MEASUREMENT OF FLEXIBLE WING DEFORMATIONS IN FLIGHT

By

JAMES D. DAVIS

A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2006
This thesis is dedicated to my family who has supported me as much as possible through the years. To my Father for teaching me how to work. To my mother for teaching me patients and persistence. To my sister for teaching me survival and compassion. And to the rest of my family for all the life lessons offered through the years.

I also dedicate this thesis to all the teachers, instructors, professors, classmates, and coworkers I have had the honor to know and work with. For all of the lessons, challenges, and clarifications.

I would not be where I am without any of you. Thank you.
ACKNOWLEDGMENTS

This work was made possible by the US Air force civil service internship program PALACE Acquire thru which I attended the University of Florida. Also, I thank the professors at the University of Florida specifically Dr. Peter Ifju for advising me through the one calendar year I was allotted to complete the required course work. I would also like to acknowledge the USAF AFRL/MN for supporting the completion of this thesis in a timely manor. In addition, I thank every one on the UF MAV team for all the help and support.

I would also like to recognize my family for helping me anyway possible. Finally I thank my dog, Adian, who I rescued from the Alachua County Humane Society, for the badly needed distractions and unconditional love. Hang in there little buddy, I promise things will get better.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>3</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>6</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>7</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>10</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>12</td>
</tr>
<tr>
<td>1.1 Challenges and Developments</td>
<td>12</td>
</tr>
<tr>
<td>1.2 Motivation and Overview</td>
<td>15</td>
</tr>
<tr>
<td>2 LITERATURE SURVEY</td>
<td>17</td>
</tr>
<tr>
<td>2.1 Research</td>
<td>17</td>
</tr>
<tr>
<td>2.2 Deformation Measurement Methods</td>
<td>18</td>
</tr>
<tr>
<td>2.2.1 Visual Image Correlation</td>
<td>18</td>
</tr>
<tr>
<td>2.2.2 Video Model Deformation</td>
<td>18</td>
</tr>
<tr>
<td>2.2.3 Projection Moiré Interferometry</td>
<td>19</td>
</tr>
<tr>
<td>2.3 Flight Test Instrumentation</td>
<td>20</td>
</tr>
<tr>
<td>3 SYSTEM LAYOUT</td>
<td>22</td>
</tr>
<tr>
<td>3.1 Platform</td>
<td>22</td>
</tr>
<tr>
<td>3.2 Camera</td>
<td>22</td>
</tr>
<tr>
<td>3.3 Tracking Points</td>
<td>24</td>
</tr>
<tr>
<td>3.4 Angle of Attack Indicator</td>
<td>25</td>
</tr>
<tr>
<td>3.5 Deformation Measurement Calibration</td>
<td>25</td>
</tr>
<tr>
<td>3.6 AOA Indicator calibration</td>
<td>29</td>
</tr>
<tr>
<td>4 FLIGHT TEST</td>
<td>37</td>
</tr>
<tr>
<td>4.1 Flight Test Setup</td>
<td>37</td>
</tr>
<tr>
<td>4.2 Processing Results</td>
<td>38</td>
</tr>
<tr>
<td>4.3 Observations</td>
<td>39</td>
</tr>
<tr>
<td>4.4 Discussion of Deformations and Plots</td>
<td>40</td>
</tr>
<tr>
<td>5 CONCLUSIONS AND RECOMMENDATIONS</td>
<td>58</td>
</tr>
<tr>
<td>5.1 Discussion of Error and Sensitivity Analysis</td>
<td>58</td>
</tr>
<tr>
<td>5.2 Recommendations</td>
<td>59</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1. Calculated airspeed and AOA of level passes with error estimations</td>
<td>42</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1.</td>
<td>16” Wingspan second generation MMALV.</td>
</tr>
<tr>
<td>3-2.</td>
<td>Various Planform Designs in use by UF MAV team: Rigid (A), Batten Reinforced (B), Perimeter Reinforced (C), and Floating Angled (D).</td>
</tr>
<tr>
<td>3-3.</td>
<td>Directional convention utilized.</td>
</tr>
<tr>
<td>3-4.</td>
<td>Color CCD snake type camera.</td>
</tr>
<tr>
<td>3-5.</td>
<td>Camera location and mounting.</td>
</tr>
<tr>
<td>3-6.</td>
<td>The two tracking point patterns investigated, suspected maximum deflection (A), and ease of processing (B).</td>
</tr>
<tr>
<td>3-7.</td>
<td>The AOA indicator and its mounting.</td>
</tr>
<tr>
<td>3-8.</td>
<td>VIC system installation and setup.</td>
</tr>
<tr>
<td>3-9.</td>
<td>The numbered order of the tracking points and the location of each centroid.</td>
</tr>
<tr>
<td>3-10.</td>
<td>Example of image of MMALV through VIC camera with VIC data field overlaid, this is the standard output from the VIC software.</td>
</tr>
<tr>
<td>3-11.</td>
<td>Image of MMALV through VIC camera with tracking points installed.</td>
</tr>
<tr>
<td>3-13.</td>
<td>A VIC data set before and after alignment.</td>
</tr>
<tr>
<td>3-14.</td>
<td>Image of the AOA indicator from SPOT camera and processed results.</td>
</tr>
<tr>
<td>3-15.</td>
<td>AOA indicator calibration curve.</td>
</tr>
<tr>
<td>4-1.</td>
<td>Flight test setup.</td>
</tr>
<tr>
<td>4-2.</td>
<td>Topographic representation of the wing in an undeformed state.</td>
</tr>
<tr>
<td>4-3.</td>
<td>Chordwise sectional lines.</td>
</tr>
<tr>
<td>4-4.</td>
<td>Cross sectional view of wing at each corresponding sectional line.</td>
</tr>
<tr>
<td>4-5.</td>
<td>Cross sectional plots of flight-test SPOT data for pass 1: estimated 20.8 m/s and 4° AOA.</td>
</tr>
<tr>
<td>4-6.</td>
<td>Cross sectional plots of flight-test SPOT data for pass 2: estimated 26.9 m/s and 4° AOA.</td>
</tr>
</tbody>
</table>
4-7. Cross sectional plots of flight-test SPOT data for pass 3: estimated 19.9 m/s and 3° AOA .................................................................45

4-8. Cross sectional plots of flight-test SPOT data for pass 4: estimated 22.9 m/s and 4° AOA .................................................................45

4-9. Cross sectional plots of flight-test SPOT data for high AOA 1: 18° AOA and unknown airspeed .................................................................46

4-10. Cross sectional plots of flight-test SPOT data for high AOA 2: 20° AOA and unknown airspeed .................................................................46

4-11. Cross sectional plots of flight-test SPOT data for high AOA 3: 24° AOA and unknown airspeed .................................................................47

4-12. Cross sectional plots of flight-test SPOT data for negative AOA: -19° AOA and unknown airspeed .................................................................47

4-13. Topographic plots of flight-test SPOT data for pass 1: estimated 20.8 m/s and 4° AOA .................................................................48

4-14. Topographic plots of wind tunnel VIC data for 20 m/s and 4° AOA .................................................................48

4-15. Topographic plots of flight-test SPOT data for pass 2: estimated 26.9 m/s and 4° AOA .................................................................49

4-16. Topographic plots of wind tunnel VIC data for 26 m/s and 4° AOA .................................................................49

4-17. Topographic plots of flight-test SPOT data for pass 3: estimated 19.9 m/s and 3° AOA .................................................................50

4-18. Topographic plots of wind tunnel VIC data for 20 m/s and 4° AOA .................................................................50

4-19. Topographic plots of flight-test SPOT data for pass 4: estimated 22.9 m/s and 4° AOA .................................................................51

4-20. Topographic plots of wind tunnel VIC data for 23 m/s and 4° AOA .................................................................51

4-21. Topographic plots of flight-test SPOT data for high AOA 1: 18° AOA and unknown airspeed .................................................................52

4-22. Topographic plots of flight-test SPOT data for high AOA 2: 20° AOA and unknown airspeed .................................................................52

4-23. Topographic plots of flight-test SPOT data for high AOA 3: 24° AOA and unknown airspeed .................................................................53

4-24. Topographic plots of flight-test SPOT data for negative AOA: -19° AOA and unknown airspeed .................................................................53

4-25. Wind tunnel VIC data for 13 m/s and 10° AOA .................................................................54
4-26. Wind tunnel VIC data for 13 m/s and -5° AOA.................................................................54
4-27. Wind tunnel VIC data for 13 m/s and 0° AOA. .................................................................54
4-28. Wind tunnel VIC data for 13 m/s and 3° AOA. .................................................................55
4-29. Wind tunnel VIC data for 13 m/s and 5° AOA. .................................................................55
4-31. Wind tunnel VIC data for 13 m/s and 12° AOA. .................................................................56
4-32. Wind tunnel VIC data for 13 m/s and 15° AOA. .................................................................56
4-33. Amount of deformation data for the hard left turn 7° AOA unknown side slip and unknown airspeed. .............................................................................................................57
4-34. Amount of deformation data for the hard right turn 9° AOA unknown side slip and unknown airspeed. .............................................................................................................57
5-1. Example of thresholded image, taken from flight test pass1..................................................61
5-2. Image captured and processed for pass 1. ..............................................................................61
5-3. Pass 1 Cross section deformation with tolerance bounds and errorbars.................................61
5-4. Pass 2 Cross section deformation with tolerance bounds and errorbars.................................62
5-5. Pass 3 Cross section deformation with tolerance bounds and errorbars.................................62
5-6. Pass 4 Cross section deformation with tolerance bounds and errorbars.................................63
5-7. High AOA 1 Cross section deformation with tolerance bounds and errorbars.......................63
5-8. High AOA 2 Cross section deformation with tolerance bounds and errorbars.......................64
5-9. High AOA 3 Cross section deformation with tolerance bounds and errorbars.......................64
5-10. Negative AOA Cross section deformation with tolerance bounds a........................................65
A-1. AOA indicator calibration curve for first run with CCD camera.............................................66
A-2. Tracking point calibration curves for first run with CCD camera.............................................66
A-3. Image taken with CCD camera during the calibration process. .............................................67
A-4. Image taken with CCD camera during the calibration process with the AOA indicator installed. ..........................................................................................................................67
Adverse flying conditions such as wind gusts are an unavoidable reality and a concern for aircraft of any scale where outdoor flight is mission critical. In the realm of Micro Aerial Vehicles (MAVs), where relative low mass inertias and low flight speeds are prevalent almost by definition, handling characteristics in such typical conditions are of primary concern. In the interest of keeping the craft volume minimal and autopilot simple these characteristics should be as inherent and unsupplemented as possible.

With these realizations and inspiration from sailing technology, the University of Florida developed a thin significantly cambered flexible membrane wing. The flexible wing design passively adapts to the changing flight conditions in such a way that it results in more stable and manageable flight characteristics. The behavior and characteristics of the flexible wing have been studied in theories, computations, and wind tunnels all of which are limited to steady or quasi steady state conditions. The research presented in this thesis is an initial investigation into developing a system to monitor and measure the deformational behavior of the flexible wing in flight as it responds to real world aerodynamic and inertial conditions.
The method proposed and investigated is one of videogrammetry. A camera was placed on the tail of the aircraft oriented so that the wing was in the view. The wing was outfitted with tracking points and an angle of attack (AOA) indicator. The system was termed single point optical tracking (SPOT). SPOT was calibrated using the University of Florida’s low speed, low turbulence wind tunnel and the visual image correlation (VIC) measurement system. A comparison of in flight deformation measurements to wind tunnel measurements at a similar angle and airspeed was made with agreeable results demonstrating the effectiveness and viability of the system. An error and sensitivity analysis was performed.
CHAPTER 1
INTRODUCTION

1.1 Challenges and Developments

Adverse flying conditions such as wind gusts are an unavoidable reality and a concern for aircraft of any scale where outdoor flight is mission critical. In the realm of Micro Aerial Vehicles (MAVs), where relative low mass inertias and low flight speeds are prevalent almost by definition, handling characteristics in such typical conditions are of primary concern. Micro Aerial Vehicles are defined as any aircraft with a maximum dimension of less than 15cm [1]. With the given maximum dimension, and the fact pilots do not come that small, MAVs are in the realm of Unmanned Aerial Vehicles (UAVs).

For micro scale aircraft typical flight speeds range between 15 to 25 mph, and on an average day gusts can vary the wind speed by more than 10 mph. These average conditions result in sudden and significant changes of not only airspeed but also angle of attack (AOA) and sideslip. For conventional rigid wing designs, these changes in flight conditions result in a proportional variation in the lift produced over a corresponding short period of time [2]. The combination of low inertias and considerable changes in lift can result in a rapid divergence from the intended flight path if left uncorrected.

Stability and controllability are not the only problematic concerns faced by MAVs. The dimensions and flight speeds place the aircraft in an aerodynamic region referred to as low Reynolds number (LRN) which is between 60,000 and 150,000. Laminar boundary layer separation is a common occurrence within this range resulting in a drop in aerodynamic efficiency for conventional airfoils [2].

Early in the development of MAV scale aircraft, emphasis was placed on the latter problem with designs that tried to maximize aerodynamic efficiency such as rigid blended wing-
fuselage and pure flying wings. These conventional designs proved to have undesirable flight characteristics at these scales, requiring control supplementation for even seasoned remote control (RC) pilots [2].

The primary mission of many UAV type craft is reconnaissance. The details of this mission could vary from bomb damage assessment to search and rescue to surveillance in a host of uninviting environments that would prove too close quartered or dangerous for larger manned aircraft. The list of missions and environments is quite extensive but always requires practicality and effectiveness from the platform selected to do the job. The mission and environmental niche that MAVs are slated to fill are among the most demanding, with the ultimate goal being operable and deployable by a single person through an urban canyon and inside buildings while collecting data.

For a MAV to meet the ultimate goal in a practical manner it is required to be flown by a remote pilot with minimal training or autonomously, both of which necessitate that the platform have reliable and benevolent flight characteristics [3]. In the interest of keeping the craft volume minimal and autopilot simple, these characteristics should be as inherent and unsupplemented as possible.

With these realizations and inspiration from sailing technology, the University of Florida MAV team implemented an alternate design option, a thin significantly cambered flexible membrane wing [4-6]. Previous work done by Waszak et al.[6], Shyy et al. [7-11], and Jenkins et al. [12] showed that a wing of this design would have more favorable aerodynamic performance in adverse flight conditions.

The flexible wing design passively adapts to the changing flight conditions in such a way it results in more stable and manageable flight characteristics. This adaptation results in significant
changes in wing geometry such as the dihedral, wing twist, maximum camber, and chord wise location of maximum camber [6].

National Advisory Committee for Aeronautics (NACA) researchers found similar conclusions for transport scale aircraft. A technical note published in 1941 stated that a torsionally flexible wing reduces the vertical acceleration increment induced by wind gusts if the torsion axis is ahead of the aerodynamic locus. In addition, the percentage in the reduction of vertical acceleration was found to be far more dependent of gust shape and duration than that of gust velocity. It was also found that in some gust conditions torsionally flexible wings have a lower bending moment at the root of the wing as compared to a rigid counterpart. Results indicated that the torsionally flexible wing slightly increased the longitudinal stability of the aircraft in a gust. The NACA researchers concluded that this method of gust alleviation would be impractical for full-scale aircraft given the design trends of the time [13].

Starting in 1997 the annual International Micro Air Vehicle Competition (IMAVC) has been a major source of inspiration for innovative MAV designs and configurations. Major collegiate competitors have been the University of Florida (UF), University of Arizona, Brigham Young University and many others. The competition has historically consisted of a surveillance category and either an endurance or payload category.

The University of Florida successfully implemented the flexible wing findings in 1999, winning the IMAVC. This marked a new step in MAV design. Previously designs generally focused on aerodynamic efficiency and incorporated a rigid flying wing and required the use of a stability augmentation system. With the flexible wing and innovative construction methods UF was able to develop a MAV of comparable size that did not require the use of any stability augmentation system [2, 5].
The UF MAV team has won first place in the last 8 consecutive IMAVC competitions establishing an impressive track record for the flexible wing of reliability, small size and big capabilities. The surveillance platform that UF fielded at the 2006 competition had a maximum dimension of 11.5 cm and has successfully flown even smaller in the past.

The focus on minimizing the maximum dimension of the craft has lead to a spherical design space and almost circular wing planform. Such planforms result in low aspect ratio (LAR) wings and tend to have unique performance characteristics due to aerodynamic phenomena.

1.2 Motivation and Overview

Flight-testing is a critical phase of any aircraft development. The information gathered during these flight tests is used to verify performance predictions or illuminate points of possible improvement for the next design iteration. In the micro scale regime, flight test results are often little more than pilot feed back and ground observations, which although insightful, are highly qualitative.

Miniature flight data recorders are commercially available equipped with sensors that record airspeed, altitude, accelerations and can interface with any sensor small enough that has an analog voltage interface [14]. Small telecommunication devices are also available that transmit the information to the ground instead of recording it onboard. To date, an effective AOA sensor has not been developed for this scale of operation. Currently, these systems are not small enough to fit on the smallest MAVs and are typically utilized on larger, further developed platforms.

The goal of this research is the initial development and implementation of a method or system that would extend the information gathered from flight tests to the structural dynamics and deformations of the flexible wing in a quantitative sense. This will enable an investigation
into the behavior and performance of the wing as the craft is performing maneuvers such as dives, turns, stalls, spins, as well as straight and level flight all in calm and gusty conditions. Extending the investigational envelope into this dynamic arena will provide new insight to the behavior of the membrane wing, allowing for not only design improvements but also quantitative comparison and further validation of observations made in wind tunnel experiments and theoretical investigations.

The platform selected for this research is the Micro Morphing Aerial Land Vehicle (MMALV). This platform was chosen for its availability, ease of system incorporation and low wing stiffness that allows relatively large magnitude displacements. The MMALV was developed at the University of Florida MAV lab in cooperation with Case Western University and Bio Robotics. The MMALV will be further described in later sections.

The subsequent chapters of this paper will discuss the work completed and accomplishments made. The second chapter will be a literature survey of relevant research into flexible wing MAVs and optical measurement systems utilized on flexible wing designs. The third chapter will detail the developed system, calibration method, and equipment used. The fourth chapter will discuss the flight test, data gathering, and data processing with a presentation of the results. The fifth and final chapter will present the conclusions drawn, recommendations for future work, and a discussion of the error and sensitivity study conducted.
CHAPTER 2
LITERATURE SURVEY

2.1 Research

Many theoretical and wind tunnel investigations have been made into the behavior of the UF flexible membrane wing and surrounding flow properties. Early theoretical and computational work by Jenkins et al. [12], Waszak et al. [6], and Shyy et al. [7, 8-11] showed that thin significantly cambered and flexible wings would perform better in the LRN range as compared to more traditional airfoil designs.

Extensive wind tunnel tests and experiments have been conducted on wings of various flexible designs, and the results have supported the theoretical findings on the performance characteristics. Albertani et al. [3, 4, 15-20] found that with an increase in velocity, corresponding dynamic pressure, or AOA, the tip of the flexible wing twists to a lower angle of incidence, the dihedral angle increases, the maximum camber increases, and the location of the maximum camber moves aft. The combinations of these changes result in a corresponding favorable change in pitching moment and lift that act to damp out sudden resulting accelerations of the vehicle, therefore obtaining a smoother flight as compared to an equivalent rigid wing [3].

Wind tunnel experiments performed by Sytsma [21] using various flow visualization techniques illuminated the flow characteristics about the 15 cm span UF MAV wing designs. The findings supported the theoretical and computational work of Lian et al. [22-25] and Viieru [26], which illustrated flexible membrane aerodynamic interactions of a LAR UF MAV wing in LRN conditions, including the effect of tip vortices and the laminar separation bubbles.

For LAR wings the tip vortices cover a significant percentage of the wing area and therefore are an important contributing factor to the aerodynamic behavior. For wings that have an aspect ratio below 1.5, tip vortices form significant low-pressure cells on the top surface of
the wing resulting in a non-linear contribution to the total lift and increases the lift-curve slope as the angle of attack increases. This non-linear effect is considered one of the effectors responsible for the high stall angle of attack [27].

2.2 Deformation Measurement Methods

2.2.1 Visual Image Correlation

Various methods of measuring the deflection and final deformed shape of the flexible wing have been developed and implemented in the wind tunnel environment. The University of Florida has implemented the Visual Image Correlation (VIC) system, which was developed at the University of South Carolina, to obtain elastic deformation measurements of wind tunnel models [3, 4, 17-20]. The VIC system was developed by Helm et al. [28] in the mid 1990s and provides a global shape and deformation measurement. The VIC system uses two cameras to obtain highly accurate 3D measurements of a surface prepared with a low luster high contrast random speckle pattern. Measurements, both in plane and out of plane, are obtained by a comparison of the test subject in the deformed state and a reference state. Error quantification is based on many variables and is different for each set up. Errors of ± 0.05 mm have been reported [28]. Calibration of the VIC system requires the use of a calibration plate with a grid of markings at known intervals [3].

2.2.2 Video Model Deformation

With the development and refinement of solid-state cameras and personal computers, a method termed Video Model Deformation system (VMD) was developed at NASA’s transonic wind tunnel facility in the 1990s to measure wind tunnel model deformation [29]. The VMD is a single camera system that finds the centroids of circular targets placed on the model at locations of interest in wind on and wind off conditions. By comparing the wind on and wind off
conditions, the deflection of the centroids can be calculated using collinearity equations. The collinearity equations relate the 2D image coordinates to the 3D object coordinates [29].

The calibration technique for VMD requires that the three Euler angles relating the camera orientation relative to the wind tunnel and distortion parameters be determined. These parameters are found through an iterative process from images taken of a calibration plate aligned with the tunnel axis at various known locations. In order to use the collinearity equations to convert from 3D space to a 2D image plane, the locations of the centroids of the circular targets must be known or precisely calculated in at least one of the directions [30]. The VMD system is still under development in an ongoing effort to refine and automate measurements [31-33].

This method was implemented at the Langley basic aerodynamic research tunnel (BART) to measure the deformation of the UF MAV flexible wing while gathering loads data to compute the stability derivatives and coefficients [6, 32]. The measurement method developed in this paper is similar to the VMD system and could be described as an in-flight version with an alternative calibration method.

2.2.3 Projection Moiré Interferometry

Projection moiré interferometry (PMI) is an optically based global measurement technique that was custom adapted by NASA for use in wind tunnels. PMI is used to measure out-of-plane deformations of models. PMI’s global measurement ability enables the collection of data to be acquired over the entire camera field-of-view, without the use of targets or contacting the surface being measured [30].

The PMI system relies on a grill of equally spaced, parallel lines projected onto the wind tunnel model surface. The optical axis of the projector system is typically aligned such that it is perpendicular to the surface being measured. Images are gathered with a charged coupled device
(CCD) camera equipped with a narrow bandpass filter that is matched to the projector illumination wavelength. The camera is positioned to view the model at a 30°-45° angle inclined from the projector optical axis [30].

Camera perspective distortions are removed by image processing routines. Further image processing routines “interfere” the images with a generated reference grid. The resulting interferograms contain moiré fringes patterns. These patterns are further processed to obtain a quantitative, spatially continuous representation of the model surface shape or deformation [30]. This method was implemented at the Langley BART to measure the deformation of the UF MAV aeroelastic deformable wing while gathering loads data to compute the static stability derivatives and coefficients [6, 34].

2.3 Flight Test Instrumentation

Previous flight tests have incorporated the use of a Micro Data Acquisition System (MDAS) developed by NASA Langley research facility specifically for MAV applications [35]. The MDAS incorporates 3-axis linear accelerometers and 27 free analog voltage channels for any sensor that has the proper interface, such as airspeed, altitude, strain sensors, thermocouples, or servo potentiometer voltage [14]. The data is sampled at 50 to 100 Hz and is recorded in a 4 MB flash chip on board the craft, which can then downloaded to a PC at the end of each flight [36].

Information gathered from this system was implemented to examine stability and controllability for aircraft with wingspans of 12” and 24” that incorporated active wing warping for flight control [14, 35-38]. In the same investigations a camera was mounted looking at the wing, this was to monitor the morphing mechanism and observe flexible deformations [37]. No measurements of wing deformation were made.
Autopilot systems have also been utilized to collect flight data. Autopilots require readings such as accelerations, global positions system (GPS) location, and airspeed to carry out their function. The systems typically record the collected data on board or if equipped with a transmitter device can relay the telemetry information to the ground station where it can then be recorded or examined in real time.

A method of recording RC pilot control input during flight was developed by the UF MAV team. Tests were conducted on the same MAV design with various stiffness wings, and center of gravity positions. The tests were also conducted in calm and gusty conditions. The system enables measurement and comparison of pilot workload and vehicle-handling qualities for various MAV wing designs [39].
CHAPTER 3
SYSTEM LAYOUT

3.1 Platform

The first generation MMALV had a 12” wingspan and was of conventional aft tail design with the incorporation of the flexible membrane wing concept. For the purpose of this investigation as well as supporting other ongoing research, the original MMALV was scaled up to a 16” wingspan. The new larger second generation MMALV, shown in Figure 3-1, allows for greater payload volume and weight. The MMALV’s wing is unique even among the UF MAV fleet in that it incorporates floating angled batten reinforcement (FA) for the membrane support structure. The term FA means that the battens are arranged in a radial angular pattern and are attached to the membrane material only instead of being aligned with the fuselage and attached to the leading edge like that of the batten reinforced (BR) designs. The FA design was chosen to allow for future development of a retracting wing feature. The various planform designs currently in use by the UF MAV team are shown in Figure 3-2.

The MMALV makes use of an AstroFlight 010 electric motor controlled by a Phoenix-25 electronic speed controller made by Castle Creations and powered by a 3-cell 1350 mAh Lithium polymer battery pack. The craft is controlled solely by rudder and elevator, which was actuated using micro servos manufactured by HiTec.

3.2 Camera

Wing deformations are three dimensional, spanwise, chordwise and vertical, which will from here on, be referred to as X Y and Z directions respectively. This directional convention is shown in Figure 3-3. Deflections in the Z direction are typically at least one order of magnitude greater than the deflections in the other two. This is supported by the author’s findings and observations from previous studies [3, 4, 17-20]. For simplicity, this work will only be
concerned with deflections in the Z direction, which will be referred to as W for the duration of this report.

The investigated method of measuring the wing deformation of a MAV while in flight consisted of a small camera rigidly mounted on the aircraft’s vertical stabilizer looking forward at the wing, which was outfitted with tracking points. The system has been termed Single Point Optical Tracking (SPOT). The proposed plan was to mount the camera in such a way that as much of the deformation as possible would be in the plane of the camera view, which would result in the highest resolution. With Z deflections being the only concern in this study a brief investigation into camera location revealed that mounting it high and far aft on the vertical stabilizer would provide the best vantage point.

The camera was to be mounted external and on a stabilization surface, therefore it was deemed prudent to minimize the size of the camera. The original camera selected was a color CCD snake type with a resolution of 380 lines. This camera was chosen for its form factor, in that the optical head and the processing board were mounted separately connected by a wire. This camera is presented in Figure 3-4. Unfortunately, during preparations for the flight tests the author accidentally electrically destroyed the two CCD cameras ordered, the second trying to figure out what went wrong with the first.

Due to time constraints, a suitable substitute was found on hand, a complementary metal-oxide-semiconductor (CMOS) type camera. The CMOS camera used has a comparable resolution and size to the CCD but falls short in other areas of quality, such as sharpness and color clarity.

The vertical stabilizer had to be extended and stiffened in order to accommodate the camera. This was accomplished by adhering a multiple layer carbon plate to the existing vertical
surface using cyanoacrylate (CA), glue typically used by model builders. A shim was constructed and installed in order to achieve a proper viewing angle. The camera was secured to the shim with CA and tied with Kevlar® thread for the flight tests. The camera location and mounting is presented in Figure 3-5. With the relatively low loads involved, the vertical tail being stiffened and the camera securely attached, it was assumed rigid so as that there was no movement of the camera relative to the fuselage or wing root. No perceptible relative motion was observed during the tests that would suggest otherwise.

3.3 Tracking Points

The primary source of data for this study was taken from image processing therefore attention had to be paid to color selection. The color of the wing was determined by the requirements of the VIC system, a dull tan with flat black speckles. These colors are used to reduce glare and provide distinguishable markings that the VIC software can locate and track. With these constraints in mind, a bright orange sticker material typically used to make visual marking on MAVs was selected for the tracking points. Using a hole punch for convenience and consistency the bright orange sticker material was cut into ¼-inch diameter circles. These circles were then securely adhered to the wing at a regular interval using CA, resulting in a local stiffening of the membrane material. This local stiffening was deemed acceptable given the scope of this work.

Two patterns were investigated, one aligned with the batten structure of the wing and the other aligned with the camera view. The former was intended to mark the areas suspected to have the maximum deflection. The latter was intended to ease processing. The two patterns are shown in Figure 3-6.
3.4 Angle of Attack Indicator

In order to establish the validity of SPOT, data taken in steady level flight at a measured velocity and AOA would be reproduced in the wind tunnel and corresponding measurements taken with the VIC to enable a comparison. To accomplish this goal two obstacles needed to be negotiated, finding the AOA and airspeed of the MMALV during flight. To that end, an AOA indicator was devised. The methodology used for the airspeed will be detailed in later sections.

The AOA indicator was a simple weathervane type that was mounted on the wing tip with a bracket fabricated from piano wire. The indicator was positioned above the wing surface a distance equivalent to one chord length at the span location where it was mounted. This location was chosen to place the indicator in the free stream airflow as much as possible, away from the propeller wash and aerodynamic effects of the wing. With location of the hinge point at the indicator, the twisting of the wing in flight was found to have little or no effect on the reading. The indicator and its mounting are presented in Figure 3-7.

The indicator was statically balanced to approximately horizontal and proved very responsive, indicating AOA changes even at a walking pace. Measurement was taken from the indicator optically using the previously discussed camera. The same bright orange marking tape was used on the indicator as was on the tracking dots. The method of calibrating and extracting the reading will be discussed in a later section.

3.5 Deformation Measurement Calibration

The calibration methodology for deformation measurement used was comparative based utilizing both VIC and SPOT. The VIC system was chosen for its ease of implementation and accuracy. The surface preparations required by VIC prohibited the presence of the SPOT tracking points during use. Therefore, both of the systems could not be employed at the same time.
time. The solution devised to obtain consistent deflections with use of either system at separate times was to make use of the wind tunnel.

The University of Florida’s Mechanical and Aerospace Engineering Department’s closed loop wind tunnel was used. This tunnel is an Engineering Laboratory Design (ELD) model 407B re-circulating type wind tunnel, which is located in room 125 of MAE-A, UF building 725. The tunnel has two test sections that can be utilized, a small section of 0.61 m x 0.61 m x 2.44 m and a large section of 0.838 m x 0.838 m x 2.44 m. An optical glass ceiling was used for the wind tunnel portion of this research. Further details and a flow field characterization of the tunnel with both test sections are reported by Sytsma [21].

The VIC was used to measure the model 3D geometry, as well as the in-plane and out-of-plane displacements. To capture the 3D geometry of a subject, the system utilizes synchronized cameras, each looking from a different viewing angles at the same target. The cameras were installed over the wind tunnel looking through the optical glass ceiling, as shown in Figure 3-8. The cameras were calibrated through the glass ceiling to ensure minimal distortion effects.

The VIC determines the displacements of the specimen by tracking the deformation of a random speckle pattern applied on the surface. The speckle pattern acquired by the digital cameras before and during loading is processed by finding the region in a deformed image that maximizes the normalized cross-correlation score with respect to a small subset of the reference image, which was taken when no load was applied at each angle measured [20].

Two continuous 250-Watt lamps were used to illuminate the wing surface. The background color and sheen on the wing’s surface was chosen to minimize noise that can result from glare and interfere with proper image processing. Further details on the application of the
VIC system in wind tunnel experiments are reported in [3, 4, 17-20]. The combination of this wind tunnel and VIC system has been previously utilized by Albertani [3].

The MMALV was equipped with a mounting bracket and installed on the wind tunnel sting balance. To avoid errors due to inconsistent results the propeller was removed during the calibration process. The wind tunnel was then run at a constant velocity of 13 m/s, as indicated by the tunnel instrumentation, and an AOA sweep was performed. The sweep was made taking data at 0, 3, 5, 10, 12, and 15 degrees AOA. On the first run, the VIC was utilized to measure the shape and deformation of the MMALV’s flexible wing. Next, the same platform was outfitted with the tracking points and AOA indicator and the wind tunnel run was duplicated. The results from the collected VIC data are shown in a later section. The presented VIC data has a tetrahedron superimposed on it representing the outline of the SPOT data for clarification and spatial referencing.

Video from the onboard camera was recorded on a Sony digital recorder and later transferred to the computer where still frame images were pulled. The images taken from the video were then processed through a custom Matlab code written by the author. The code found the centroids of each tracking point in pixels with reference to the image plane using the image processing toolbox commands incorporated into Matlab. These centroids were then sorted and stored in a specific order to ease future processing.

The locations of the centroids of the tracking points were determined for each angle of attack and a reference wind off condition. Utilizing this data the deflection of the centroid of each tracking point relative to the camera view plane could be determined in pixels. These deflections were stored in the same order established for the tracking points. The numbered order of the tracking points along with the location of each centroid is shown in Figure 3-9. A
brief investigation was made into the reference condition and it was found that the pitch angle had minimal or no effect on the location of the centroids in the image plane, and therefore only one reference image was needed.

The calibration curves established for each tracking point is a comparison of the displacement of each centroid location in mm, from the VIC data, and the corresponding displacement in pixels, from the SPOT data. In order to find the desired data points from the X Y Z locations and U V W displacements of the VIC data field, the X Y locations of the tracking point centroids needed to be found. The index that corresponds to the X Y location of the centroids would be the same index for the correct Z U V and W data.

With the X Y locations in mm and the centroid locations in pixels, a common basis needed to be found. This was accomplished by processing and comparing images taken of the MMALV wing from the VIC cameras with the tracking points installed and images produced by the VIC program with the data field overlaid. Examples of these images are shown in Figure 3-10 and 3-11.

The closest data point to the centroid location of interest was used, since the VIC data is a continuous and subtly varying surface the possible error introduced was considered minimal. The calibration curves for each tracking point and a bar plot of the normalized residuals for each curve is presented in Figure 3-12.

A linear assumption was made for the calibration curves. This assumption is supported from the calibration performed with the original CCD camera. The resulting curves from this first data set also showed a linear tendency. The results from the CCD based system calibration are presented in Appendix A.
The VIC software computes an origin and orientation for each data set and arranges the output data relative to it. Due to the change in angle and other variables, the orientation of the output data from one measurement to the next was not the same. A standard origin and orientation was chosen, full-field rotation and translation matrices were used to achieve the alignment with the angles being derived from each data set. Each VIC data set was properly aligned before it was utilized. A data set before and after alignment is presented in Figure 3-13.

3.6 AOA Indicator calibration

The measurement taken from the AOA indicator also required processing the captured images from the SPOT camera in the wind tunnel. In order to extract the data the pixels containing the orange marking tape were taken as data points. These data points were then placed on a scatter plot and a linear fit made through them. The angle of the slope of this linear fit was termed the indicated angle. An example is presented in Figure 3-14. The commanded angle of the wind tunnel was taken as the actual AOA and was measured with respect to the chordline of the wing root and the floor of the wind tunnel.

The indicated angle was plotted against the actual angle for the three velocities and six angles investigated. Another linear fit was made through the resulting scatter plot of 18 data points and was used as the AOA calibration curve. The AOA calibration curve is shown in Figure 3-15. A linear fit was assumed for the AOA indicator calibration curve based on the simplified reasoning that the angle shown from the camera’s perspective was a rotational change of coordinates from the actual angle of the indicator, which would not introduce any non-linearity.

The AOA indicator calibration curve from the original CCD camera is presented in Appendix A. This curve serves to support the linear assumption in the same way as the deflection calibration curves.
Figure 3-1. 16” Wingspan second generation MMALV.

Figure 3-2. Various Planform Designs in use by UF MAV team: Rigid (A), Batten Reinforced (B), Perimeter Reinforced (C), and Floating Angled (D).
Figure 3-3. Directional convention utilized.

Figure 3-4. Color CCD snake type camera.

Figure 3-5. Camera location and mounting.
Figure 3-6. The two tracking point patterns investigated, suspected maximum deflection (A), and ease of processing (B).

Figure 3-7. The AOA indicator and its mounting.
Figure 3-8. VIC system installation and setup.

Figure 3-9. The numbered order of the tracking points and the location of each centroid.
Figure 3-10. Example of image of MMALV through VIC camera with VIC data field overlaid, this is the standard output from the VIC software.

Figure 3-11. Image of MMALV through VIC camera with tracking points installed.
Figure 3-12. Calibration curves for each tracking point.
Figure 3-13. A VIC data set before and after alignment.

Figure 3-14. Image of the AOA indicator from SPOT camera and processed results.

Figure 3-15. AOA indicator calibration curve.
CHAPTER 4
FLIGHT TEST

4.1 Flight Test Setup

The flight test was conducted on the UF campus in a field typically utilized for flight-testing of other UF MAV designs. The test was conducted in the late afternoon, when lighting conditions were more favorable. The craft was flown by a RC pilot with visual contact.

The method used to estimate the flight speed involved two markers set at 15.24 m apart and a fixed camera approximately centered between the two markers and perpendicularly sat back at a distance of approximately 60 m. The test setup is shown in Figure 4-1. With the flight path being from one marker to the other, a crosswind condition steady at 3 m/s and gusting to 4.5 m/s prevailed as reported by a weather station that was also located on campus.

The SPOT equipped MMALV was flown over the two markers as straight and level as possible. Four such passes were made and each was in view of the fixed camera. The estimated velocity was found by examining the video of the fixed camera that was recording at the standard rate of 30 frames per second.

The largest contributing sources of errors involved in calculating the airspeed are parallax and temporal resolution. The parallax error is due to the possibility of the platform not flying directly over the markers but in front or behind the markers relative to the fixed camera. From the perspective of the fixed camera the same, known, distance would be traveled even though the actual distance traveled would be longer or shorter. Assuming the flight path was maintained within a corridor of 3 m either side of the markers, a difference of ± 1.5 m was possible from the assumed 15.24 m and the actual distance traveled.

The temporal resolution is a result of the camera utilizing the standard frame rate of 30 frames per second. As the frames were used to measure the time it took the craft to cross the
markers this resolution had a direct effect on the estimated airspeed. A quantified estimation of the two error sources discussed was found by artificially changing measurements taken by the amounts prescribed of ± 1.5 m in distance and ± 1/30\textsuperscript{th} of a second. The error estimations are presented in Table 4-1 along with the nominally estimated airspeed and AOA for each pass.

Various maneuvers were performed after the passes were made. The maneuvers included left and right banked turns, stalls, dives, and a spin. During the flight, the maneuvers were noted in the order performed. Due to the poor image quality of the CMOS camera and problems with lighting, results could not be extracted for all maneuvers. Measurements could be made for one negative AOA, three high AOA, one hard left and one hard right turn maneuvers as well as the four level passes. These results will be presented in subsequent sections.

The video feed from SPOT was recorded on a UF MAV lab ground station, which is equipped with a Sony digital recorder, video receiver and two flat panel antennas. The same onboard CMOS camera discussed previously was used. The recorded video was later transferred to the computer where the still images were captured in the same manner as previously discussed for the wind tunnel calibration data.

4.2 Processing Results

The images captured from the test flight had to be processed individually with custom threshold adjustments for each due to the varying lighting conditions encountered during the flight. The processed images were then run through the same centroid locating algorithm used previously. By comparing the located centroids and the location of the reference centroids, a difference was found between the two in pixels of displacement. These pixels of displacement were then put into the appropriate calibration equation for the corresponding tracking point to find the deflection in mm. The same reference image used in the wind tunnel was used to calculate the in flight results.
Due to deflections of an unanticipated magnitude on some of the images the forward most row of tracking points were not visible on two of the maneuvers investigated, the right and left rolls. For these maneuvers, only the portion of the wing visible was processed.

The method previously described to find the AOA of the MMALV was implemented on the same image used to obtain the deflection measurements. The AOA calculated utilizing the calibration curve was rounded to the nearest integer. The resulting resolution proved adequate for the purpose of this research and confidently encompassed possible errors from aerodynamic and optical influences.

A preliminary error and sensitivity analysis was performed on some of the computational aspects of the system. These aspects include the image thresholding, centroid-locating algorithm and the statistical error in the calibration equations. The analyses performed will be discussed in more detail in the conclusion section of this report.

4.3 Observations

The video captured from the SPOT camera reveals new insight into the dynamic behavior of the flexible wing. Most of the deflection takes place near the tip of the wing as is shown in nearly all of the following figures. Deflection in this outboard area was expected based on previously conducted studies that were reviewed in the first chapter of this report.

The leading edge spar cannot be observed in the SPOT camera view however, the bracket attaching the AOA indicator to the spar was visible. Throughout the flight, this bracket was observed changing angle relative to the camera, this indicated that the leading edge spar undergoes regular torsional deformations. This deformation is readily apparent with the onset of a vibration condition.

Several vibration modes were observed throughout the flight, most of them appearing in the outboard section and tip of the wing. These vibration modes appear to occur at relatively low
AOA. This reveals that the observed vibration is a situation of flow separation instead of a stall condition. The current state of the system is not of high enough fidelity to withdraw detailed or quantitative conclusions on such rapid dynamics.

A similar state was observed for the same craft in the wind tunnel portion of this work. A vibration mode was observed at 0 degree AOA and 26 m/s flow velocity. The vibrations subsided as the AOA was increased to 4 degrees, this coupled with observations made by Sytsma [21] it is believed that the vibration was due to flow separation along the lower surface.

4.4 Discussion of Deformations and Plots

The wing design utilized as the subject of the presented work featured combination characteristics documented by Albertani et al [3, 4, 17, 18, and 20] for the perimeter and the batten reinforced wings. The MMALV wing exhibited the twisting, or wash out, deformation tendencies of the batten reinforced design and the changes in camber of the perimeter reinforced designs. This behavior can be attributed to the floating angled batten configuration as well as the significant flexibility of the structural members of this particular wing.

A topographic representation of the wing in an undeformed state is shown in Figure 4-2. This geometric data was gathered utilizing the VIC system and is oriented as discussed earlier. The measurements from the SPOT system are presented in multiple methods to aid in the interpretation of the results.

The wing was sectionalized with lines that were aligned with the tracking points in the chord wise direction. This division is shown in Figure 4-3. A cross section view of the wing at each line was found from the VIC data of the undeformed state. The cross sections are shown in Figure 4-4.

The measurement data from both SPOT and VIC is presented in two forms, the amount of out of plane deformation, and the deformed shape. The amount of deformation data from the
SPOT system is superimposed over an image of the wing for spatial orientation. The displacement of each tracking point as measured with SPOT was added to the height of the corresponding location in the undeformed state to find the deformed shape. The deformed shape data collected from the SPOT system is presented in cross sectional plots with the undeformed cross sections previously discussed in figures 4-5 thru 4-12. The data presented in the deformed cross sectional plots is also shown topographically in figures 4-13 thru 4-24. The data for the four passes is presented with the corresponding VIC data from the wind tunnel tests for comparison in figures 4-13 thru 4-20.

The presented VIC data collected during the wind tunnel portion of this investigation has a tetrahedron superimposed on it representing the outline of the SPOT data for clarification and spatial referencing. The first wind tunnel run was made at 13 m/s and at -10, -5, 0, 3, 5, 10, 12, and 15 degrees, the measurements amassed were utilized to generate the calibration curves. The VIC data collected at 13 m/s is presented in figures 4-25 thru 4-32 to illustrate the effects of various AOA on wing deformations. This was done to enable a metric for a general comparison of the high and negative AOA SPOT data presented in figures 4-21 thru 4-24. Data collected from the flight test for a hard right and left turn is presented in figures 4-33 thru 4-34 due to deformed portions of the wing blocking the camera view of the forward most row of tracking points data could not be collected for the entire wing area.

The second wind tunnel run conducted at 20, 23, and 26 m/s at 0 and 4 degree AOA was made after the flight test was conducted and the flight speed and AOA for each pass calculated. The data from the second run was obtained to facilitate a comparison of data gathered from the VIC and SPOT at the same conditions of airspeed and AOA. The data from the SPOT shows a remarkable agreement with the VIC data. The minor differences that are apparent could be attributed to the dynamic effects of the quasi steady state flight conditions, which would effect
wing deformations and AOA readings. These dynamic effects were not measured or monitored. Even with the differences, the results are remarkably similar in shape and magnitude attesting to the validity of the system and method utilized.

<table>
<thead>
<tr>
<th>Pass</th>
<th>AOA (degrees)</th>
<th>Airspeed (m/s)</th>
<th>Paralax (%)</th>
<th>Temporal resolution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>20.79</td>
<td>5.00</td>
<td>4.76</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>26.93</td>
<td>5.00</td>
<td>6.26</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>19.90</td>
<td>5.00</td>
<td>4.55</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>22.85</td>
<td>5.00</td>
<td>5.26</td>
</tr>
</tbody>
</table>

Figure 4-1. Flight test setup.

Figure 4-2. Topographic representation of the wing in an undeformed state.
Figure 4-3. Chordwise sectional lines.

Figure 4-4. Cross sectional view of wing at each corresponding sectional line.
Figure 4-5. Cross sectional plots of flight-test SPOT data for pass 1: estimated 20.8 m/s and 4° AOA.

Figure 4-6. Cross sectional plots of flight-test SPOT data for pass 2: estimated 26.9 m/s and 4° AOA.
Figure 4-7. Cross sectional plots of flight-test SPOT data for pass 3: estimated 19.9 m/s and 3° AOA.

Figure 4-8. Cross sectional plots of flight-test SPOT data for pass 4: estimated 22.9 m/s and 4° AOA.
Figure 4-9. Cross sectional plots of flight-test SPOT data for high AOA 1: 18° AOA and unknown airspeed.

Figure 4-10. Cross sectional plots of flight-test SPOT data for high AOA 2: 20° AOA and unknown airspeed.
Figure 4-11. Cross sectional plots of flight-test SPOT data for high AOA 3: 24° AOA and unknown airspeed.

Figure 4-12. Cross sectional plots of flight-test SPOT data for negative AOA: -19° AOA and unknown airspeed.
Figure 4-13. Topographic plots of flight-test SPOT data for pass 1: estimated 20.8 m/s and 4° AOA.

Figure 4-14. Topographic plots of wind tunnel VIC data for 20 m/s and 4° AOA.
Figure 4-15. Topographic plots of flight-test SPOT data for pass 2: estimated 26.9 m/s and 4° AOA.

Figure 4-16. Topographic plots of wind tunnel VIC data for 26 m/s and 4° AOA.
Figure 4-17. Topographic plots of flight-test SPOT data for pass 3: estimated 19.9 m/s and 3° AOA.

Figure 4-18. Topographic plots of wind tunnel VIC data for 20 m/s and 4° AOA.
Figure 4-19. Topographic plots of flight-test SPOT data for pass 4: estimated 22.9 m/s and 4° AOA.

Figure 4-20. Topographic plots of wind tunnel VIC data for 23 m/s and 4° AOA.
Figure 4-21. Topographic plots of flight-test SPOT data for high AOA 1: 18° AOA and unknown airspeed.

Figure 4-22. Topographic plots of flight-test SPOT data for high AOA 2: 20° AOA and unknown airspeed.
Figure 4-23. Topographic plots of flight-test SPOT data for high AOA 3: 24° AOA and unknown airspeed.

Figure 4-24. Topographic plots of flight-test SPOT data for negative AOA: -19° AOA and unknown airspeed.
Figure 4-25. Wind tunnel VIC data for 13 m/s and -10° AOA.

Figure 4-26. Wind tunnel VIC data for 13 m/s and -5° AOA.

Figure 4-27. Wind tunnel VIC data for 13 m/s and 0° AOA.
Figure 4-28. Wind tunnel VIC data for 13 m/s and 3° AOA.

Figure 4-29. Wind tunnel VIC data for 13 m/s and 5° AOA.

Figure 4-30. Wind tunnel VIC data for 13 m/s and 10° AOA.
Figure 4-31. Wind tunnel VIC data for 13 m/s and 12° AOA.

Figure 4-32. Wind tunnel VIC data for 13 m/s and 15° AOA.
Figure 4-33. Amount of deformation data for the hard left turn 7° AOA unknown side slip and unknown airspeed.

Figure 4-34. Amount of deformation data for the hard right turn 9° AOA unknown side slip and unknown airspeed.
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

Flexible wings make use of inherent elastic properties of the wing for alleviation of gust loads. With the torsion axis of a wing of low torsional rigidity located ahead of the aerodynamic center for that wing a passively deformable system is created. This passively deformable system’s reaction is directly dependent on the wing loading and results in a washout condition. This adaptive washout reduces the total lift and bending moment at the wing root therefore reducing the dynamic response of the overall aircraft to sudden and temporary changes in flight conditions.

The SPOT system has proven to be effective at obtaining quantitative deformation information of a flexible wing in flight. This system is a valuable addition to the test instrumentation already utilized for the characterization of the flexible wing MAV. Information gathered with this system has provided new insights into the behavior of the flexible wing design as well as the flight envelope for this class of aircraft.

5.1 Discussion of Error and Sensitivity Analysis

The sensitivity analysis performed on the image thresholding, and centeroid-locating algorithm was accomplished by artificially moving the deformed location of the centeroid up and down by one pixel and recalculating the displacement. Changing the threshold parameters in the program would typically change the selected area around each tracking point equally in all directions. The centeroid was then calculated from the selected areas. The selected areas, typically comprising of 200 or more pixels, were generally arranged in an elliptical form. An example of a thresholded image is shown in Figure 5-1.

Considering the magnitude of the area involved and even changes induced by the threshold parameters it was concluded that a tolerance of ± one pixel is a reasonable if not conservative
assumption. The top and bottom lines marked by circles and squares are the centroid location tolerance bounds. The final effect of this tolerance is different for each point due to the differing slopes of the calibration curves.

Errors induced by the linear assumption of the calibration equations are plotted as error bars and were calculated utilizing the Matlab statistical toolbox. The possible error calculated and presented with the error bars relates to the goodness of the linear fit to the calibration data points collected and is related to the norm of the residuals presented with the calibrations curves in Figure 3-12. The previously presented cross sectional plots of each data set taken with the SPOT system are presented again with the error bars and pixel tolerance bounds included in Figures 5-3 thru Figure 5-10.

As mentioned in a previous section to obtain the VIC measurement during the calibration process the closest data point to the centeroid location of interest was used, since the VIC data is a continuous and subtly varying surface the possible error introduced was minimal.

5.2 Recommendations

Further research is needed to refine the SPOT system. Recommendations include the use of a high quality camera, more robust image processing procedure, and implementation of a flight data recorder to record airspeed and accelerations.

It is strongly recommended that a quality CCD camera be used if possible. Superior qualities, such as sharpness and color clarity would ease image processing as well as increase the accuracy of the centroid locations. In addition, the camera should be positioned such that the maximum wing deflection does not obstruct the view of any of the tracking points. In addition, the calibration curves should be expanded to include negative deflections.

It is also recommended that research be conducted into a more robust image processing procedure than the simple technique implemented for this initial investigation. With a more
robust image processing procedure in place and further refinement of the developed code the system could be automated to analyze each frame of a flight video. This capability would greatly increase the volume of information gathered and the understanding of flexible wing dynamics.

It is also recommended that investigations be conducted into different combinations of the wing skin and tracking point colorations that would enable the simultaneous use of the VIC and the SPOT. During the flight test, at certain attitudes, the red icarex would glow through the tan paint with a color similar to the orange used for the tracking points making automated differentiation difficult. Possibilities include the use of light outside the visible spectra such as using a special camera filter and markings that fluoresce in ultra violet or infrared.

Use of the VIC and SPOT simultaneously would greatly reduce the time consumption of the calibration procedure and would eliminate the need to use the wind tunnel. The wind tunnel was utilized to obtain a repeatable global deflection of the flexible wing. If the two systems could be used simultaneously, the requirement of repeatability would be eliminated and another method of global deformation could be implemented in the lab to provide the information necessary for calibration.

Implementation of a flight data recorder such as the Micro Data Acquisition system previously mentioned would greatly expand the overall capabilities and depth of information. The challenge that would be posed by such utilization is a common problem for flight test equipment, time synchronization. Possibilities include mounting multiple pitot tubes, one in the typical forward position, and the rest facing other directions. Such an arrangement could measure air speed and possibly gusts or at least provide an indicator of a gust encounter aside from the dynamic response of the platform.
Figure 5-1. Example of thresholded image, taken from flight test pass 1.

Figure 5-2. Image captured and processed for pass 1.

Figure 5-3. Pass 1 Cross section deformation with tolerance bounds and errorbars.
Figure 5-4. Pass 2 Cross section deformation with tolerance bounds and errorbars.

Figure 5-5. Pass 3 Cross section deformation with tolerance bounds and errorbars.
Figure 5-6. Pass 4 Cross section deformation with tolerance bounds and errorbars.

Figure 5-7. High AOA 1 Cross section deformation with tolerance bounds and errorbars.
Figure 5-8. High AOA 2 Cross section deformation with tolerance bounds and errorbars.

Figure 5-9. High AOA 3 Cross section deformation with tolerance bounds and errorbars.
Figure 5-10. Negative AOA Cross section deformation with tolerance bounds a
APPENDIX A
CALIBRATION OF CCD CAMERA

Shown below are the calibrations results using original CCD camera. These initial results are presented to further illustrate the linearity of the calibration curves using for the SPOT system. The repeatability of the calibration method is revealed with duplication of the linearity in the calibration curves utilizing two different camera types.

Figure A-1. AOA indicator calibration curve for first run with CCD camera.

Figure A-2. Tracking point calibration curves for first run with CCD camera.
Figure A-3. Image taken with CCD camera during the calibration process.

Figure A-4. Image taken with CCD camera during the calibration process with the AOA indicator installed.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

James D. Davis was born in a small Alabama town and raised in an even smaller Alabama town not far away. Growing up in a rural unincorporated area, he did some of the typical things like playing in the woods, riding his bike, and going to the river. He usually kept busy by helping his parents around the property and lending a hand wherever possible in building the house his parents still live in today. He tried his legs at running track and cross-country, which only ended in shin splints, sore knees, and short-term friends but it did aid in the discovery of his flat feet, which would later keep him out of the Marines.

Like many people growing up in small towns, he knew there had to be more somewhere else. After a brief interest in cars, he knew he wanted to do something mechanical. The fall following his high school graduation, he attended a technical school for aircraft maintenance from which he had received a pamphlet a few months prior to his graduation. The school was in yet another small Alabama town and this is where he discovered aviation. Not long before finishing the two-year program and earning his airframe and power plant mechanics certificate he decided he could do more than turn a wrench for a living, so he turned his attention to aerospace engineering.

Staying in-state, he attended Auburn University where he made several accomplishments including assisting in the design and development of a VTOL UAV with a team headed by Dr. Ron Barrett. The platform was almost a commercial success. While at Auburn, he was also the team captain of Auburn’s first entry to the SAE Aerodesign Heavy lift competition. Fielding an aircraft James co-designed the team won the east competition and placed second in the west competition. That was the closest any team had come to winning both competitions, rookie or otherwise.
A few weeks before his graduation ceremony from Auburn, he started work as a civil servant for the US Air Force at Eglin ABF in an internship program that included earning a master’s degree. With the constraints on school selection from the Air Force, he attended the University of Florida. At UF, he successfully struggled to complete the course requirements in the single calendar year allotted by the internship program. While attending UF James worked with the UF MAV team and Dr. Peter Ifju from which he learned of the flexible wing design on which this thesis is based. He is now looking forward to continuing his career in aviation at the Air Force Research Lab developing the future of UAV’s. His next academic goal is to earn a pilots license and never stop learning.