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Methodology for Designing Dynamically-Scaled Flight Testing Research with the Avistar Series of UAVs

Or D. Dantsker*
Indiana University, Bloomington, IN 47408

This paper presents methodology to compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. The research will utilize two commercial-off-the-shelf (COTS) geometrically similar aircraft: the Avistar Elite, which has been extensively characterized in previous work, and the approximately 50% larger, Avistar 30cc. This research effort aims to modify the larger Avistar 30cc into a dynamically-scaled-up version of the baseline Avistar Elite aircraft, using the methodologies described within the literature and with results within the error margins of previous dynamic-scaling efforts. The planned research effort will specifically target longitudinal flight test maneuvers, as these longitudinal motions are typically not coupled to lateral motions simplifying the process. Thus, this paper discusses the dynamic-scaling process, Avistar testbeds, instrumentation, and aircraft development and testing plans, therefore forming a basis for future research.

Nomenclature

AHRS	=	attitude and heading reference system	*IMU*	=	inertial measurement unit
CAD	=	computer aided design	*PWM*	=	pulse width modulation
COTS	=	commercial-of-the-shelf	*Re*	=	Reynolds number
DOF	=	degree of freedom	*RC*	=	radio control
ESC	=	electronic speed controller	*UAV*	=	unmanned aerial vehicle
GPS	=	global positioning system			

I. Introduction

In the past several years, there has been a major increase in the popularity of unmanned aerial vehicles (UAVs) for military, commercial, and civilian applications. Part of this uptrend in UAV use includes increase in the research related to them. There have been UAVs used to study aerodynamic qualities,[1,2] especially in high angle-of- attack conditions.[3–5] Others have been used as testbeds to develop new control algorithms.[6–11] Additionally, some unmanned aircraft are used as low-cost stand-ins for experiments that are too risky or costly to perform on their full scale counterparts.[12–17] Yet other times, unmanned aircraft are developed to explore new aircraft configurations[18–21] or flight control hardware and software.[22–26]

Though a large number of studies have been conducted using free-flying scaled models, there is very little flight test data publicly available that can be used to develop scaling projects. Scaling laws are typically used to design and validate dynamically scaled models, whereas a emphasis is placed on matching predicted results using data obtained from flight testing.[27,28] Results from wind tunnel tests are typically validated using a calibration model,[29–34] which is typically not conducted for flight tests as it is not practically feasible due to limited time and resources. Though validating every dynamically scaled model is not feasible, the flight test procedures, development, and results can still be refined using a validated database as is typical for wind tunnel results.

*Assistant Professor, Department of Intelligent Systems Engineering, odantske@iu.edu

This paper focuses on developing the methodology to compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. The research will utilize two commercial-off-the-shelf (COTS) geometrically similar aircraft, the Avistar Elite, which has been extensively characterized in previous work,[35–38] and the approximately 50% larger, Avistar 30cc. As the Avistar Elite already has extensive flight and ground testing datasets, this research effort aims to modify the larger Avistar 30cc into a dynamically-scaled-up version of the baseline Avistar Elite aircraft, using the methodologies described within literature and with results within the error margins of other scaling efforts such as NASA AirSTAR.[12,13] The planned research effort will specifically target longitudinal flight test maneuvers, as these longitudinal motions are typically not coupled to lateral motions simplifying the process. This paper will therefore detail the scaling process, aircraft testbeds, instrumentation, and development and testing plans, forming the basis for this research.

This paper is structured as follows: Section II provides a description of the dynamic scaling methodology. Next, Section III presents and compares the Avistar aircraft. Afterwards, Section IV presents the instrumentation. Then, Section V discusses existing data sets and aircraft ground measurement including 3D scanning data, moment of inertia measurement, and propeller performance testing. And finally, Section VI will discuss the aircraft development and flight testing plan. The paper concludes in Section VII with a summary and statement of future work.

II. Dynamic Scaling Methodology

A dynamically-scaled model is a free-flying scaled aircraft model that is capable of simulating the relative motions of a larger full-scale aircraft.[39] This means that in a proportional period of time, the scaled model would react in a similar manner to external stimulus, such as control input and loads. Scaling is accomplished by matching simulatude parameters such as those described in Table 1. These parameters are derived from the law of square-cubes, which correlates the linear scaling of an aircraft geometry to a cubic scaling of the mass properties. In addition to scaling the mass properties of an aircraft, aerodynamic scaling is also applied to to model as the decreasing the geometry of the aircraft will change the Reynolds number (Re) of the model, which will effect flight test results within non-linear operating regimes such as stall. Aerodynamic scaling is typically accounted for by modifying the geometry of the wing planform of the dynamically scaled model, such that the airfoil lift curve slope, maximum lift coefficient, and moment curves match the full-scale aircraft in its operating regime. As the model is scaled down, the flight test maneuvers are time scaled by a factor of $1/\sqrt{n}$, meaning that model will perform a maneuver in less time than the full-scale aircraft. These models are typically used in the development of aircraft configurations and test flight controllers as they are a safer and more cost effective alternative to developing manned aircraft.

An example of a dynamically-scaled model is the NASA AirSTAR which is a 5.5% scale model of a general transport model (GTM) aircraft that wa used to research the motions of commercial transport aircraft flying outside of their fight envelopes.[12,13] The NASA AirSTAR was designed using the same scaling laws in Table 1, with the dynamically-scaled model matching the inertias by 3% and weight by 0.1%. Another example of a dynamically scaled model includes the GA-USTAR project which aimed to develop and test a 1/5th scale model of the Cessna 182 to model upset and stall recovery maneuvers for general aviation (GA) aircraft .[16,17,40] The GA-USTAR project was developed using a COTS ”Almost-Ready-to-Fly” (ARF) model aircraft, similar to the Avistar aircraft that are planned for this research effort. As upset and stall requires analysis within the non-linear operating regime of the aircraft, this project made also made use of aerodynamic scaling factors as well by modifying airfoil of the Cessna 182.[41] As the current scope of this project aims to evaluate the longitudinal characteristics of the Avistar aircraft within a linear operating regime, emphasis will be placed on the mass scaling aspect of the project, specially Iyy which is longitudinal/pitch axis of the aircraft.

Table 1: Derived Scale Factors based on Similitude Parameters

Parameter	Symbol	Scaling Factor
Geometric		
Length	l	n
Density	ρ	σ
Inertial		
Mass	m	σn^3
Moment of Inertia	I	σn^5
Kinematic		
Time	t	$\sqrt{n}$
Velocity	V	$\sqrt{n}$
Attitude	α'	1
Control Surface Deflection	δ'	1
Angular Rate	Ω	$1/\sqrt{n}$
Angular Displacement	ϕ'	1
Angular Acceleration	$\dot{\Omega}$	$1/n$
Linear Displacement	s	n
Linear Acceleration	a	1
Oscillatory Frequency	ω	$1/\sqrt{n}$

III. Aircraft, Comparison, and Specifications

The Avistar series of aircraft is comprised of the Great Planes Avistar Elite[42] and the approximately 50% larger, Great Planes Avistar 30cc,[43] and are shown in Figs. 1 and 2, respectively. The Avistar aircraft were chosen for the planned dynamically-scaled flight testing research as the smaller of the vehicles, the Avistar Elite has been extensively characterized in previous work, including flight testing,[37,38] ground measurement, and modeling and simulation efforts. These existing data sets are presented in Section V.

The Avistar Elite is a commercial-off-the-shelf (COTS) model aircraft designed for radio control flight training. Specifically, the aircraft has a fixed high-wing configuration and is primarily constructed from wood and plastic film covering. Given the aircraft's ease of construction and operation, robustness, re-configurablity, and procurement availability, it has made an excellent UAV research testbed;[44–48] and was also available for this research. The larger Avistar 30cc is also a commercial-off-the-shelf (COTS) model aircraft and is described as a "giant-scale" sport trainer, which enables the freshly minted pilot (who has graduated from the Avistar Elite) to move onto a larger aircraft. The

Figure 1: The flight-ready Great Planes Avistar Elite.

Figure 2: The flight-ready Great Planes Avistar 30cc.

Avistar 30cc shares the same airfoil and aircraft configuration as the Avistar Elite. Figs. 3 and 4 present the top and side views of the Avistar Elite and Avistar 30cc, which show relatively similar aircraft proportions.

Table 2 presents the physical specifications for the Avistar Elite and the Avistar 30cc and scale factors for each measurement. As can be seen in the table, the scale factors for the geometric measurements of the wing are between 1.45 and 1.50 while those for the horizontal stabilizer are between 1.34 and 1.48. Comparing the Avistar Elite and Avistar 30cc aircraft, they have nearly identical wing aspect ratios at 5.8 and 5.7, respectively; while their horizontal stabilizer aspect ratios are similar but not at close as 3.6 and 3.3, respectively. In general, the wings of the Avistar 30cc are scaled mostly proportionally to the Avistar Elite; however, the horizontal tail is relatively smaller and closer to the wing on the Avistar 30cc than on the Avistar Elite.

The scale factor for the manufacturer estimated gross takeoff weights are 1.36. The flight-ready, fully-instrumented Avistar Elite weighs 8.70 lb (3.945 kg) as-built, which is 1.70 lb (0.77 kg) or 24% greater than the upper end of the manufacturer weight range, due to the instrumentation and necessary modifications. As the target scale factor between the two aircraft is approximately 1.5, the 8.70 lb Avistar Elite yields that the Avistar 30cc should weigh 29.36 lb (13.33 kg). Given that the fully-built, un-instrumented Avistar 30cc currently weighs 20.50 lb (9.31 kg), to achieve the 1.50 scale factor for weight/mass, there is 8.86 lb (4.022 kg) available for instrumentation and ballast. Note that not only will the ballast be used to achieve the desired weight, but also to achieve the dynamically-scaled moment of inertia.

Table 3 presents the component specifications for the Avistar Elite and Avistar 30cc. The Avistar aircraft share similar airframe construction techniques with a balsa and plywood built-up structure, an aluminum wing tube, aluminum landing gear, and the entire aircraft is sheeted in plastic film. There are aesthetic differences (e.g. color scheme) between the two aircraft as were seen in Figs. 1 through 4, however, the design is very similar overall. The aircraft utilize the

Figure 3: Top and side views of the Great Planes Avistar Elite [taken from Great Planes[42]].

Figure 4: Top and side views of the Great Planes Avistar 30cc [taken from Great Planes[43]].

same flight controls and use the same RC transmitter and receiver. The servos, flight control power regulator, and battery are (as expected) larger on the Avistar 30cc than the Avistar Elite. Similarly, the propulsion system components are scaled up on the Avistar 30cc compared to the Avistar Elite. In previous research, the Avistar Elite used an APC 13x8E Thin Electric propeller. However, in order to more easily match the propeller pitch-to-diameter (P/D) ratio between the Avistar aircraft, the propeller on the Avistar Elite will be changed to a APC 13x6.5E, which has a 1 to 2 P/D ratio; this propeller will exactly match the ratio the 53.8% larger APC 20x10E propeller that is used on the Avistar 30cc. Propeller performance data for these two propellers was measured in previous work as will be discussed in Section V.

Table 2: Avistar Elite and Avistar 30cc physical specifications and scaling factors.

	Avistar Elite	**Avistar 30cc**	**Scaling Factor (n)**
Geometric			
Wing Chord	10.7 in (272 mm)	16.0 in (406 mm)	1.50
Wing Span	62.5 in (1590 mm)	90.5 in (2300 mm)	1.45
Wing Area	672 in^2 (43.3 dm^2)	1448 in^2 (93.4 dm^2)	1.46
Wing Aspect Ratio	5.8	5.7	–
Wing Airfoil	Avistar	Avistar	–
H. Stab Mean Chord	6.3 in (160 mm)	9.2 in (234 mm)	1.46
H. Stab Span	22.9 in (582 mm)	30.7 in (780 mm)	1.34
H. Stab Area	144 in^2 (9.3 dm^2)	282 in^2 (18.3 dm^2)	1.40
H. Stab Aspect Ratio	3.6	3.3	–
H. Stab Airfoil	Flat Plate, 8.6 mm Thick	Flat Plate, 12.4 mm Thick	1.44
Distance from Wing LE to H. Stab LE	30.7 in (780 mm)	41.3 in (1048 mm)	1.34
Aircraft Length	55.0 in (1395 mm)	77.25 in (1962 mm)	1.41
Inertial			
MFG Weight	6.5-7.0 lb (2.95-3.17 kg)	16.5-17.5 lb (7.48-7.94 kg)	1.36
As-Built Weight	8.70 lb (3.95 kg) *Instrumented*	20.50 lb (9.31 kg) *Un-Instrumented*	1.33

Table 3: Avistar Elite and Avistar 30cc component specifications.

	Avistar Elite	**Avistar 30cc**
Airframe Construction	Built-up balsa and plywood structure, aluminum wing tube, aluminum landing gear, and plastic film sheeted.	
Flight Controls		
Controls	Aileron (2), elevator, rudder, throttle, and flaps (2)	Aileron (2), elevator (2), rudder, throttle, and flaps (2)
Transmitter	Futaba T14MZ	
Receiver	Futaba R6014HS	
Servos	(6) Futaba S3004	(6) Hitec HS-5645MG
Power Regulator	Castle Creations CC BEC	SmartFly SportReg
Battery	Thunder ProLite 20c 2S 7.4V 450 mAh	(2) Thunder ProLite RX 2S 7.4V 900 mAh
Propulsion		
Motor	AXI 4120/14 Outrunner	Hacker A60-5S V4 Outrunner
ESC	Castle Creation Phoenix Edge 75	Castle Creation Phoenix Edge HV 120
Propeller	APC 13x6.5E	20x10E
Battery	Thunder Power ProPower 30c 4S 14.8 V 5 Ah	Thunder Power ProLiteX 25c 8S 29.6 V 6 Ah
Flight Time	10-20 min	

IV. Instrumentation

The Avistar Elite aircraft is instrumented with an Al Volo FC+DAQ[49] flight control and data acquisition system, which is able to collect high-frequency, high-fidelity data from a large number of sensors.[50] The system operates at 400 Hz and integrates a 9 degree-of-freedom (9-DOF) XSens MTi-G-710[51] IMU with a GPS receiver. The pilot commands are also logged by measuring the pulse width modulation (PWM) signals generated by receiver for each servo channel. The propulsion system information is logged by the FDAQ through an interface with the Castle Creations Edge 75 electronic speed controller (ESC); additionally, an integrated Hall-effect current sensor was added between the ESC and the battery to monitor current input.[52] Using the sensors, the system is able to log and transmit: 3D linear and angular accelerations, velocities, and position along with GPS location; pitot-static probe airspeed; 3D magnetic field strength and heading; control surface deflections; and propulsion system voltage, motor and ESC current, RPM, and power. Specifications for the instrumentation can be found in Table 4. An identical system will be installed in the Avistar 30cc, with the only difference likely being that the pitot-static probe will be mounted further in front from the LE of the wing top.

Table 4: Instrumentation specifications.

Data acquisition system	Al Volo FDAQ 400 Hz system
Sensors	
Inertial measurement unit	XSens MTi-G-700 AHRS with GPS
Airspeed sensor	Al Volo Pitot Static Airspeed Sensor
Motor sensor	Al Volo Castle ESC Interface
Power	
Regulator	Built into FC+DAQ
Battery	Thunder Power ProLiteX 3S 1350 mAh

V. Ground Measurements and Existing Data

In previous work, the Avistar Elite was extensively characterized through the use of flight testing and ground measurement. Specifically, ground testing has included 3D scanning of geometry,[35] moment of inertia measurement,[53] and propeller performance testing, which will be expanded upon below. The data generated from these testing efforts were used to create models of the Avistar Elite, which included a Solidworks CAD model, computational aerodynamics tool models in AVL, XFLR5, and Fluent,[36] a propulsion system power model, and a flight simulation model in the X-Plane 11 flight simulator.[54]

A. 3D Scanning

The Avistar Elite was 3D scanned using a ZCorporation ZScanner 800 self-positioning handheld 3D scanner,[35] as can be seen in Fig. 5. The 3D scanner generated a point cloud, which was then processed, eventually yielding airfoils, dimensions, and coordinates for all of the flight surfaces, as presented in Table 5. The data generated from the 3D scan was used to create the Solidworks CAD model shown in Fig. 6, as well as computational aerodynamics tool models and a flight simulation model.

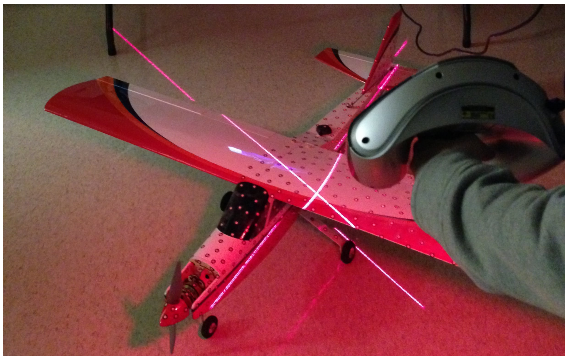


Figure 5: The Avistar UAV being 3D scanned from above.

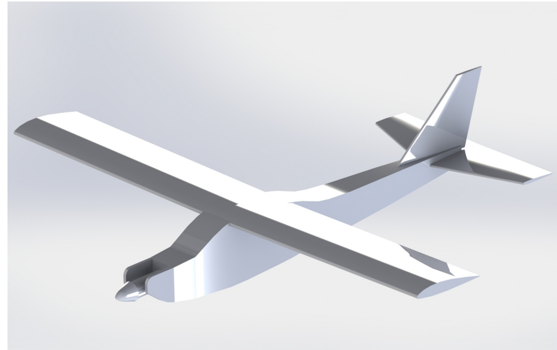


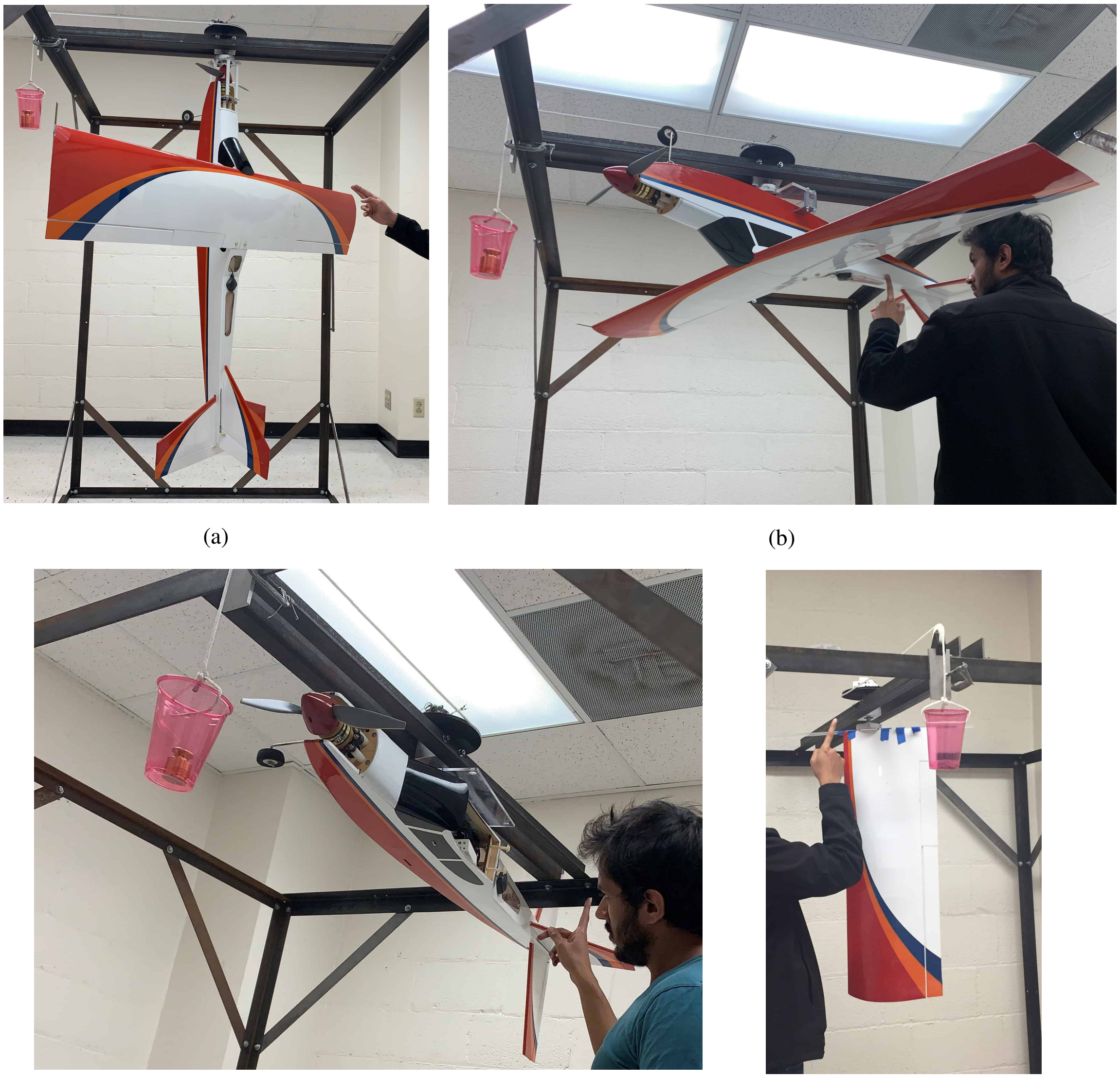
Figure 6: The SolidWorks CAD model of the Great Planes Avistar Elite.

Table 5: Avistar UAV flight surface specifications.

Wing							
LE x pos	**LE z pos**	**Incidence**	**y span pos**	**Chord**	**Offset**	**Dihedral**	**Airfoil**
380.4 mm	95.5 mm	3.58 deg	0 mm	237.10 mm	0 mm	0.9 deg	AVISTAR
-	-	-	793.75 mm	237.10 mm	0 mm	-	AVISTAR
Horizontal Stabilizer							
LE x pos	**LE z pos**	**Incidence**	**y span pos**	**Chord**	**Offset**	**Dihedral**	**Airfoil**
1160 mm	-2.04 mm	2.36 deg	0 mm	210 mm	0 mm	0 deg	AVISTARHSTABROOT
-	-	-	291 mm	110 mm	100 mm	-	AVISTARHSTABTIP
Vertical Stabilizer							
LE x pos	**LE z pos**	**Incidence**	**y span pos**	**Chord**	**Offset**	**Dihedral**	**Airfoil**
1160 mm	17.96 mm	2.36 deg	0 mm	273 mm	-95 mm	0 deg	AVISTARVSTABROOT
-	-	-	200 mm	96 mm	133 mm	-	AVISTARVSTABTIP

B. Moment of Inertia Measurement

A moment of inertia testing rig was developed in previous work and used to measure the moment of inertia of the flight-ready, instrumented Avistar Elite. Specifically, the aircraft was hard mounted to the rig about the 3 axes with a fixed torque being applied. Due to the mount designs, certain components, e.g. main landing gear, were tested separately. Photos of the Avistar Elite being measured are shown below in Fig. 7. This same testing rig will be used to measure the moment of inertia of the Avistar 30cc. A thorough explanation of the measurement process can be found in the previous literature.[53]



(a) (b)

(c) (d)

Figure 7: Moment of inertia measurement of the flight-ready, instrumented Avistar UAV about the (a) roll axis, (b) yaw axis, and (c-d) pitch axis.

C. Propeller Performance Testing

Propeller performance and efficiency data is required for flight testing data analysis. To obtain this data, one may either derive propeller performance models using blade element momentum theory (BEMT) and sectional airfoil theory as done in[55] or may do so experimentally through propeller performance testing – the latter technique is used in this work for the Avistar Elite and Avistar 30cc. Recently 17 APC Thin Electric 2-bladed, fixed propellers with diameters of 12 to 21 in with various pitch values were tested in the UIUC low-turbulence subsonic wind tunnel. Specifically, both the APC 13x6.5E, to be used on the Avistar Elite, and the APC 20x10E, to be used on the Avistar 30cc, were tested. Results for these two propellers are shown in Fig. 8-11 under freestream conditions at rotation rates between 3,000 and 7,000 RPM and static at rotation rates between 1,000 and 7,500 RPM, respectively. Testing results for these APC-E Thin Electric propellers, as well as of several other propellers that could be used on the Avistar Elite and Avistar 30cc, are available on Unmanned Aerial Vehicle Database[56] and the UIUC Propeller Database.[57]

1. APC 13×6.5 Thin Electric Propeller

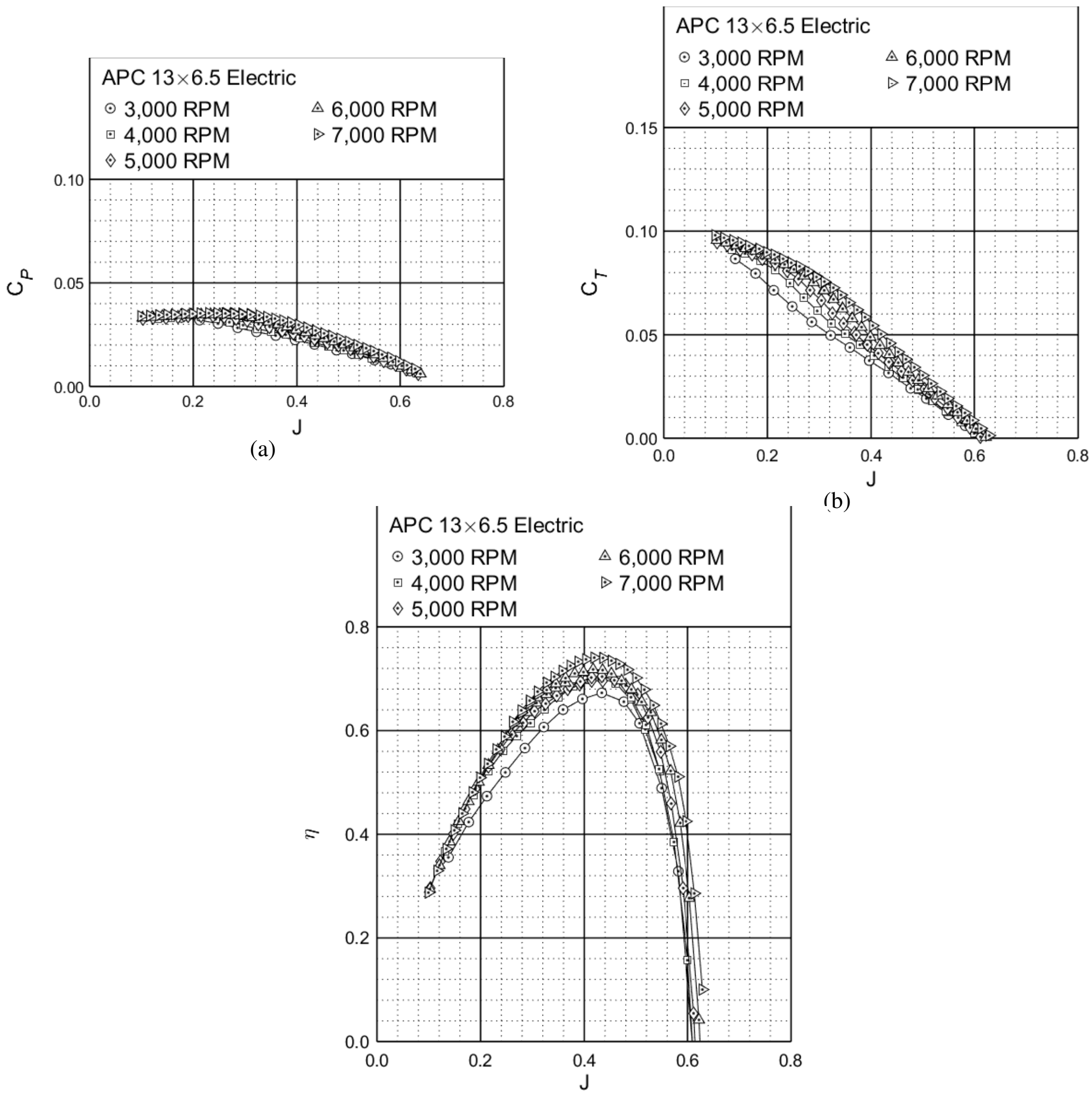


Figure 8: Performance of the APC 13×6.5 Thin Electric propeller: (a) thrust coefficient, (b) power coefficient, (c) efficiency.

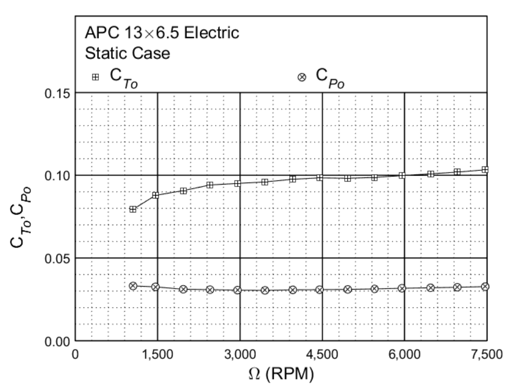


Figure 9: Static performance of the APC 13×6.5 Thin Electric propeller: thrust and power coefficient.

2. APC 20×10 Thin Electric Propeller

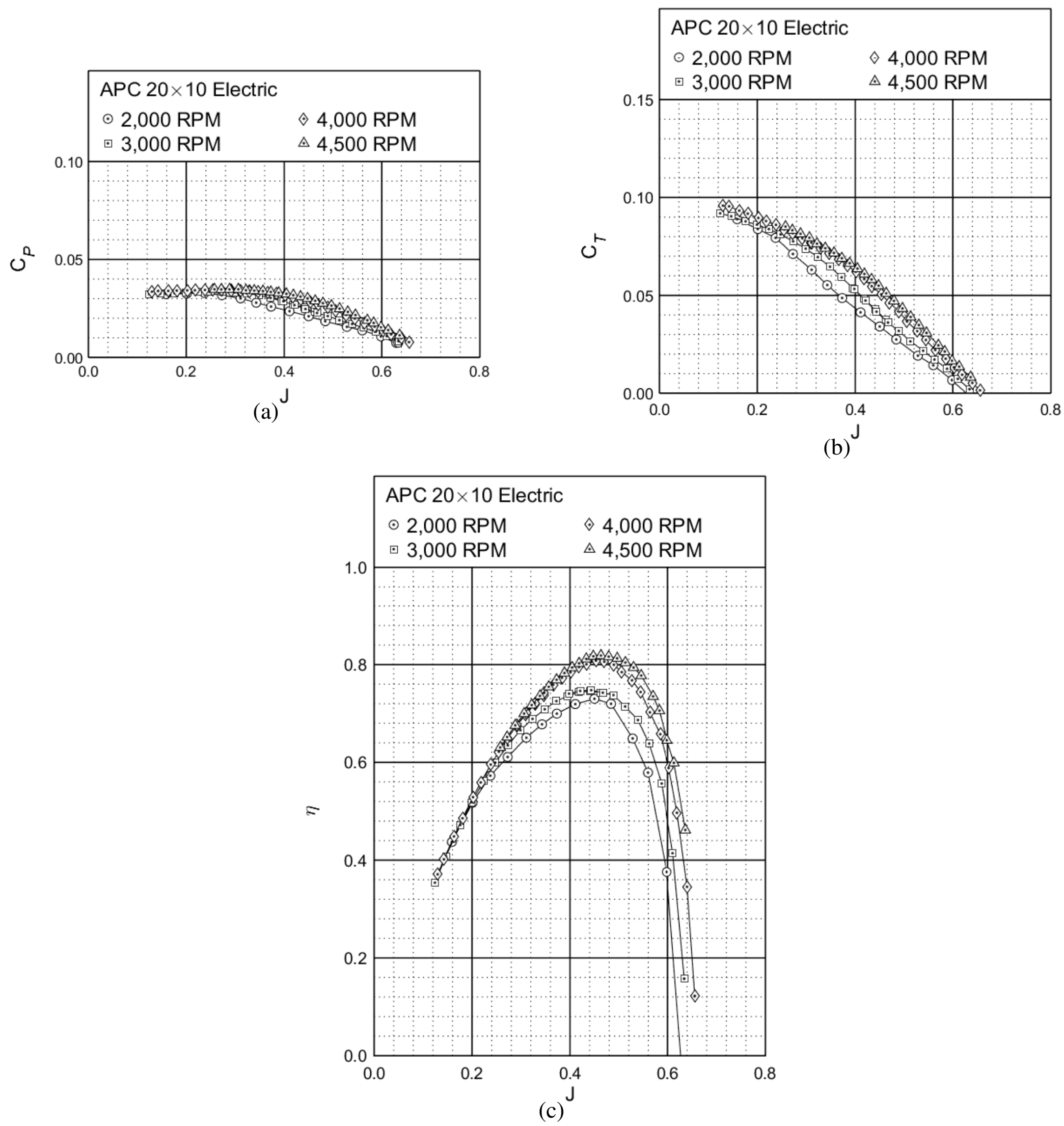


Figure 10: Performance of the APC 20×10 Thin Electric propeller: (a) thrust coefficient, (b) power coefficient, (c) efficiency.

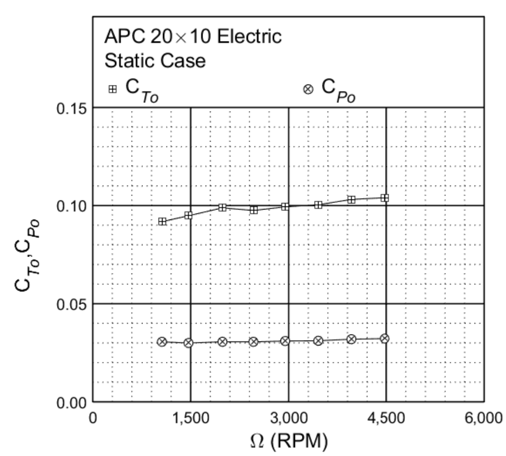


Figure 11: Static performance of the APC 20×10 Thin Electric propeller: thrust and power coefficient.

VI. Dynamically-Scaled Aircraft Development and Flight Testing Plan

In order to compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign, an aircraft development and flight testing plan was developed. The starting point and 4 phases are detailed below.

Phase 0: Extensive ground and flight testing exists for the Avistar Elite. Ground testing data includes geometric and inertial measurements for the aircraft, as described in Sections III and V. Existing flight testing data includes 51 maneuvers that were performed using a flight testing automation tool,[58] which could repeatedly perform these parameterizable flight testing maneuvers with minimal human error. The maneuvers include trimmed level and gliding flight, phugoids, stalls, singlets and doublets for aileron, elevator, and rudder.

Phase 1: The Avistar 30cc will be instrumented and then ground testing will be performed, including mass and moment of inertia measurement in order to characterize the baseline aircraft. The flight testing automation tool will then be configured into the Avistar 30cc instrumentation, followed by preliminary flight testing to acquire baseline aircraft flight performance and verify proper aircraft-instrumentation integration and operation.

Phase 2: The Avistar 30cc will be dynamically scaled by strategically placing ballasts about the aircraft to achieve desired mass and moment of inertia. Ballasts should be attached such that they will not come apart in flight, however, can be easily removed and re-configured if needed. The mass and moment of inertia measurement will be performed to confirm the desired values. If these values are not properly achieved, ballast adjustment will occur and the measurements will be re-done.

Phase 3: A flight testing campaign will be performed using the dynamically-scaled Avistar 30cc, which will include the maneuvers described below. Additional flight tests of the Avistar 30cc and Avistar Elite will be performed as needed to collect all data required.

Phase 4: The data sets collected will enable assessment of the dynamic-scaling procedures and flight test campaign. A final report/paper will be written documenting and discussing this effort, including results, method validity, and best practices.

Flight testing of the dynamically-scaled Avistar 30cc will involve executing the maneuvers outlined in Table 6. Most of these maneuvers have already been performed using Avistar Elite, however, additional flight testing will be performed with the Avistar Elite such that all maneuvers are available for direct comparison between it and the dynamically-scaled Avistar 30cc. This effort will primarily utilize longitudinal flight test maneuvers, as these longitudinal motions are typically not coupled to lateral motions, therefore simplifying the process of accessing scaling and flight test procedures. This comparison data set will also be publicly available on the UAVDB in addition to the flight test results for Avistar 30cc.

Table 6: Flight Test Maneuvers Planned

Maneuver	Flap Configuration	Description
Trimmed Flight	Clean	Trimmed flight at various airspeeds
Idle Descent	Clean	Descent using idle power with different amounts of trim
Phugoid	Clean	Entry with aircraft trimmed and elevator deflected to change airspeed
Roll Response	Clean	Aileron momentarily deflected
Pitch Response	Clean	Elevator momentarily deflected
Yaw Response	Clean	Rudder momentarily deflected
Power-Off Stall		Entry with wings level
	Clean	limited elevator deflection
		full elevator deflection
	Half-Flaps	limited elevator deflection
		full elevator deflection
	Full-Flaps	limited elevator deflection
		full elevator deflection
Power-Off Spin		Entry with wings level
	Clean	limited elevator deflection
		full elevator deflection
	Half-Flaps	limited elevator deflection
		full elevator deflection
	Full-Flaps	limited elevator deflection
		full elevator deflection
Takeoff	Clean Half-Flaps Full-Flaps	Trimmed with either no of limited no elevator deflection
Landing	Clean Half-Flaps Full-Flaps	Trimmed

VII. Summary and Future Work

This paper presented a methodology to compare the flight characteristics of two dynamically-scaled flight test models and ascertain the validity of the scaling procedures and flight test campaign. Planned research will utilize two geometrically similar COTS aircraft: the Avistar Elite and the approximately 50% larger Avistar 30cc. Extensive flight and ground testing datasets have already been collected for the Avistar Elite and thus the larger Avistar 30cc will be modified into a dynamically-scaled-up version of the baseline Avistar Elite, per the aircraft development plan that was discussed. This dynamic scaling process will be performed using the methodologies described within the literature and with results within the error margins of previous dynamic-scaling efforts, such as NASA AirSTAR. Planned flight testing will specifically target longitudinal maneuvers, as longitudinal motions are typically not coupled to lateral motions.

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References

[1] Lykins, R. and Keshmiri, S., "Modal Analysis of 1/3-Scale Yak-54 Aircraft Through Simulation and Flight Testing," AIAA Paper 2011-6443, AIAA Atmospheric Flight Mechanics Conference, Portland, Oregon, Aug. 2011.

[2] Johnson, B. and Lind, R., "Characterizing Wing Rock with Variations in Size and Configuration of Vertical Tail," *Journal of Aircraft*, Vol. 47, No. 2, 2010, pp. 567–576.

[3] Perry, J., Mohamed, A., Johnson, B., and Lind, R., "Estimating Angle of Attack and Sideslip Under High Dynamics on Small UAVs," Proceedings of the ION-GNSS Conference, Savannah, Georgia, 2008.

[4] Uhlig, D., Sareen, A., Sukumar, P., Rao, A. H., and Selig, M. S., "Determining Aerodynamic Characteristics of a Micro Air Vehicle Using Motion Tracking," AIAA Paper 2010-8416, AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario, Canada, Aug. 2010.

[5] Dantsker, O. D. and Selig, M. S., "High Angle of Attack Flight of a Subscale Aerobatic Aircraft," AIAA Paper 2015-2568, AIAA Applied Aerodynamics Conference, Dallas, Texas, Jun. 2015.

[6] Mockli, M., *Guidance and Control for Aerobatic Maneuvers of an Unmanned Airplane*, Ph.D. thesis, ETH Zurich, Department of Mechanical and Process Engineering, 2006.

[7] Frank, A., McGrewy, J. S., Valentiz, M., Levinex, D., and How, J. P., "Hover, Transition, and Level Flight Control Design for a Single-Propeller Indoor Airplane," AIAA Paper 2007-6318, AIAA Guidance, Navigation, and Control Conference, Hilton Head, South Carolina, Aug. 2007.

[8] Johnson, E. N., Wu, A. D., Neidhoefer, J. C., Kannan, S. K., and Turbe, M. A., "Test Results of Autonomous Airplane Transitions Between Steady-Level and Hovering Flight," *Journal of Guidance, Control, and Dynamics*, Vol. 31, No. 2, 2008, pp. 358–370.

[9] Gaum, D. R., *Aggressive Flight Control Techniques for a Fixed-Wing Unmanned Aerial Vehicle*, Master's thesis, Stellenbosch University, Department of Electrical and Electronic Engineering, 2009.

[10] Bilodeau, P. R., Poulin, E., Gagnon, E., Wong, F., and Desbiens, A., "Control of a Hovering Mini Fixed Wing Aerial Vehicle," AIAA Paper 2009-5794, AIAA Guidance, Navigation and Control Conference, Chicago, Illinois, Aug. 2009.

[11] Johnson, B. and Lind, R., "Trajectory Planning for Sensing Effectiveness with High Angle-of-Attack Flight Capability," AIAA Paper 2012-0276, AIAA Aerospace Sciences Meeting, Nashville, Tennessee, Jan. 2012.

[12] Jordan, T. L. and Bailey, R. M., "NASA Langley's AirSTAR Testbed: A Subscale Flight Test Capability for Flight Dynamics and Control System Experiments," AIAA Paper 2008-6660, AIAA Atmospheric Flight Mechanics Conference, Honolulu, HI, Aug. 2008.

[13] Gregory, I. M., Cao, C., Xargay, E., Hovakimyan, N., and Zou, X., "L_1 Adaptive Control Design for NASA AirSTAR Flight Test Vehicle," AIAA Paper 2009-5738, AIAA Guidance, Navigation, and Control Conference, Chicago, IL, Aug. 2009.

[14] Ragheb, A. M., Dantsker, O. D., and Selig, M. S., "Stall/Spin Flight Testing with a Subscale Aerobatic Aircraft," AIAA Paper 2013-2806, AIAA Applied Aerodynamics Conference, San Diego, CA, Jun. 2013.

[15] Bunge, R. A., Savino, F. M., and Kroo, I. M., "Approaches to Automatic Stall/Spin Detection Based on Small-Scale UAV Flight Testing," AIAA Paper 2015-2235, AIAA Atmospheric Flight Mechanics Conference, Dallas, Texas, Jun. 2015.

[16] Dantsker, O. D., Ananda, G. K., and Selig, M. S., "GA-USTAR Phase 1: Development and Flight Testing of the Baseline Upset and Stall Research Aircraft," AIAA Paper 2017-4078, AIAA Applied Aerodynamics Conference, Denver, Colorado, June 2017.

[17] Ananda, G. K., Vahora, M., Dantsker, O. D., and Selig, M. S., "Design Methodology and Flight-Testing Protocols for a Dynamically-Scaled General Aviation Aircraft," AIAA Paper 2017-4077, AIAA Applied Aerodynamics Conference, Denver, Colorado, Jun 2017.

[18] Risch, T., Cosentino, G., Regan, C., Kisska, M., and Princen, N., "X-48B Flight-Test Progress Overview," AIAA Paper 2009-934, AIAA Aerospace Sciences Meeting, Orlando, FL, Jan. 2009.

[19] Lundstrom, D. and Amadori, K., "Raven: A Subscale Radio Controlled Business Jet Demonstrator," International Congress on the Aeronautical Sciences Systems (ICUAS), Anchorage, Alaska, Sep. 2008.

[20] Regan, C. D. and Taylor, B. R., "mAEWing1: Design, Build, Test - Invited," AIAA Paper 2016-1747, AIAA Atmospheric Flight Mechanics Conference, San Diego, California, Jun. 2016.

[21] Regan, C. D., "mAEWing2: Conceptual Design and System Test," AIAA Paper 2017-1391, AIAA Atmospheric Flight Mechanics Conference, Grapevine, Texas, Jun. 2017.

[22] Leong, H. I., Keshmiri, S., and Jager, R., "Evaluation of a COTS Autopilot and Avionics System for UAVs," AIAA Paper 2009-1963, AIAA Infotech@Aerospace, Seattle, Washington, April. 2009.

[23] Esposito, J. F. and Keshmiri, S., "Rapid Hardware Interfacing and Software Development for Embedded Devices Using Simulink," AIAA Paper 2010-3415, AIAA Infotech@Aerospace, Atlanta, Georgia, June 2010.

[24] Garcia, G. and Keshmiri, S., "Integrated Kalman Filter for a Flight Control System with Redundant Measurements," AIAA Paper 2012-2499, AIAA Infotech@Aerospace, Garden Grove, California, June 2012.

[25] Sobron, A., Lundström, D., Staack, I., and Krus, P., "Design and Testing of a Low-Cost Flight Control and Data Acquisition System for Unstable Subscale Aircraft," International Congress on the Aeronautical Sciences Systems, Daejeon, Korea, Sep. 2016.

[26] Theile, M., Dantsker, O. D., Caccamo, M., and Yu, S., "uavAP: A Modular Autopilot Framework for UAVs," AIAA Paper 2020-3268, AIAA Aviation 2020 Forum, Virtual Event, Jun. 2020.

[27] Dantsker, O. D., Haviland, S. T., Mukherjee, J., Allford, R., Danowsky, B. P., Kendall, G., Lisoski, D. L., Peltz, A., and Bershadsky, D., "Flight Testing of Subscale HAPS Models to Evaluate Aircraft Configurations," AIAA Paper 2022-3638, AIAA Aviation Forum, Virtual Event, Jun. 2022.

[28] Dantsker, O. D., Haviland, S. T., Allford, R., Daley, D., Danowsky, B. P., Haplin, D., Kendall, G., Lisoski, D. L., Liu, Z. T., Mukherjee, J., Peltz, A., Price, B., Sano, G., Warner, R. B., and Bershadsky, D., "Flight Testing of Tailless Subscale HAPS Aircraft," AIAA Paper 2023-3780, AIAA Aviation Forum, Virtual Event, Jun. 2023.

[29] Barlow, J. B., Rae, W. H., Jr., and Pope, A., *Low-Speed Wind Tunnel Testing, Third Ed.*, John Wiley and Sons, New York, 1999.

[30] Selig, M. S., Donovan, J. F., and Fraser, D. B., *Airfoils at Low Speeds*, Soartech 8, SoarTech Publications, Virginia Beach, VA, 1989.

[31] Selig, M. S., Guglielmo, J. J., Broeren, A. P., and Giguère, P., *Summary of Low-Speed Airfoil Data, Vol. 1*, SoarTech Publications, Virginia Beach, Virginia, 1995.

[32] Selig, M. S., Lyon, C. A., Giguère, P., Ninham, C. N., and Guglielmo, J. J., *Summary of Low-Speed Airfoil Data, Vol. 2*, SoarTech Publications, Virginia Beach, Virginia, 1996.

[33]Lyon, C. A., Broeren, A. P., Giguère, P., Gopalarathnam, A., and Selig, M. S., *Summary of Low-Speed Airfoil Data, Vol. 3*, SoarTech Publications, Virginia Beach, Virginia, 1998.

[34]Selig, M. S., *Summary of Low-Speed Airfoil Data, Vol. 4*, SoarTech Publications, Virginia Beach, Virginia, 2005.

[35]Dantsker, O. D., "Determining Aerodynamic Characteristics of an Unmanned Aerial Vehicle using a 3D Scanning Technique," AIAA Paper 2015-0026, AIAA Aerospace Sciences Meeting, Kissimmee, Florida, Jan. 2015.

[36]Dantsker, O. D. and Vahora, M., "Comparison of Aerodynamic Characterization Methods for Design of Unmanned Aerial Vehicles," AIAA Paper 2018-0272, AIAA Aerospace Sciences Meeting, Kissimmee, Florida, Jan 2018.

[37]Dantsker, O. D., Caccamo, M., Vahora, M., and Mancuso, R., "Flight & Ground Testing Data Set for an Unmanned Aircraft: Great Planes Avistar Elite," AIAA Paper 2020-0780, AIAA SciTech Forum, Orlando, Florida, Jan 2020.

[38]Dantsker, O. D., Caccamo, M., and Mancuso, R., "Expanded Flight & Ground Testing Data Set for an Unmanned Aircraft: Great Planes Avistar Elite," AIAA Paper 2023-2105, AIAA SciTech Forum, Virtual Event, Jan. 2023.

[39]Wolowicz, C. H., Brown, J. S., Jr., and Gilbert, W. P., "Similitude Requirements and Scaling Relationships as Applied to Model Testing," NASA TP 1435, NASA, 1979.

[40]Qadri, M., Vahora, M., Hascaryo, R., Finlon, S., Dantsker, O. D., Ananda, G. K., and Selig, M. S., "Undergraduate Contribution to Dynamically Scaled General Aviation Research at the University of Illinois at Urbana-Champaign," AIAA Paper 2018-1069, AIAA Aerospace Sciences Meeting, Kissimmee, Florida, Jan. 2018.

[41]Vahora, M., Ananda, G. K., and Selig, M. S., "Design Methodology for Aerodynamically Scaling of a General Aviation Aircraft Airfoil," AIAA Paper 2018-1277, AIAA Aerospace Sciences Meeting, Kissimmee, Florida, Jan. 2018.

[42]Hobbico, Inc., "Great Planes Avistar Elite .46 Advanced Trainer RTF," http://www.greatplanes.com/airplanes/gpma1605.html, Accessed Oct. 2017.

[43]Hobbico, Inc., "Great Planes Avistar 30cc Sport Trainer," http://www.greatplanes.com/airplanes/gpma1675.php, Accessed Oct. 2018.

[44]Mancuso, R., Dantsker, O. D., Caccamo, M., and Selig, M. S., "A Low-Power Architecture for High Frequency Sensor Acquisition in Many-DOF UAVs," Submitted to International Conference on Cyber-Physical Systems, Berlin, Germany, April 2014.

[45]Dantsker, O. D., Mancuso, R., Selig, M. S., and Caccamo, M., "High-Frequency Sensor Data Acquisition System (SDAC) for Flight Control and Aerodynamic Data Collection Research on Small to Mid-Sized UAVs," AIAA Paper 2014-2565, AIAA Applied Aerodynamics Conference, Atlanta, Georgia, June 2014.

[46]Dantsker, O. D., Imtiaz, S., and Caccamo, M., "Electric Propulsion System Optimization for a Long-Endurance and Solar-Powered Unmanned Aircraft," AIAA Paper 2019-4486, AIAA/IEEE Electric Aircraft Technologies Symposium, Indianapolis, Indiana, Aug. 2019.

[47]Theile, M., Yu, S., Dantsker, O. D., and Caccamo, M., "Trajectory Estimation for Geo-Fencing Applications on Small-Size Fixed-Wing UAVs," IEEE International Conference on Intelligent Robots and Systems, Macau, China, Nov. 2019.

[48]Dantsker, O. D., *A Cyber-Physical Prototyping and Testing Framework to Enable the Rapid Development of Unmanned Aircraft*, Master's thesis, University of Illinois at Urbana-Champaign, Department of Aerospace Engineering, Urbana, IL, 2021.

[49]Al Volo LLC, "Al Volo: Flight Systems," http://www.alvolo.us, Accessed Jan. 2022.

[50]Dantsker, O. D. and Mancuso, R., "Flight Data Acquisition Platform Development, Integration, and Operation on Small- to Medium-Sized Unmanned Aircraft," AIAA Paper 2019-1262, AIAA SciTech Forum, San Diego, California, Jan 2019.

[51]Xsens Technologies B.V., "XSens, MTi-G-700," https://www.xsens.com/products/mti-g-700/, Accessed Jan. 2016.

[52]Dantsker, O. D. and Mancuso, R., "Propulsion System Instrumentation Development and Integration on Small- and Medium-Sized Electric Unmanned Aircraft," AIAA Paper 2022-2156, AIAA SciTech Forum, Virtual Event, Jan. 2023.

[53]Dantsker, O. D., Vahora, M., Imtiaz, S., and Caccamo, M., "High Fidelity Moment of Inertia Testing of Unmanned Aircraft," AIAA Paper 2018-4219, AIAA Applied Aerodynamics Conference, Atlanta, Georgia, Jun. 2018.

[54]Laminar Research, "X-Plane 11," http://www.x-plane.com/, Accessed Jan. 2022.

[55]Ol, M., Zeune, C., and Logan, M., "Analytical/Experimental Comparison for Small Electric Unmanned Air Vehicle Propellers," *26th AIAA Applied Aerodynamics Conference*, American Institute of Aeronautics and Astronautics, Reston, Virigina, 8 2008.

[56]O. Dantsker and R. Mancuso and M. Vahora and M. Caccamo, "Unmanned Aerial Vehicle Database," http://uavdb.org/, Accessed Jan. 2022.

[57]Brandt, J., Deters, R., Ananda, G., Dantsker, O., and Selig, M., "UIUC Propeller Database," http://m-selig.ae.illinois.edu/props/propDB.html, Accessed Jan. 2022.

[58]Dantsker, O. D., Yu, S., Vahora, M., and Caccamo, M., "Flight Testing Automation to Parameterize Unmanned Aircraft Dynamics," AIAA Paper 2019-3230, AIAA Aviation and Aeronautics Forum and Exposition, Dallas, Texas, June 2019.