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Developmental Flight Testing of the SPAARO UAV *

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The Department of Aerospace and Ocean Engineering of Virginia Tech designed and built a new fleet of UAVs for use in augmenting the aircraft flight mechanics curriculum for undergraduates. This paper describes the flight testing of this new UAV. Issues associated with autonomous UAV flight testing are discussed and compared to traditional manned flight testing. Lessons learned during testing and data reduction are presented. Analysis results include specific excess power for a large portion of the UAV's flight envelope, stability derivatives derived from experimental test, and airspeed for best range in a glide. Further the short period, dutch roll, and roll modes are excited and then characterized for the UAV.

I. Introduction

The Department of Aerospace and Ocean Engineering at Virginia Tech has designed and built a new UAV called the SPAARO (Small Platform for Autonomous Aerial Research Operations). The SPAARO was built as an educational opportunity for students to design, build, and flight test a new UAV from a specific set of requirements. The SPAARO was designed by a master's level graduate student that then lead a team of undergraduates in building of the UAV. Design constraints included stability and performance requirements for airframe and sensor integration research and ease of manufacture and repair. A design drawing of SPAARO can be seen in Figure 1(a) , and a photograph of the SPAARO fleet ready for flight testing can be found in Figure 1(b) .

Two previously published papers address the development of the SPAARO. The design, building, and early testing of the SPAARO is discussed by Murtha et al.[1] The integration of SPAARO into the curriculum at Virginia Tech is discussed in Cotting et al.[2] This paper focuses on the flight testing of the SPAARO. Using a modified form of manned flight test techniques, the SPAARO was tested for standard performance data as well as for stability characteristics. Typical manned aircraft flight tests are done with a significant amount of situational augmentation buy a pilot. Since no pilot is present in an autonomous UAV, modifications to standard flight test techniques were required to place the aircraft in proper state to gather data during a flight test.

The flight tests were performed May 20-22, 2009 at Ft. Pickett, VA. Ft. Pickett is primarily used as an Army National Guard maneuver training center for the Virginia National Guard. It possesses a range for live fire artillery shells, and within that range airspace a dirt runway has been cleared for use in UAV flight tests. The geographic location of Ft. Pickett is shown in Figure 2 . The SPAARO flight tests at Ft. Pickett were designed to fulfill three objectives. First the data generated during design analysis was to be verified or corrected as required. Second, gaps in data from design analysis , such as rate derivative data, were to

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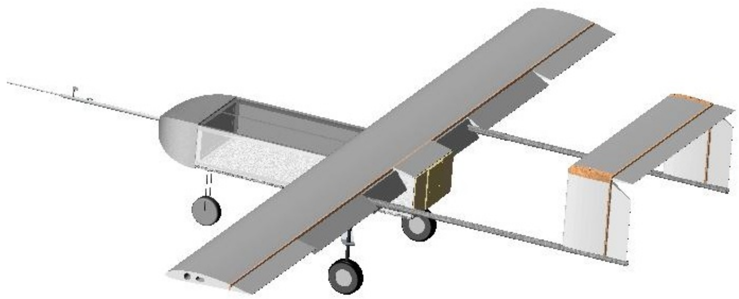
be filled such that a full 6-DOF simulation of the SPAARO could be augmented with data measured during flight test. Finally, data were needed to design laboratory experiments for future students as described in Cotting et al.[2] The data collected during these flight tests will serve as a baseline set of data that can be used in future course instruction, and also as a surrogate in the event that students can not collect adequate data in their own flight test laboratory experiments. The data will also be used in example calculations while teaching students how to reduce flight test data.



(a) SPAARO UAV designed and built by Va. Tech students.

(b) Three SPAARO UAVs readied for flight test at Ft. Pickett, VA.

Figure 1. SPAARO UAV

II. Flight Test Objectives

During SPAARO preliminary design, the aircraft was modeled in SolidWorks® . Using Drela's Athena Vortex Lattice (AVL) stability derivatives and basic aerodynamic parameters for the vehicle were calculated.[3] The SPAARO's mass properties were measured using scales, and the moments of inertia were measured using a bifilar pendulum.[4] The vehicle's characteristics as calculated during design were reported by Murtha et al.[1] A preliminary 6-DOF simulation model of the aircraft using these values was created in FlightGear.[5] When data were not available, data from similar aircraft were used to create a preliminary data set to be used in simulation. The FlightGear simulation[5]was used to create and tune gains for autonomous aircraft operation prior to first flight. These gains were used on initial airframe check flights. As the initial flight tests were performed, it became apparent that modification to the flight control gains were required in order to safely operate the aircraft. These gain modifications were required because the initial modeling did not match the aircraft's flight characteristics, and motivated further flight testing to characterize the SPAARO.

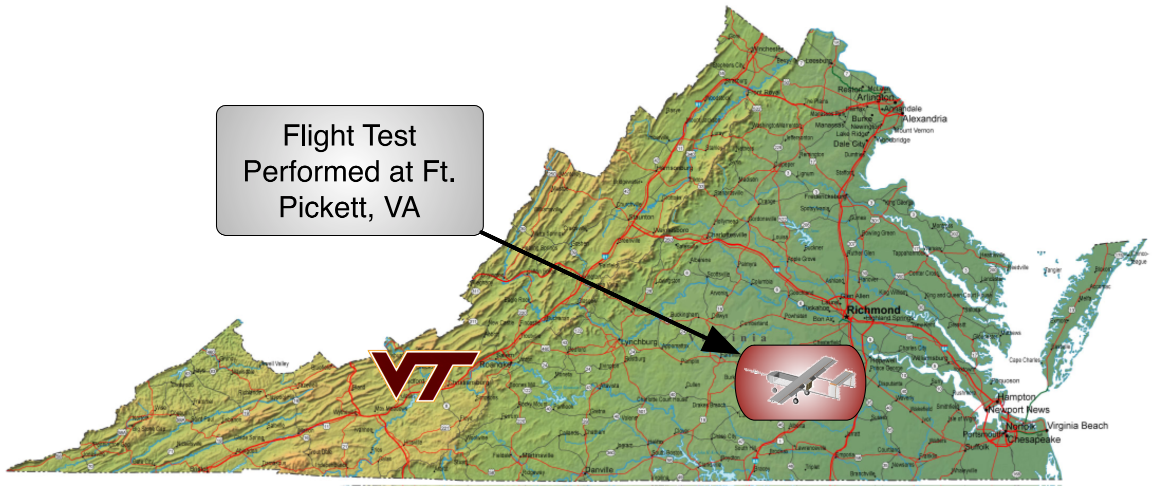


Figure 2. Ft. Pickett, VA.

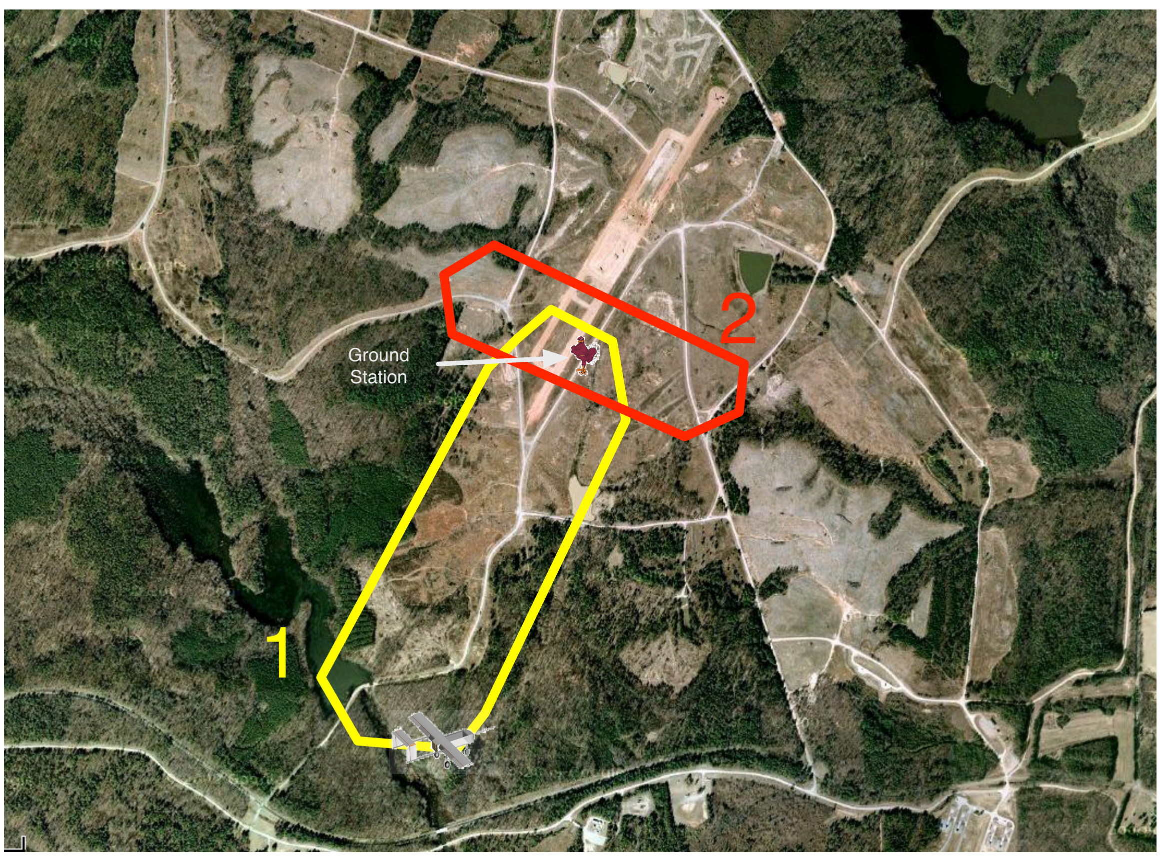


Figure 3. Flight test racetrack patterns used at Ft. Pickett.

A primary objective of these SPAARO flight tests was to characterize the aircraft so that the simulation model could be modified to accurately represent the SPAARO's flight dynamics. This characterization included modifying predicted data, as well as providing flight tested estimates where previous data had not existed. Data were also required to design laboratory experiments for students. This data set would also serve as a default data set in the event that future students are unable to successfully flight test the UAV. By collecting data during the design of the laboratory experiments, the flight tests done were able to serve as a "dry run" of testing for the student laboratories as described by Cotting et al.[2] . The SPAARO is to be used in aircraft performance classes as well as aircraft stability and control classes, where students will observe flight tests of the vehicle and then use those test results to calculate the vehicle performance and stability characteristics. The flight testing of the aircraft should be simple enough for undergraduates to perform with the aid of an experienced aircraft operator. The data reduction techniques must also be straight forward so that they can be readily demonstrated to an undergraduate class. The desired end result is a "real-life" application of a problem posed in a classroom environment that can be used to reinforce theoretical concepts. The following specific flight test objectives were created based on the high level objectives mentioned above.

1. Measure specific excess power over a large range of the aircraft's flight envelope.
2. Experimentally find L/D_{max} and verify calculations for best engine-out glide performance.
3. Identify parameters and characteristics of the short period mode.
4. Identify parameters and characteristics of the dutch roll mode.
5. Identify roll mode time constant.

III. Flight Test Instrumentation

The primary instrumentation for the aircraft flight test was the Eagle Tree Systems Seagull Pro Data Logging system. This was used instead of the native data logging present on the Cloud Cap Piccolo II autopilot due to concerns with ITAR restrictions. The inertial sensors on the Eagle Tree Systems Seagull Pro Data Logging system were augmented with an air data boom purchased from Space Age Control. This air data boom was mounted on the body axis of the vehicle, and was calibrated before flight in the Virginia Tech 6ft x 6ft Stability Wind Tunnel.[1] The air data boom measures angle of attack, angle of sideslip, and pitot and static pressure. The air data boom mounted on a SPAARO UAV is shown in Figure 4 . The Eagle Tree unit was able to give back up pressure readings, outside air temperature, inertial velocity, inertial altitude, and rotation rates and angles in pitch, roll, and yaw, as well as linear accelerations.

IV. Flight Test Plan

The flight test occurred over a period of three days, requiring two days of flight with one day in reserve. The first day was primarily used for a functional check flight of the flight instrumentation. During this functional check flight the level acceleration test method was tried to ensure proper functionality in the autopilot. The level acceleration points were re-flown on the next day along with the rest of the aircraft flight tests. In order to maintain consistency of the experimental data all flight tests were flown with the SPAARO airframe #3.

The flight test range used for this specific test at Ft. Pickett, VA allowed the aircraft to be cleared up to 18,000 ft. Ground level at the Ft. Pickett runway is 110 ft MSL. Using this range allowed initial tests to be done with less risk to the airframe by flying at a high initial altitude for the tests. The Ft. Pickett, VA range also allowed the specific excess power tests to cover a large range of the UAV's flight envelope.

A. Level Accelerations

The specific excess power of the SPAARO was measured using level acceleration test techniques.[6] The aircraft was commanded to accelerate from near stall speed to maximum speed while holding altitude constant and vertical acceleration near 1 g. Altitudes from 800 ft to 6000 ft MSL were flown in approximate

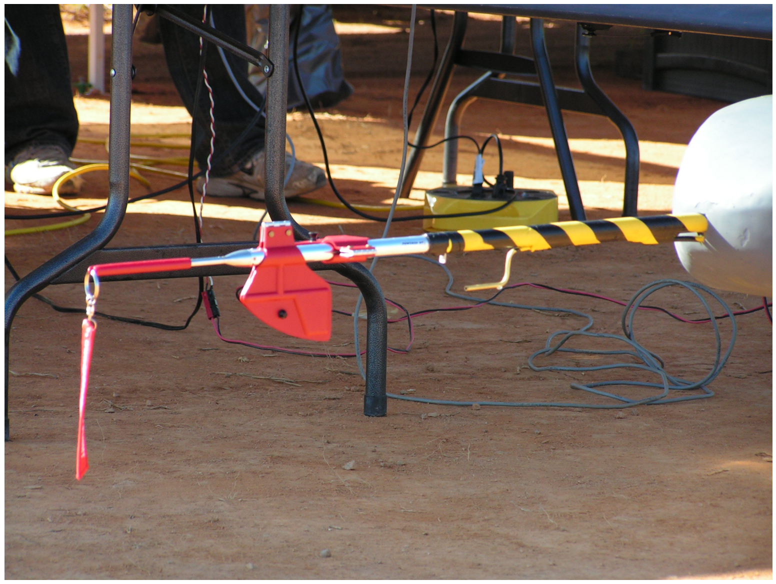


Figure 4. Air data boom mounted on SPAARO prior to flight testing.

300 ft increments. Denser altitude points were taken lower in the flight envelope since this is the area where students would be flight testing the aircraft for their laboratory experiments. The aircraft's autopilot was programmed to fly in an oval racetrack pattern aligned in the direction of the measured wind. A diagram of this racetrack can be found as course 1 in Figure 3 . The aircraft was commanded to fly just above an estimated stall speed at the beginning of a straight section of the racetrack, and once this speed was reached, the throttle minimum limit was set to 99.9%, while an airspeed above the known maximum airspeed was commanded. The aircraft's altitude hold loop gains were reduced to aid in keeping the normal accelerations within desirable limits. The altitude hold loops were still engaged, however, to ensure that the aircraft remained within desired altitude limits. The test was repeated for both upwind and downwind legs of the racetrack to account for effects due to wind.

For this flight test restrictions were placed as follows:

- altitude desired ± 50 ft, adequate ± 100 ft from reference altitude
- vertical acceleration desired $\pm 1/2$ g, adequate ± 1 g from reference 1g condition
- airspeed to be as low as possible without stalling aircraft
- maximum airspeed should be taken after aircraft has finished accelerating

Groundspeed and altitude were taken at discrete intervals during the acceleration profile. The groundspeed and altitude are then used to calculate specific energy during the acceleration profile using the following relationship:

$$E = mgh + \frac{1}{2}mV^2, \qquad P = \frac{\mathrm{d}E}{\mathrm{d}t}$$

$$E_h = h + \frac{1}{2g}V^2, \qquad P_s = \frac{\mathrm{d}E_h}{\mathrm{d}t}$$

.

A numerical derivative of the specific energy calculations was used to find specific excess power using the relationship:

$$\frac{\mathrm{d}E_h}{\mathrm{d}t} = P_s$$

for different times along the acceleration run for each altitude. Lines of constant specific excess power were then plotted as a contour plot for given altitudes and velocities.

B. Glide Testing

The glide testing flights were conducted to experimentally find the L/D_{max} for the SPAARO. The glide testing was also done to ensure that the autopilot control loops would give priority to maintaining airspeed over altitude in the event of an engine out. The flight tests were started at 2500 ft MSL to ensure adequate altitude for recovery from an inadvertent stall. The throttle maximum was set to 0.1%, and the aircraft was commanded to a desired airspeed. After a loss of altitude of 500 ft, the test was ended, and throttle was added to climb back to 2500 ft MSL. This was repeated for a range of airspeeds in order to find the airspeed corresponding to L/D_{max}. These tests were important for flight envelope clearance to give a maximum range in autonomous glide in the event of an engine out event. During the test both sink rate ($\dot{h}$) and airspeed (V) were recorded. Flight path angle (γ) was then calculated using the geometric relationship

$$\gamma = \sin^{-1}\left(\frac{\dot{h}}{V}\right).$$

Knowing the flight path angle, the L/D for that condition can then be calculated as

$$\tan(\gamma) = \frac{1}{L/D}.$$

C. Short Period Mode Identification

The short period mode identification test was the first of several parameter identification tests performed. The aircraft was trimmed at 1000 ft MSL and 90 ft/sec. Next a series of elevator doublets ($\pm 10^o$) were commanded to the aircraft over a range of frequencies. The frequencies were chosen to excite the aircraft's modal resonance frequency. Doublets were chosen over step inputs to reduce phugoid excitation during the tests. The air data recorded from the air data boom was used to augment inertial data in order to collect complete aircraft state information needed to calculate the aircraft short period mode.[7] The pEst software[8] from NASA Dryden Flight Research Center was used to compare flight test time histories to estimates generated during the UAV design. The stability derivatives were then optimized using pEst to match the time histories found in flight test. The pEst optimized stability derivatives are then able to used as flight validated values for future SPAARO simulations.

D. Dutch Roll Identification

The dutch roll mode identification test was performed at the same flight condition as the short period, an altitude of 1000 ft MSL, and an airspeed of 90 ft/sec. A rudder doublet of $\pm 20^o$ was commanded over various frequencies in order to excite the dutch roll mode. During flight testing, observers watched to ensure an adequate roll to yaw ϕ/β excursion was seen. The flight test results were reduced in a similar manner as the short period mode. Natural frequency and damping were graphically determined, and then the pEst software was be used to compare flight test time histories to those predicted with design estimates.

E. Roll Mode Identification

A roll pulse was also performed at the same trim condition as above. The roll pulse amplitude was chosen in order to assure the maximum roll rate was achieved. The aircraft was then re-trimmed and the bank command was reversed. The data collected was also reduced with pEst in order to determe lateral directional parameters of the aircraft.

V. Results

This section presents the results of the previously described flight tests. Issues specific to UAV flight test are addressed in each section where relevant. The results are broken into two major sections: the results that relate to performance testing, and the results that relate to parameter identification. Experimental results were collected in two flights, the first to obtain the performance results, and the second to obtain the parameter identification, or stability parameter results.

A. Performance Testing

1. *Specific Excess Power*

The level acceleration test technique was used to measure the specific excess power of the SPAARO UAV. Using racetrack 1 in Figure 3 two level accelerations per altitude were performed. One acceleration was done upwind, and another was performed downwind in order to cancel the effects of the wind on the testing. An example of data taken for this test can be found in Figure 5 . The particular test run shown is for 1700 ft MSL, and is representative of data taken over the entire range of altitudes, from 800 to 6000 ft MSL. The 1700 ft acceleration case was repeated at both the beginning and ending of the test matrix. Repeating the 1700 ft case was done because the aircraft fuel state could not be monitored in flight. The aircraft did not have a fuel gage or a fuel flow meter, so calculating the vehicle change in mass with respect to fuel burn was not possible. The two 1700 ft tests showed that there is a small change in vehicle performance for both low and full fuel cases as shown in Figure 6 . The disparity in specific energy shown in Figure 6 is caused by two factors. The tests were started at close, but not exact altitudes, and the initial airspeeds for the test were not the same.

One issue that presents itself with UAV flight testing is the prediction of stall. On a UAV it is very difficult to sense stall as in a piloted aircraft, and a margin above stall speed must be maintained at all times to ensure the safe flight of the vehicle. While the vehicle was "heavy" there was a reluctance to drop the initial speed to as low of a value as when the vehicle was "light." This also resulted in losing some of the desired low speed data in the power curves in Figure 8 . As shown in Figure 5 the normal acceleration during the test went beyond what would normally be acceptable for piloted aircraft, even though the gain on the aircraft's altitude hold control loop was reduced in order to minimize normal acceleration excursions while still maintaining desired altitude. The autopilot could not mimic the light touch that would normally be used by a human pilot, and resulted in excursions in energy that would normally be considered unacceptable in piloted aircraft. In order to account for the added noise in measurements a best fit was established for the calculated specific energy during the acceleration run. An example of the calculated results for a level acceleration can be found in Figure 7 . By smoothing the measured specific energy, a smooth power curve can be established. After all the data were reduced, a plot of specific excess power as a function of airspeed was created for each altitude run as seen in Figure 8 . The data were then reformatted into a traditional energy contour plot as found in Figure 9 . The dashed lines represent lines of constant energy. The flight test was halted before the aircraft's ceiling was encountered, capping the top of the power contour in Figure 9 . Concerns due to altitude effects on the aircraft such as cold temperatures and an inability to adjust mixture ratio on the engine were factors in halting the test at 6000 ft MSL. Another factor in halting the test was the amount of fuel required to perform the test at higher altitudes. Another flight test would have been required to complete higher altitude points, and the combination of the added flight test, the uncertainty of temperature effects on the aircraft system, and no foreseeable need to operate the UAV above 6000 ft MSL suggested that the test be ended before the aircraft's ceiling could be achieved.

The contour plot in Figure 9 has an interesting characteristic not normally present in a typical power contour plot. At approximately 1700 ft MSL a widening of the contour is present across the entire speed regime. At first this result was puzzling during the data analysis. Upon further investigation, this appears to be an artifact of using an engine without a supercharger, and with a fixed mixture ratio carburetor. From Figure 9 it is apparent that the carburetor is tuned for optimal operation at 1600 ft MSL.

2. *Best Glide Condition Test*

To test for best glide condition, the autopilot was set to maintain a constant airspeed with the throttle set to idle. This test was performed to verify that airspeed would be held constant at the expense of altitude in the Piccolo autopilot, and to also find the best airspeed to maintain in the event of an engine failure during flight. The same ractrack pattern used in the level acceleration testing was used in this test. The aircraft was flown at 2500 ft MSL in order to provide adequate altitude to recover from a stall. While the test was flown on autopilot a human pilot stood ready to take control of the aircraft in the event of an aircraft stall. Without the benefit of motion sensation with a pilot on board the aircraft, the stall onset could not be easily predicted. Several tests were aborted at the low end of the flight test due to stalls. Once the test commenced, a constant sink rate was measured for a commanded airspeed with the throttle set to idle. The

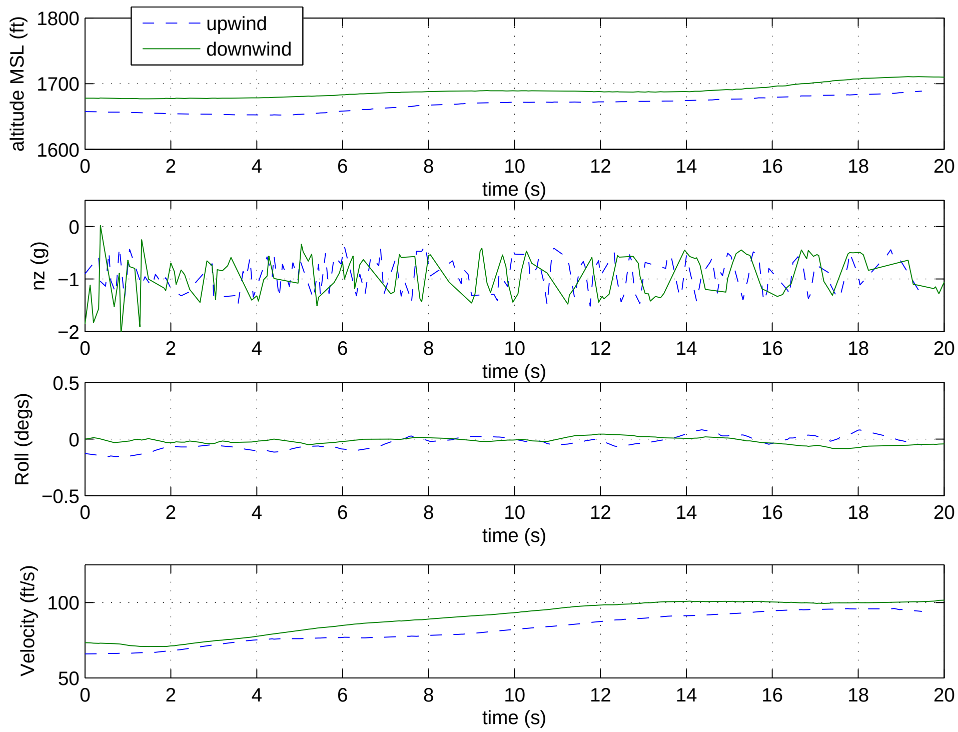


Figure 5. Sample flight test data from level acceleration at 1700 ft.

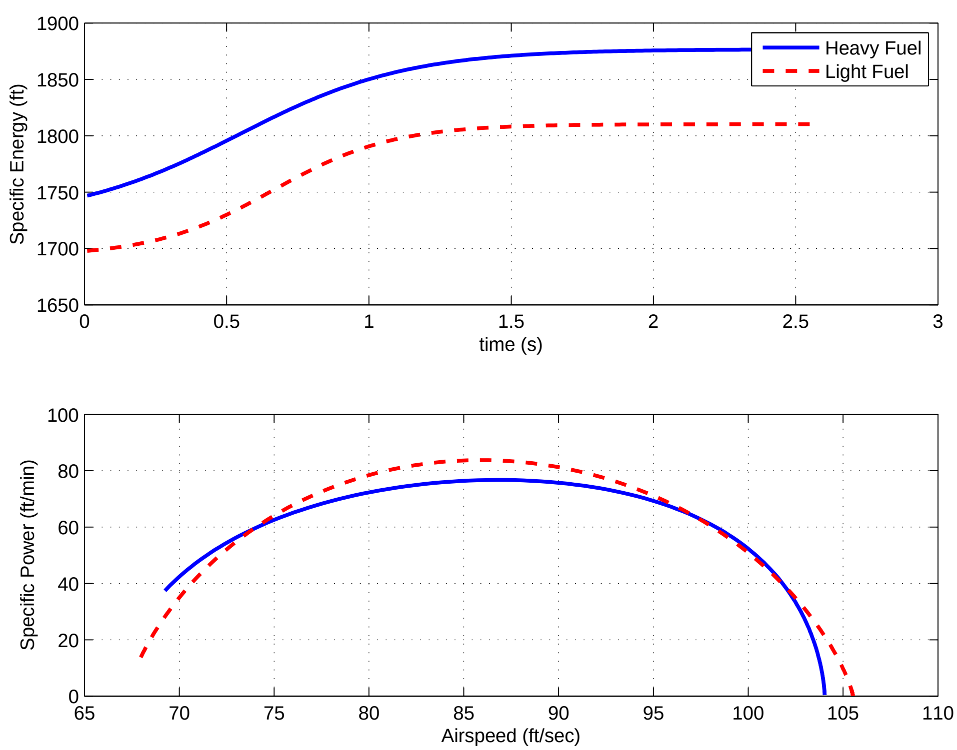


Figure 6. Sample reduced flight test data from heavy and light level acceleration at 1700 ft.

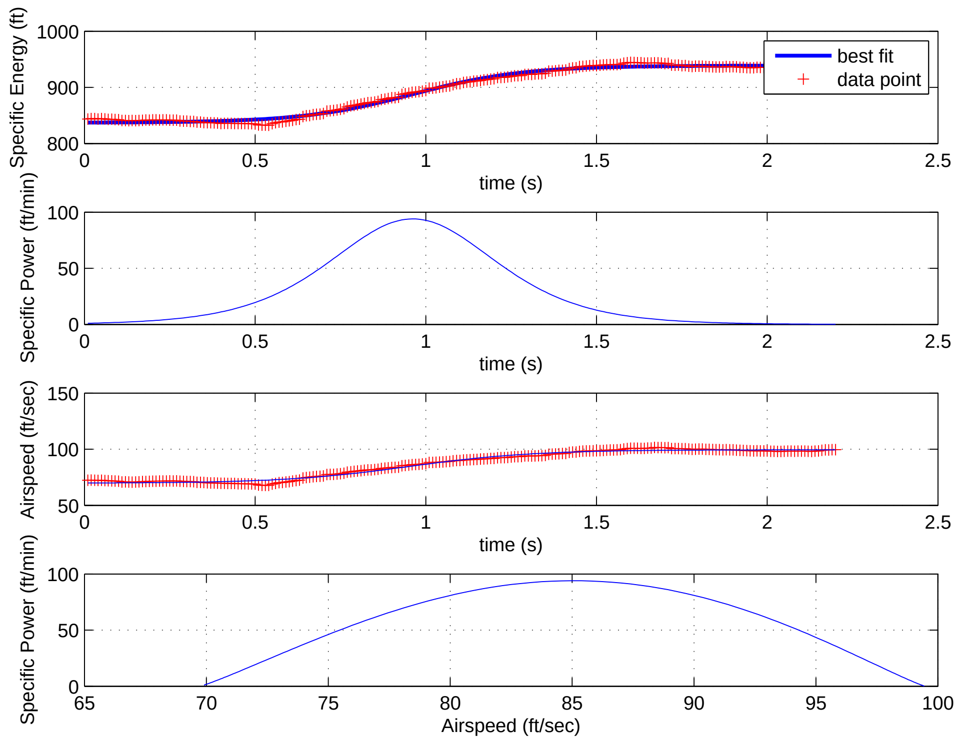


Figure 7. Sample calculation results from level acceleration at 800 ft.

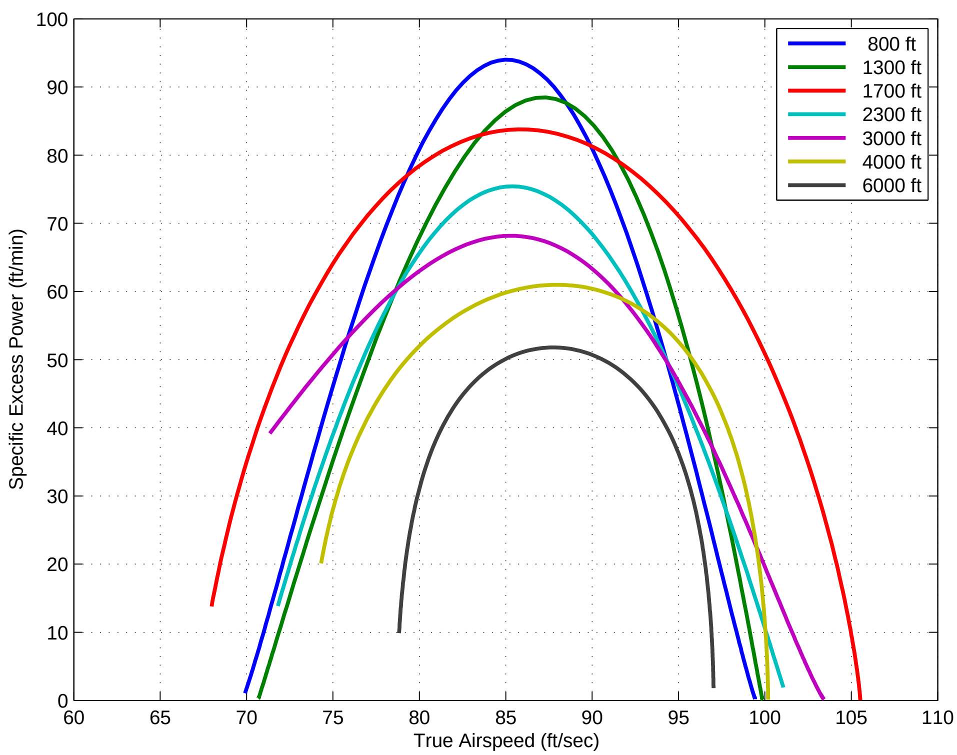


Figure 8. Power curves taken from level acceleration testing.

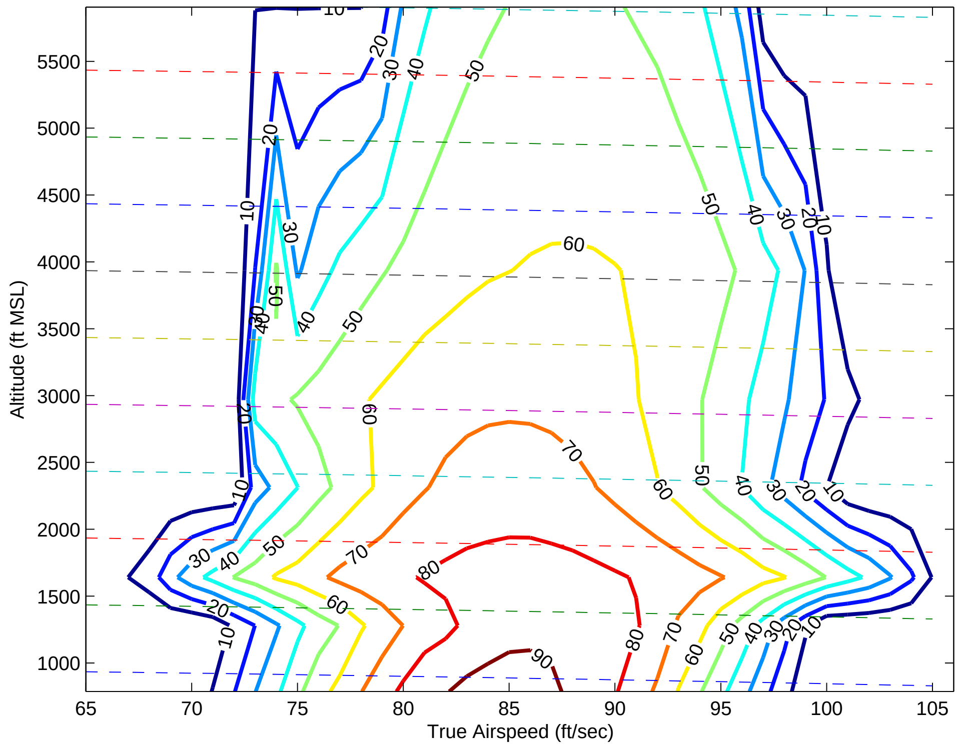


Figure 9. Power contour plot taken from level acceleration testing

results of the test can be seen in Figure 10 . A best fit quadratic trend was plotted for the data points in Figure 10 . The flight path angle and L/D were calculated for each airspeed and are presented in Table 1 . From this data with engine out, the best airspeed to maintain during flight would be 77 to 79 ft/sec. Commanding this airspeed will allow for the best chance of bringing the SPAARO back to the runway or a safe landing site while engine restart procedures are initiated.

Airspeed (ft/sec)	Flight Path Angle (deg) γ	L/D
58	46	1
77	8	7.12
79	8	7.15
82	9	6.6
92	12	6.65
105	25	2.58

Table 1. SPAARO Glide Data

B. Parameter Identification

For the parameter identification tests, a dedicated flight test was performed. For these tests racetrack # 2 in Figure 3 was used. The aircraft was trimmed at 1000 ft MSL and 90 ft/sec before starting each parameter identification test. Doublets were commanded separately to the elevator, aileron, and rudder. Using the parameter estimation software pEst version 4.0 from NASA DFRC, the flight test results were analyzed in order to determine vehicle stability derivatives from flight testing.

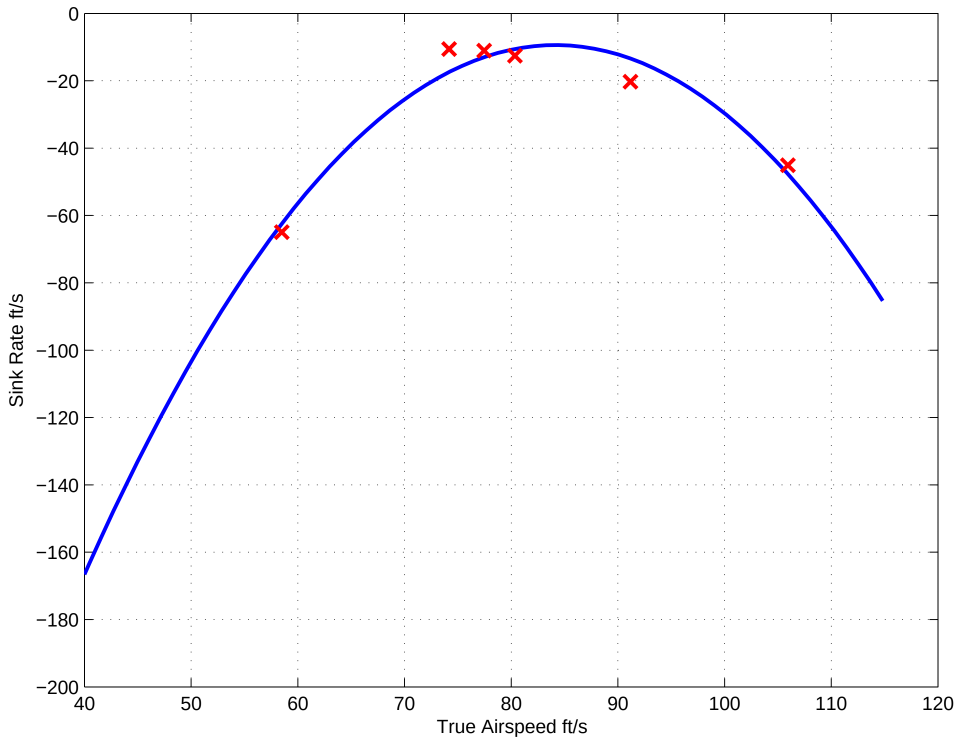


Figure 10. Sink rate in glide for various tested airspeeds.

1. Short Period

The short period parameter identification was performed by a series of elevator doublets excited by a range of frequency inputs. An elevator doublet was introduced with a half period of 200, 400, and 600 ms. A doublet was chosen over a step input in order to reduce the phugoid interaction with the short period. A sample time history is presented in Figure 11 where the elevator was excited with a half period of 600 ms. Results from the flight test time histories were analyzed with the pEst software. Figure 11 gives a comparison between the flight test time history (measured data) and the time history best match as generated by pEst (estimated data). For brevity the 200 and 400 ms results are not listed. The 600 ms test case is presented because it demonstrated the largest amplitude response for the control input. Further analysis of the short period response found it to be deadbeat using graphical techniques,[7] inferring that the damping ratio of the short period $\zeta > 0.5$. Comparing the time histories from flight test, the amplitude of pitch rate, angle of attack, and pitch attitude all continue to increase as the input frequency decreases. While an exact natural frequency can not be determined from the data analyzed, the natural frequency of the short period can be implied to be $\omega_n \leq 5.25\ rad/sec$. The stability derivative results from the pEst can be found in Table 2 .

Introducing a doublet into the Piccolo autopilot was relatively easy with the existing controller software. In order to narrow the natural frequency of the short period, however, a frequency sweep should be introduced into the control software. This feature is not present in the current flight software, and introducing it would be difficult in its current configuration. Future tests with lower frequency inputs should be conducted on this airframe to bound the short period natural frequency.

2. Dutch Roll

The dutch roll parameter identification was tested by a series of rudder doublets excited by a range of frequency inputs. A rudder doublet was introduced with a half period of 200, 500, and 750 ms. The flight test time history of the 750 ms case can be seen in Figure 12 and Figure 13 . Just as in the short period case, pEst was also used to estimate parameters required to reproduce the flight test time histories.

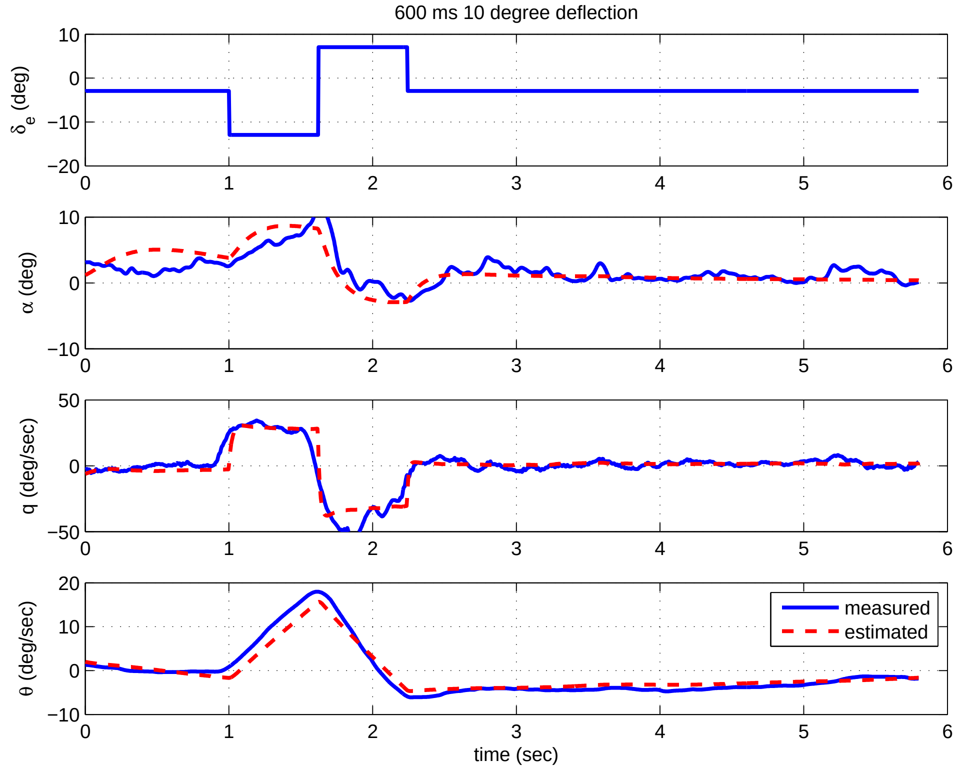


Figure 11. Sample flight test and estimation data from pitch doublet.

The matching of the pEst estimated and flight test time histories can be seen in Figure 12 and Figure 13 . For brevity the other results are not shown. The response in this case was not deadbeat, so a graphical analysis[7] could be used to determine the damping ratio and natural frequency of the dutch roll mode. The damping ratio for the relationship between yaw rate and rudder input is $\zeta = 0.32$, and the natural frequency is $\omega_n = 4.15\ rad/sec$. The damping ratio for the relationship between sideslip and rudder input is $\zeta = 0.15$ and the natural frequency is $\omega_n = 4.4\ rad/sec$. The stability derivative results from pEst can be found in Table 2 .

Visual contact with the aircraft was kept to ensure the dutch roll was excited. While the SPAARO exhibited a large enough dutch roll response to be visually verified from the ground, other UAVs may not exhibit a large dutch roll response. The use of a camera mounted so that it is pointing out one of the wings of the aircraft would be helpful to ensure that the proper response is being generated.

3. Roll Mode

The roll parameter identification was tested by a series of aileron pulses excited by two different frequency inputs. A roll pulse was introduced with a half period of 200 ms and another at 400 ms. An example of the flight test time history for the 400 ms case can be found in Figure 14 . Just as in the previous two cases, pEst was used to estimate parameters to reproduce the flight test time histories, and the matching estimated time history can be seen in Figure 14 . Using graphical techniques[7] the roll mode time constant for the roll rate to aileron input was found to be 0.11 seconds. The stability derivative results from the pEst can be found in Table 2 .

VI. Lessons Learned

The flight testing of a UAV presents several challenges that are different from piloted flight test. The differences between UAVs and piloted aircraft cause modification in testing methodology, but do not neces-

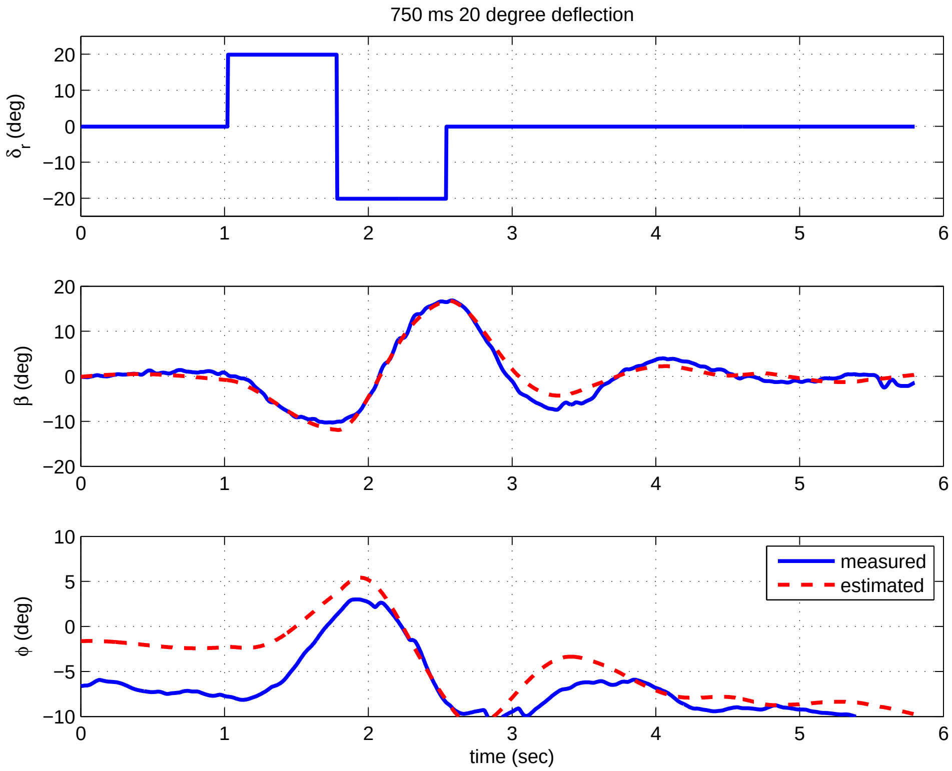


Figure 12. Sample flight test and estimation data from rudder doublet.

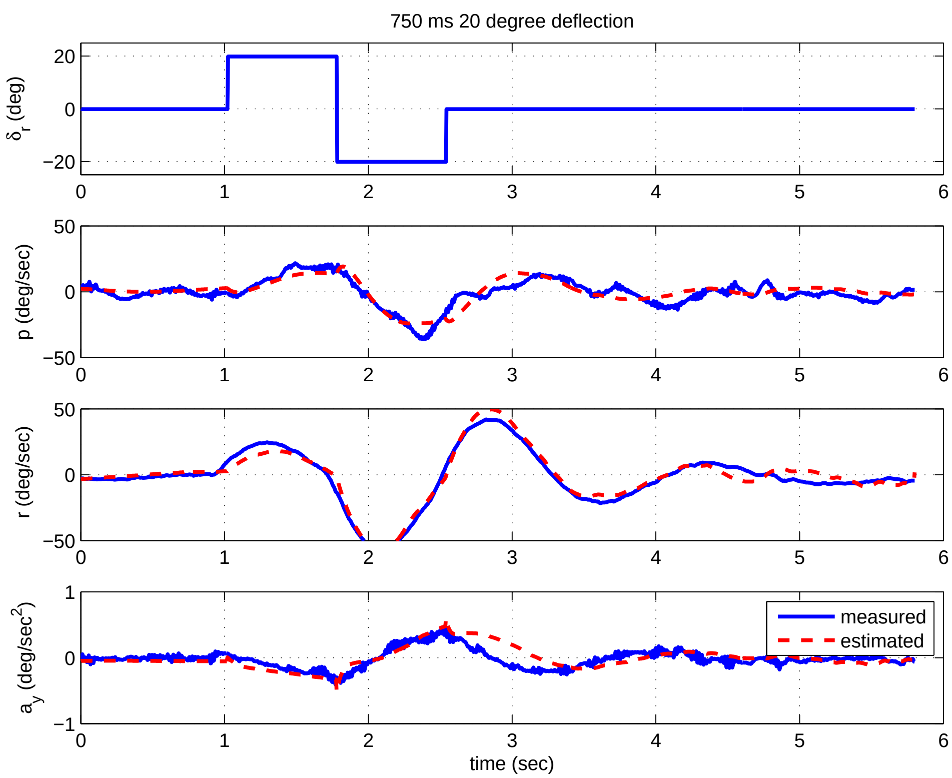


Figure 13. Sample flight test and estimation data from rudder doublet.

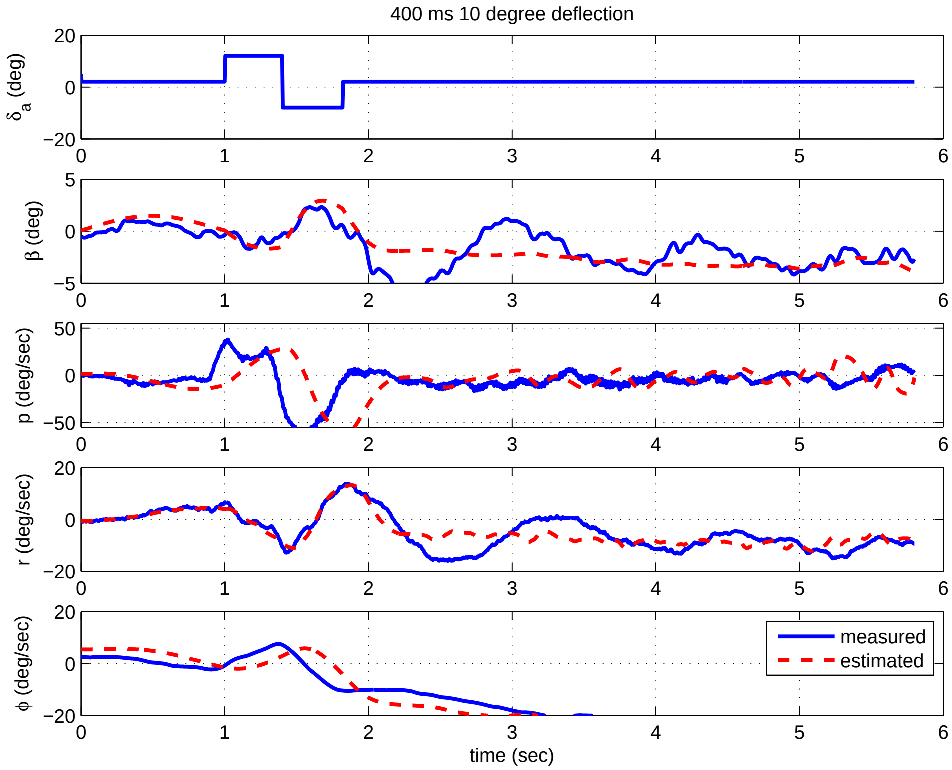


Figure 14. Sample flight test and estimation data from aileron pulse.

$C_{m\alpha}$	C_{mq}	$C_{M\delta_e}$		
-0.015	-1.76	-0.471		
$C_{y\beta}$	C_{yp}	C_{yr}	$C_{y\delta_a}$	$C_{y\delta_r}$
0.02	0.10	-0.04	-0.014	0.001
$C_{l\beta}$	C_{lp}	C_{lr}	$C_{l\delta_a}$	$C_{l\delta_r}$
-0.001	-0.011	0.004	-0.0015	-0.00025
$C_{n\beta}$	C_{np}	C_{nr}	$C_{n\delta_a}$	$C_{n\delta_r}$
0.0017	0.006	-0.003	-0.018	0.0004

Table 2. SPAARO stability derivatives. All derivatives estimated by pEst from flight test time histories are per degree, for a speed of 90 ft/sec.

sarily require new test methods. Several lessons were learned during the testing of the SPAARO, and are highlighted here. First, the situational awareness that a pilot provides during a flight test is often invaluable, and provides insight that is difficult to readily interpreted in the data stream. With a UAV no pilot is present on board the aircraft, and situational awareness is primarily provided by ground observation. The only results from testing are in the data stream telemetered from the test aircraft. Visual reference was kept on the UAV as much as possible in order to maintain situational awareness that would normally be provided by a pilot. While that awareness was decreased from being on board an aircraft, it still proved valuable in realtime assessment of maneuvers. A video camera on board the aircraft would further aid in situational awareness giving a "pilot's eye view" of the test as it is being conducted.

Just as in piloted testing, a close coordination between the flight test engineer, ground station operator, and the UAV pilot was required to ensure the test objectives were accomplished. Flexibility was also required by all three persons in order to adapt in real time to the aircraft response during the flight to ensure that the proper data could be recorded with minimal flight time. Unfortunately realtime access to the data recorded for the flight test was not available to the flight test engineer, and as such monitoring the flight test data was not possible. To ensure tighter bounds on the flight condition during tests a real time data monitoring system should be present, and a second flight test engineer to monitor the data. The use of two flight test engineers to monitor data and visually monitor the aircraft would aid in keeping situational awareness as well as ensure data integrity. This level of staffing is markedly different than that required for a piloted aircraft. Often these tests only require a pilot, or a pilot and a flight test engineer to complete. With the tests conducted with the SPAARO a team of three individuals was required, and a team of four would have been more effective.

Having a range where the flight of the aircraft was minimally restricted proved to be a valuable resource, allowing engineers to focus on flight testing instead of de-conflicting range assets that are often present in large scale aircraft testing. The proper instrumentation is also key to the successful completion of any test. The air data boom was necessary to measure angle of attack and sideslip for parameter identification. The full scale UAV with air data boom was calibrated beforehand in a wind tunnel. This greatly reduced the amount of calibration time with ground runs prior to flight that are required on piloted aircraft. Integration of the air data boom can be a much bigger issue with a UAV than a piloted aircraft. The size of the instrument relative to the size of a UAV is a significant factor. In the case of the SPAARO the UAV was large enough to carry a commercially available air data boom. Special structural mounts were required, however, on the UAV to keep the air data boom properly aligned and isolated from vibration during the flight test. The use of a pusher prop also was a significant benefit to reducing aerodynamic interference on the air data boom.

One advantage to flight testing a small UAV is that the fuel fraction of the aircraft was small, and concerns that normally occur in large scale flight testing relating to the fuel state of the aircraft were not present. While this proved to be convenient, it was also a hindrance in data collection. A UAV often does not have a fuel gage or fuel flow meter since the close monitoring of fuel state is not as critical as in piloted aircraft. A fuel gage or a fuel flow gage would have been extremely helpful in maximizing the flight time of the aircraft. It would also allow for added information to be collected during level accelerations so that minimum fuel to altitude schedules could be created.

VII. Conclusions

Using a flight test program patterned after piloted aircraft a UAV has been successfully flight tested to determine performance characteristics as well as stability and control data. The flight test program was further able to complete all of its desired flight test objectives. Unique challenges related to the small size of the aircraft as well as the lack of a pilot caused modification in flight test methods, but not a need to make large changes to traditional piloted flight testing methods. Using data reduction techniques normally used for piloted aircraft the SPAARO aircraft has been characterized. The data presented in this paper will be used for simulation of the SPAARO to aid in control law design as well as a teaching aid for future students. A series of lessons learned from this flight test program have been compiled and presented for future tests.

References

[1]Murtha, J. F., Cotting, M. C., Techy, L., and Woolsey, C. A., "The Educational Impact of Designing, Building, and Testing a New UAV form Curriculum Enhancement," 27^{th} *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, No. AIAA-2009-5851, AIAA, Chicago, Illinois, August 10-13 2009.

[2]Cotting, M. C., Murtha, J. F., Techy, L., and Woolsey, C. A., "Examples of Augmentation of an Atmospheric Flight Mechanics Curriculum with an Unmanned Aerial Vehicle," 27^{th} *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, No. AIAA-2009-5852, AIAA, Chicago, Illinois, August 10-13 2009.

[3]Drela, M. and Youngren, H., *Athena Vortex Lattice (AVL)*, http://web.mit.edu/drela/Public/web/avl/, version 3.27 ed., 2009.

[4]Jardin, M. R. and Mueller, E. R., "Optimized Measurements of UAV Mass Moment of Inertia with a Bifilar Pendulum," *AIAA Guidance, Navigation and Control Conference and Exhibit*, No. AIAA-2007-6822, AIAA, Hilton Head, SC, August 20-23 2007.

[5]Open Source, *Flightgear*, v. 1.9.1, http://www.flightgear.org/, 2009.

[6]Gallagher, G. L., Higgins, L. B., Khinoo, L. A., and Pierce, P. W., "U.S. Naval Test Pilot School Flight Test Manual, Fixed Wing Performance," Tech. Rep. USNTPS-FTM-NO. 108 (Preliminary), Veda Incorporated Contract N00421-90-C-0022, 30 September 1992.

[7]Aircraft Division, "U.S. Naval Test Pilot School Flight Test Manual, Fixed Wing Stability and Control: Theory and Flight Test Techniques," Tech. Rep. USNTPS-FTM-No. 103, Naval Air Warfare Center, Patuxent River, Maryland, January 1997.

[8]Murray, J. E. and Maine, R. E., "pEst Version 2.1 User's Manual," Technical Memorandum 88280, NAS, Edwards Air Force Base, CA, September 1987.