping. In this case, the pulling of the threads toward the leading-edge attachment at the fuselage causes the wing to both twist and bend. The effect is similar in nature to a curling of the wings. The basic parameters that are readily observed to change are the twist, camber, chord, and span.

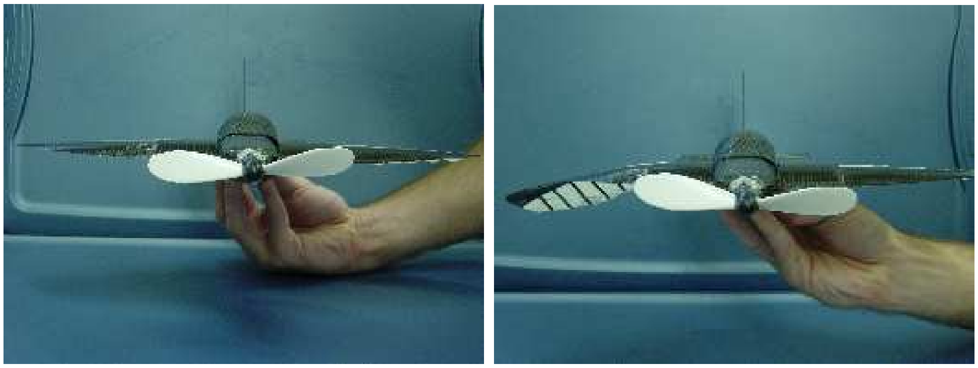

Figure 6–4: Front View of the 12 *in* MAV with Undeflected (left) and Morphed (right) Wing

The morphing is designed for a biologically-inspired effect. The displacement of the wing resembles shapes observed in birds like gulls. For instance, the bending along the span is concentrated around a single point which correlates to the elbow in birds. The twist is concentrated near the trailing-edge outboard which correlates with the feathers near the wrist of birds. A more formal approach to this concept is being designed by NASA but this current vehicle is sufficient to investigate control issues [6].

Only a single wing is altered in Figure 6–4. The vehicle actually contains separate servos for each wing that allow the morphing to act simultaneously on both wings; however, this thesis will restrict attention to morphing a single wing. The current objective considers roll control but the longitudinal issues will be investigated in the future.

Also, this vehicle is ideal for the focus of this thesis. Specifically, the morphing strategy is quite simple but the morphing effect is complicated. This approach allows the control issues associated with morphing to be easily studied. The vehicle is not designed to study the optimal strategies for morphing; rather, the vehicle is designed to study the optimal strategies for control.

6.3 Flight Testing

Flight testing is also done on the 12 *in* MAV in an open area for R/C airplanes. The flight tests for this MAV are performed in similar conditions as the tests for the 24 *in* MAV. This MAV is equiped with a data acquisition board which begins logging when the motor is turned on.

This MAV is then similarly hand launched into the incoming wind for takeoff. The primary forms of control for this MAV are the elevator and wing morphing. The airplane is controlled with these surfaces for takeoff, turns, climbs, and level flight. The airplane is then trimmed for straight and level flight. Achieving trimmed flight is necessary as a neutral reference point for the control surfaces and in performing different flight test maneuvers.

This MAV is then tested by commanding doublets to the morphing servos. A representative doublet command is shown in Figure 6–5. The units of this command are just count commands to the servo because the actual deflection caused by morphing is difficult to quantify.

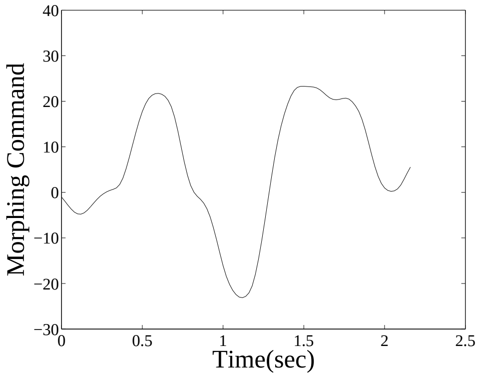

Figure 6–5: Doublet Command to Morphing Servo

The responses to the morphing doublets are measured by the on-board data acquisition system. The roll rate and yaw rate are presented in Figure 6–6.

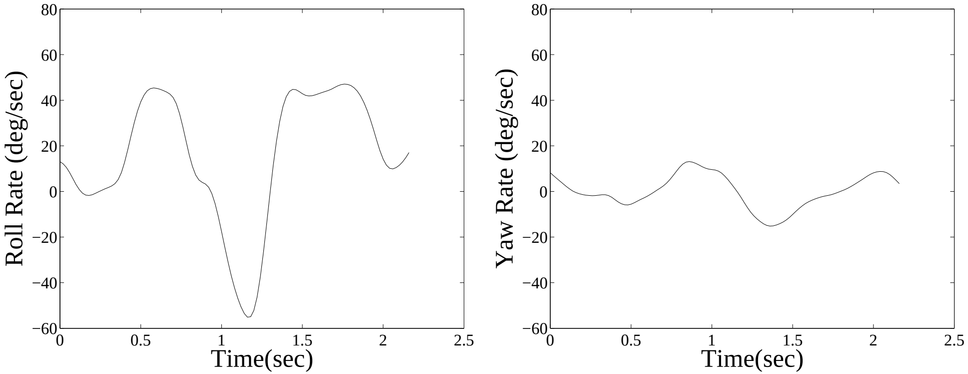

Figure 6–6: Roll Rate(left) and Yaw Rate(right) in Response to Morphing Doublet

The roll rate is clearly correlating well with the commanded doublet and demonstrates the morphing is capable of commanding roll maneuvers. The yaw rate is somewhat more difficult to understand. Notably, the aircraft builds up yaw rate approximately 0.5 *seconds* after the onset of the doublet command. This flight characteristic results from the single-sided nature of the morphing. Essentially, the wing that is morphed loses lift but also increases drag. The loss of lift immediately causes rolling and the increase of drag causes a slight delay in building up the yaw rate.

A separate morphing doublet is commanded at a different time as shown in Figure 6–7 in order to consider the modeling for a different maneuver. This maneuver consists of strictly morphing actuation.

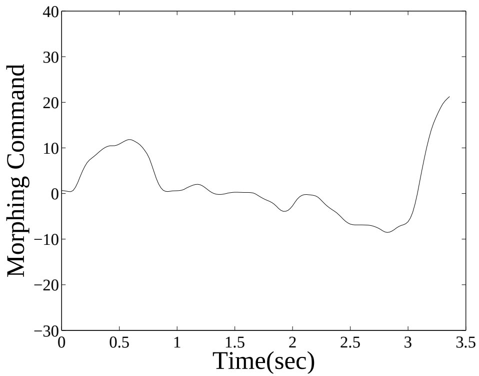

Figure 6–7: Second Doublet Command to Morphing Servo

The roll rate and yaw rate responses to the second morphing doublet are shown in Figure 6–8. It can be seen that the morphing doublet commanded in the second maneuver was of a slightly smaller magnitude than the first maneuver. This results in a smaller roll rate response due to a smaller morphing deflection.

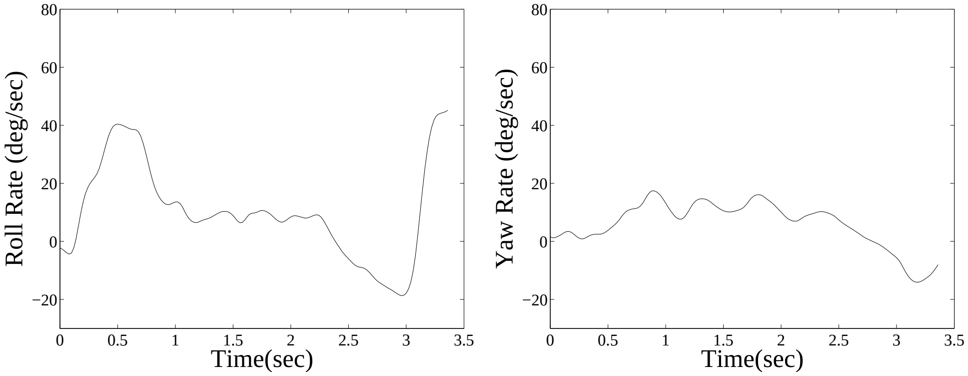

Figure 6–8: Response to Second Morphing Doublet Command for Roll Rate(left) and Yaw Rate(right)

6.4 Modeling

A linear model is identified from the flight data. A 6-state model was originally identified but reduced to a 3-state model as shown in Table 6–2. The simulated responses of this model are compared with measured values of roll rate and yaw rate in Figure 6–9.

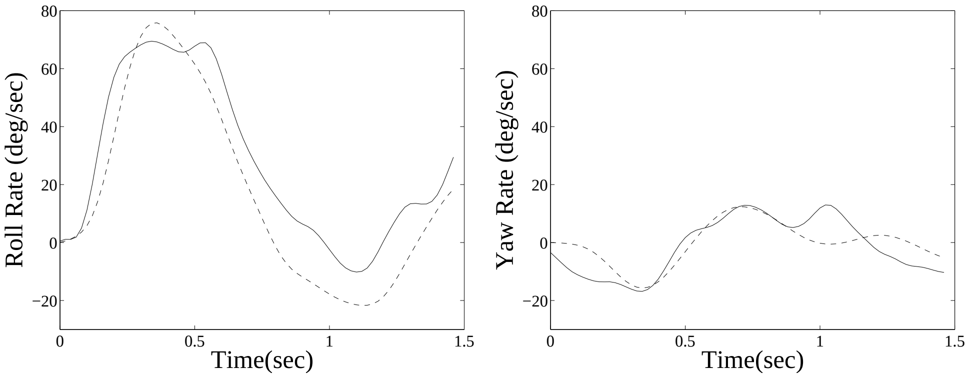

Figure 6–9: Simulated(− − −) and Actual(-) Roll Rate(left) and Yaw Rate(right) Responses to a Doublet

Table 6–2: Poles of a linear model of the 12 *in* MAV

Poles	Value
Dutch Roll	-3.6704 ± 14.732▮
Roll	-7.521

The responses of the model are reasonably close to the measured responses. The roll rate shows a good correlation although the yaw rate is somewhat less accurate. The model contains a roll convergence mode which, based on the accuracy of roll simulations, is accepted. The model also contains a dutch roll mode which attempts to capture the dynamics associated with yaw rate. The inability of this mode to represent the yaw dynamics may indicate some nonlinearity is associated with the vehicle. Such nonlinear dynamics would not be unexpected given the extreme nature of the morphing and the asymmetry resulting from morphing a single wing.

In order to study whether this model is a good enough linear approximation of the dynamics of the 12 *in* MAV, different inputs are considered for the same model. These inputs are doublet morphing commands at different times throughout the same set of data. The simulated and measured values of roll rate and yaw rate are shown in Figure 6–10 for several inputs.

It is clearly shown that the simulated and actual roll rate and yaw rate responses demonstrate good correlation. The simulations shown in Figure 6–10 show that the model which was obtained from a doublet maneuver responds well to different inputs. The yaw rate; however, is difficult to model because the vehicle is morphed asymmetrically and this introduces nonlinearities. These nonlinearities have to be considered in an approximation in order to obtain an accurate model.

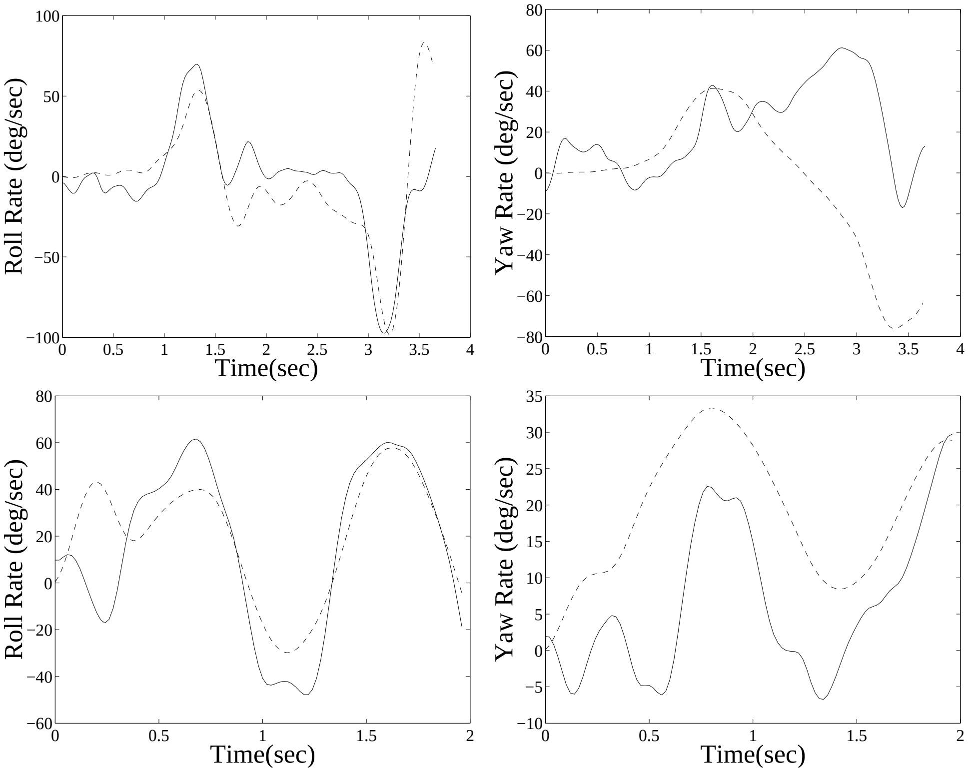

Figure 6–10: Simulated (– – –) and Actual (—) Roll Rate(left) and Yaw Rate(right) Responses to Morphing Doublets

6.5 Evaluation

When using the ARX simulation in Matlab, a linear approximation could not be made on the maneuvers which were not centered around trim. Therefore, not only are maneuvers around trim desired for a linear approximation, but they are also necessary in order for the simulation to be done.

It is particularly difficult to find maneuvers to use for a linear approximation for this specific vehicle due to the fact that it is very hard to trim. Therefore, before most maneuvers there is an indication in the data that there are some oscillations about the roll axis. Similarly, the data indicates that several seconds after a maneuver has been initiated, a component of yaw rate begins to develop.

The build up of yaw rate after a morphing maneuver has been initiated can be attributed to the fact that the shape of the wing is being altered. The wings on this vehicle are being curled underneath, one at a time resulting in an asymmetric morphing actuation. This leads to nonlinearities in the flight characteristics of the vehicle which can explain the oscillations and the build up of yaw seconds after a maneuver has been initiated.

The modeling is a linear approximation of coefficients, and when considering nonlinear behavior it might not provide data that can be trusted. The 24 *in* MAV is morphed by twisting the wings symmetrically, which can be approximated as a linear behavior. However, the 12 *in* MAV is being morphed asymmetrically, and therefore requires further studies to obtain a better approximation of the model.

CHAPTER 7
CONCLUSION

Current micro air vehicles are designed with the common features of carbon fiber airframes and flexible membrane wings. The typical control surfaces which can be implemented on MAVs consist of rudder and elevator. The conventional control surfaces such as ailerons can not be easily included in the design of the common MAVs due to the fact that the wings are made of flexible material.

A different form of actuation is necessary in order to improve maneuverability and performance for MAVs if they will be assigned to evolving missions. A particularly demanding mission is one which takes place in an urban environment which requires these vehicles to have advanced maneuvering capabilities. A simple approach to increasing maneuverability is to include an additional control effector such as wing morphing.

This paper has demonstrated that morphing can be an effective means to achieve roll control for a micro air vehicle. The flexible nature of the wings enables their shapes to be easily altered. Simple mechanisms, such as a torque rod and Kevlar threads, are used on a 24 *in* MAV and a 12 *in* MAV. In each case, the vehicle was flown using morphing as the primary effector for roll maneuvers. The flight data clearly shows the morphing produces significant roll rates and provides significant controllability.

These vehicles are flown in an R/C field and are equipped with a data acquisition system(DAS). This DAS consists of gyros and accelerometers for the three axis. The data is then retrieved and the accelerations and rates of the three axis can be studied. This data is then used for a linear modeling technique.

A linear approximation is then considered using an ARX modeling technique in Matlab. This shows a good correlation with the data for the 24 *in* and the 12 *in* MAV. However, further studies have to be considered for the modeling of the 12 *in* MAV since it is being morphed asymmetrically by curling one wing at a time. This then introduces nonlinearities in the flight characteristics which have to be considered in modeling approximations. The 24 *in* MAV can be approximated linearly since the morphing is being induced with symmetric wing twisting.

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BIOGRAPHICAL SKETCH

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