AIAA Paper 2012-0845

From Blank Slate to Flight Ready New Small Research UAVs in Twenty Weeks - Undergraduate Airplane Design at the University of Washington

Eli Livne and Chester P. Nelson

Department of Aeronautics and Astronautics
University of Washington, Seattle, WA, 98195-2400

Presented at the AIAA Aerospace Sciences Meeting
Nashville, TN
January 9th-12th, 2012

The World's Forum for Aerospace Leadership

From Blank Slate to Flight Ready New Small Research UAVs in Twenty Weeks - Undergraduate Airplane Design at the University of Washington

Eli Livne* and Chester P. Nelson**

Department of Aeronautics and Astronautics
University of Washington, Seattle, WA, 98195-2400

Abstract

The capstone airplane design course at the University of Washington, two academic quarters long, has evolved in recent years to cover the airplane design experience from market and needs studies through conceptual design, preliminary design, and detail design, and up to the construction, ground testing, and flight testing of complex research-type small UAVs. Significant engineering resources are devoted to this effort including substantial CAD, CFD-based aerodynamics, NASTRAN-based structural analysis, as well as performance, and stability and control simulations. Wind tunnel tests of commercial quality models at the University of Washington's Kirsten wind tunnel are carried out, plus structural static and modal tests, airframe / propulsion system integration tests, together with systems and system integration testing. An emphasis is placed on test / simulation correlation assessment and the development in students of the appreciation of alternative numerical / analytic modeling methods, their strengths and limitations, advantages and disadvantages. The course emphasizes team work, communication skills, leadership, initiative, and innovation. It runs with tight budget and schedule constraints which the students must meet. Each year a new design challenge is pursued leading to new and unique research UAVs. The program leverages the University's own wind tunnel labs, local flight test locations, and the availability of experienced mentors. Significant support from the Boeing Company and from Aeronautical Testing Service, Inc. (Arlington, Washington), allows the students access to, and interaction with, world class experts in the various areas airplane design has to cover.

Introduction

How to develop effective airplane design education programs in both the undergraduate and graduate curricula is a challenge all academic aeronautical / aerospace engineering programs face. The multidisciplinary nature of aerospace engineering, with the many required courses that must cover the key disciplines involved, leaves little room in the aerospace engineering curriculum for long sequences of inter-related airplane design courses required for introducing students to airplane design in a thorough way. Such sequences should begin with reviews, from an applied perspective, of what students had covered earlier as well as the fundamentals of general design and airplane design, and they should end, desirably, with the completion of detailed designs and construction of new vehicles. Even though aerospace engineering programs cover the fundamentals in aerodynamics, structures, propulsion, control, as well as airplane performance and flight mechanics, undergraduate students often reach their senior year without enough applied knowledge and experience in these disciplines and without the capacity for disciplinary integration and multidisciplinary perspective. In addition to the theoretical and practical technical issues involved it has been long recognized that airplane design education at the undergraduate level is to prepare engineering

---

* Professor, eli@aa.washington.edu
**Affiliate Associate Professor and Boeing Technical Fellow

Students transition to and enter professional life in the "real world". This means developing experience with and appreciation for innovation, communications and teamwork, along with the importance of market needs, environmental and social considerations, and, finally, project management and decision making in the face of real-world analytical uncertainty and experimental limitations, and operating within budget and schedule constraints.

Over the course of over 15 years the University of Washington in Seattle has been developing an undergraduate airplane program that aims at meeting the challenges listed above. The state of the program in its early stages was reported in Ref. 1, which also covered in its bibliography general developments in and approaches to airplane design education to the end of the 1990s . References 2-6 here are important articles discussing airplane design education and reflecting a wave of interest in the subject in the 1990s. References 8-14 represent perspectives and recent national and international development in airplane design education. The present paper describes the University of Washington's program at its present stage. As it has become one of the most ambitious internationally, it is hoped that some of the lessons learned and experience gained may be of interest and help to others struggling to develop state of the art undergraduate airplane design programs.

Educational Goals & Approach

The undergraduate airplane design program at the University of Washington is aimed at and is structured for meeting the following goals.

At the senior (capstone) level:

a) Integrate all that students have covered in the constituent disciplines into a coherent body of knowledge that allows students to apply disciplinary know-how to the airplane design task and to appreciate the inter-connected nature of the multidisciplinary interactions and considerations involved.

b) Build engineering experience and "engineering feel" by using a hierarchy of analytical / computational modeling tools in each of the contributing disciplines, and insisting on both the construction of physical models and on significant experimental work throughout the project. This allows assessment of strength and limitations of various modeling approaches, weighing tradeoffs between math model generation & analysis execution speeds, and the accuracy of numerical simulations as measured by correlation with experiments.

c) Use industry standard level of numerical simulation and testing, but, simultaneously, insist on using simple "back of the envelope" and handbook type estimates to assess order of magnitude of design change effects and to detect possible modeling input errors when results of high level simulations are much different in order of magnitude than back of the envelope estimates. Examples: Use simple beam and plate equations to validate order of magnitude of detailed finite element results, use component drag build-up hand calculation methods to compare with full Navier-Stokes CFD simulations, or use DATCOM and NACA report type approximations alongside panel code and CFD code prediction of stability derivatives. In this vein, allow students to build experience with a useful hierarchy of math modeling techniques linked to the stages of the evolution of the design and to time and budget constraints.

d) Provide significant *hands-on* experience: from planning, designing, and executing tests of components and subsystems through complete construction, systems integration, and ground & flight tests of complex small UAVs. Incorporate the use of project management tools and basic Systems Engineering principles throughout the project. To quote Le Corbusier (Ref. 15): "Teaching is only possible in the very centre of a craft. Arithmetic and handwriting can be taught in schools. But an invention originates only in the workshop. The door of the workshop opens upon life. The practical application of created things produces an immediate verdict as to their worth."

e) Provide significant systems integration experience covering all aspects of systems engineering from requirements and component selection to integration and packaging design, implementation, iron-bird testing, and final testing on the completed UAV. Systems integration should cover avionics as well as avionics integration with the airframe, its structure, dynamics, aerodynamics, and control.

e) Create a design and development environment representative of such environments in industry and government agencies and lead to student transition from the individual, structured, and micro-managed world of the high school and college student to the world of teamwork, collaboration, decision making in the face of uncertainty, budget, and schedule constraints. Encourage and guide the development of management and leadership skills.

f) Nurture innovation and contribution to the profession by presenting the students each year with a new design challenge, and by the design, construction, and testing of small research UAVs that are unique and that allow wind tunnel and flight testing of technologies that are topics of current interest and relevance to industry and NASA for future aircraft designs. Produce, at the end of each design project, quality computational and test data of potential research value to future thesis projects, government agencies and the aerospace industry.

At the freshman to junior levels:

g) Include an application design-oriented element in all aerospace engineering disciplinary courses. This has to be carefully planned and balanced to augment and not hurt the building of depth and covering the fundamentals in the disciplinary courses.

h) Encourage students to participate in AIAA design, build, fly (DBF) competitions and gain experience via simple radio-control model design and development. Such early experience is very valuable even though the engineering analysis and testing involved and the configurations created can be quite limited in depth, scope, and complexity.

i) Introduce students to leading experts from industry via seminar series and invited class talks, and encourage expert - student mentoring and consulting help.

Brief presentations of recent capstone design projects in the following sections will be used to highlight the key elements of the University of Washington's capstone design course, describe its scope, and share with the reader lessons from the development in an undergraduate engineering environment of some very interesting UAVs.

University of Washington Capstone Airplane Design Projects 2006 - 2011

The variety of research UAVs designed, built, and flown by students in the airplane capstone design courses over the last 6 years are shown in Figure 1. The challenge for the 2006 class was to design and build a scaled supersonic business jet configuration UAV to help investigate critical low-speed flying qualities and field performance characteristics of very slender configurations. In 2007 the class was tasked with the conversion of a NASA F16-XL to a low sonic boom research platform aircraft, with focus, again, on the viability of the resulting low-speed flight characteristics with such a drastic modification. The interest in the modified F16-XL as a low sonic-boom research vehicle was driven in 2005-2006 by NASA and industry's pursuit of low-cost flight vehicle with supersonic cruise capability to meet research needs in this area. In 2008 the focus of the design course shifted to subsonic airplanes and the challenge to the students was to design, build, and fly a UAV representing a subsonic regional jet concept configured for low noise by using airframe surfaces to largely shield engine inlet and exhaust noise from ground observers. The 2006-2008 UAVs used electric ducted fan (EDF) propulsors to simulate turbofan engines. The design challenges in 2009 and 2010 focused on developing turbojet propelled UAVs for research regarding the subsonic handling qualities and propulsion-airframe integration issues of future supersonic passenger jets configured for engine-airframe noise shielding (similar to concepts in NASA's Fundamental Aeronautics Program "N+2/N+3" aircraft technology studies) . Returning to subsonic commercial flight, the 2011 design project focused on very high aspect ratio future subsonic commercial airliners using strut-braced or truss-braced wings. The resulting scaled down UAV was again propelled by electric ducted fans to simulate very high bypass ratio geared turbofan (GTF) engines.

This 2011 UAV was constructed with an aeroelastically scaled flexible wing and can serve as a test bed for follow-on aeroelastic flight tests of alternative wing / strut and wing / truss designs.

All University of Washington UAVs of the last few years flew successfully from the Navy's Coupeville OLF air strip on Whidbey, Island, WA. The 2007 UAV did suffer a loss-of-control crash due to instabilities at high angles of attack but was not heavily damaged. This incident offered the student team some crucial lessons about the importance of checklists and careful CG location tracking during flight tests of potentially unstable configurations.

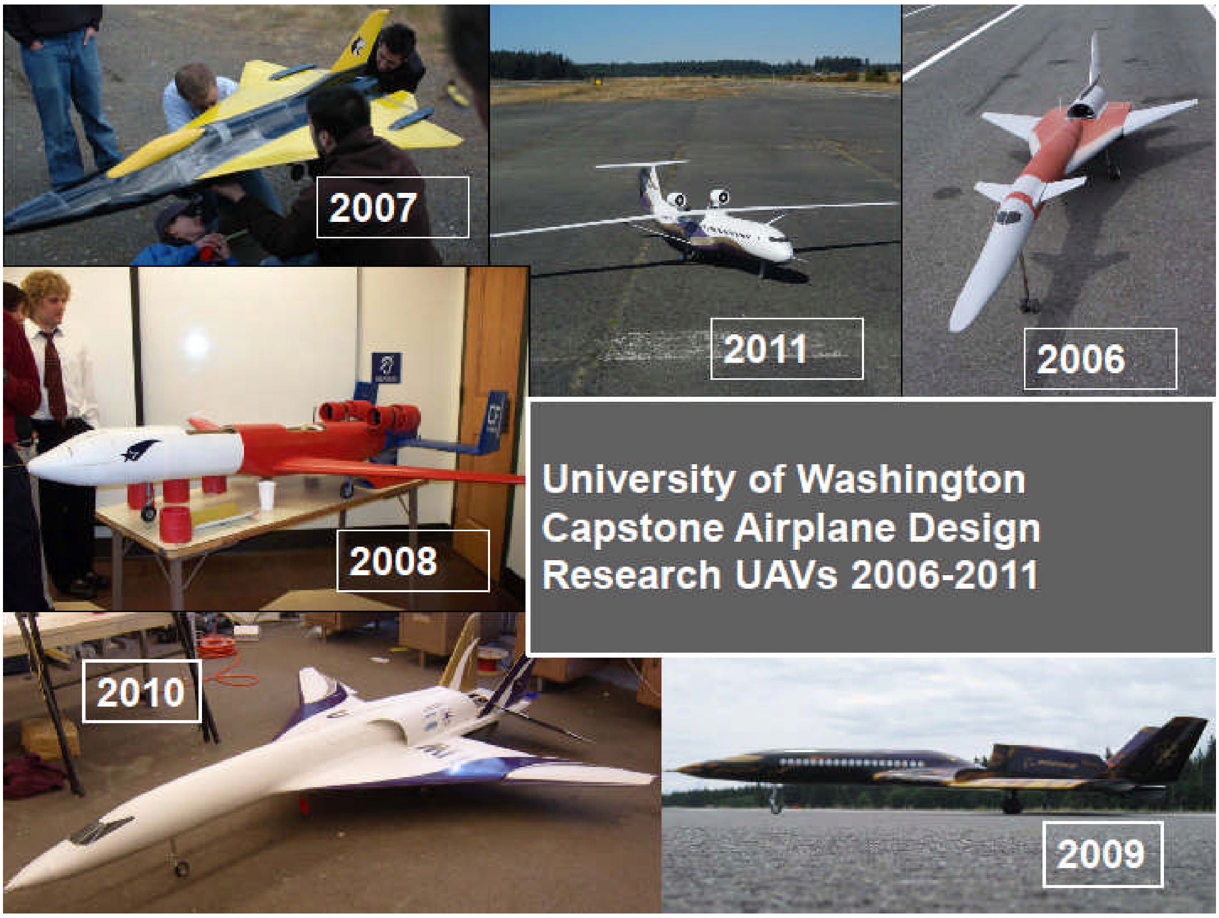


Figure 1: University of Washington capstone airplane design UAVs 2006-2011 (note: the different pictures are not to the same scale).

The 2006 University of Washington Capstone Design Project

Initially, a discussion of the 2006 capstone project will provide an overview of the typical class. The design challenge to the students of the 2006 capstone airplane design class was to develop a conceptual 12 seat, Mach 1.6, 4000 NM supersonic business jet (SSBJ) design, having a very slender general arrangement representative of low sonic boom design requirements. The fineness ratio was specified to be appropriate for a ground level boom overpressure of 0.35psf or about an 85% sonic boom reduction relative to Concorde. The full scale resulting SSBJ design concept had then to be scaled down dynamically, and the students were challenged to design, build, and flight test a low speed UAV for studying its handling qualities and flight characteristics at takeoff, approach, and landing conditions. Following lessons from the development of HSCT and other supersonic examples students spent a considerable amount of time studying the stability and controllability of alternative wing / control surface planforms using a hierarchy of aerodynamic simulation techniques from a commercial linear panel code to nonlinear Navier-Stokes CFD simulations (Fig. 2).

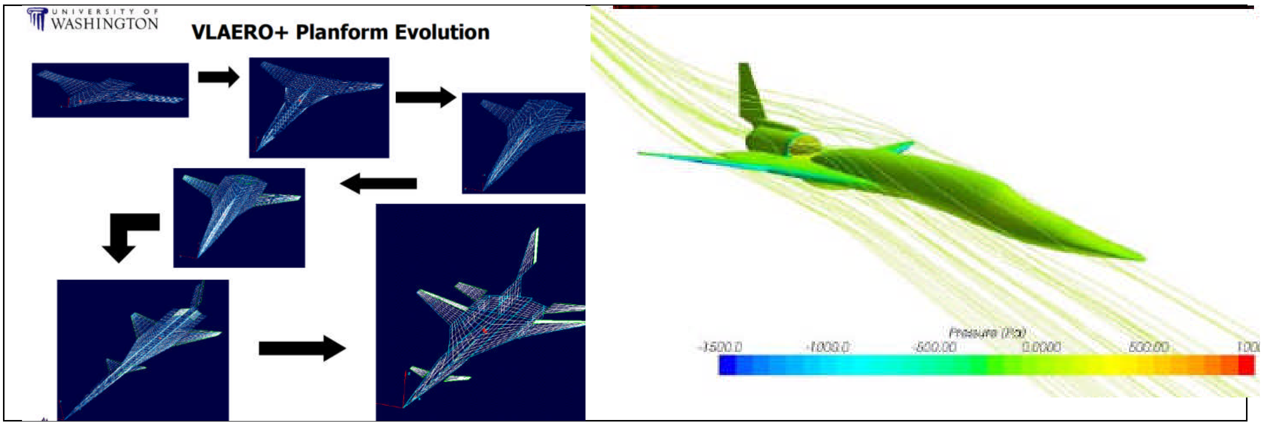


Figure 2: Panel code and STAR-CCM+ Navier-Stokes CFD simulations of the 2006 SSBJ design.

A final baseline configuration was down-selected out of the matrix of alternatives and was further developed to converge the vehicle sizing, define the preliminary outer mold line (OML) aerodynamic contours, propulsion and structural arrangement, estimated mass properties, and major systems and interior features. Based on this full scale configuration concept, a dynamically scaled UAV was designed, including structural layout, selection of materials based on available data and dedicated coupon tests, systems needs definition, and the selection of commercially adaptable propulsion, landing gear, controls, and all communication and flight test instrumentation systems. A wind tunnel model was built by Aeronautical Testing Service, Inc. (ATS), including parts for a large number of planform and control surface variations, and wind tunnel tests were carried out at the University of Washington's Kirsten 12ft x 8ft low speed wind tunnel. Such tests are crucial for the low-speed/ high angle of attack aerodynamic evaluation of supersonic configurations, where vortex shedding and vortex breakdown may play a significant role and can be hard to capture apriori using CFD. Similarly, tests of key UAV structural components are usually carried out each year (statically and dynamically) to validate finite element structural models.

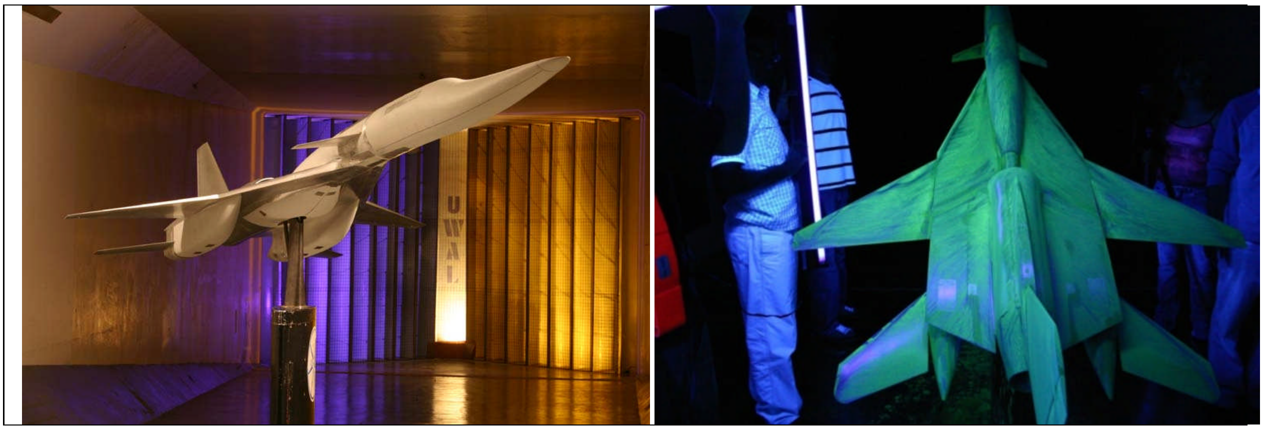


Figure 3: A 2006 model of a supersonic cruise configuration installed at the University of Washington's 12' x 8' low speed Kirsten Wind Tunnel (left) with China Clay flow visualization patterns at a high angle of attack (right).

With the conclusion of the wind tunnel tests the final UAV configuration was frozen and UAV detail design could proceed, followed by construction, systems integration, systems tests, ground tests, and first flight of the vehicle.

Figure 3 shows the wind tunnel model in one of its configurations at the Kirsten Wind Tunnel together with a China Clay flow visualization pattern representing a particular angle of attack and tunnel dynamic pressure. Students in the capstone airplane design courses in general spend a considerable amount of time working with the wind tunnel model in the tunnel during tests and developing greater insights into the aerodynamic issues involved. They are required to correlate measured wind tunnel results with CFD and handbook predictions which usually results in improvements to the configuration, improvements to the CFD solutions, or both. CFD has also been helpful in understanding configuration-specific wind tunnel support interference and tunnel wall effects.

During the wind tunnel tests of the 2006 configurations 622 runs were carried out over 11 shifts. Variations of the tested configurations included three outboard wing planforms, two canard planforms in four locations, two stabilizer sizes at two heights, outboard wind dihedral variations, drooped leading edge and trailing edge control surfaces, forebody chines, two vertical tail chords and rudders at two longitudinal locations. The tests also covered ground effects, and thrust effects (with an EDF powered nacelle) in complete angle of attack and side-slip angle sweeps.

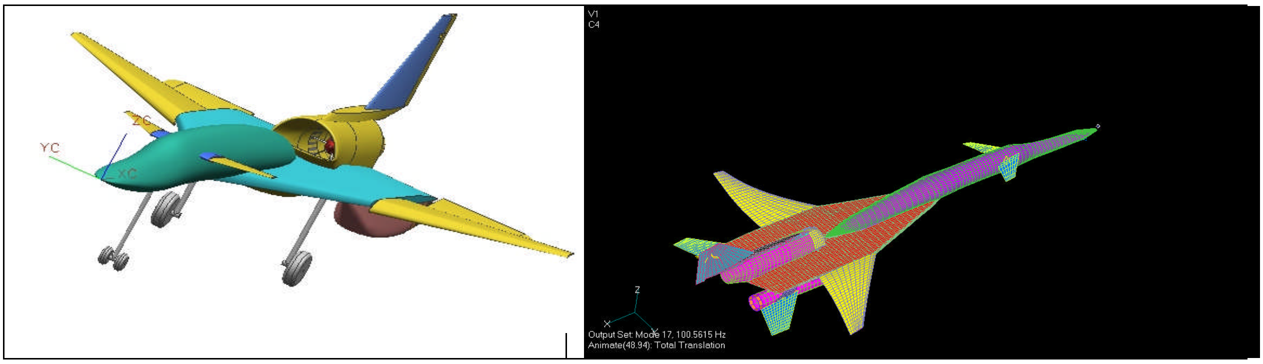


Figure 4: A CAD definition (Unigraphics) and FEMAP/NASTRAN models of the 2006 UAV.

A Unigraphics CAD definition of the 2006 UAV and a rear ¾-view image of its FEMAP/NASTRAN model are presented in Figure 4, while pictures showing the construction of the UAV are shown in Figure 5. The outer shell of the airframe is made of Kevlar cloth/Epoxy layups. The wing ribs, spars, body keels, and body frames are of carbon fiber/Epoxy and Divinycell-core sandwich construction. The nose gear mount is a student-designed machined aluminum structure and most other fittings and fasteners are metal. The larger size and higher design airspeeds of the UW capstone UAVs provides experience with modern composite construction similar to that of full-scale aircraft to a much greater extent than is practical on the modest, lower cost radio controlled foam and balsa wood models used in DBF competitions or in design courses that split each class into multiple DBF-like projects. Students must choose their materials and structural arrangement for fabrication and assembly considerations as well as strength, stiffness, and light weight. Classroom structures theory, load-paths, stress concentrations, and fastener edge margins, and systems accessibility take on tangible importance for the UAV element of the course---lessons that are not easy to teach effectively in “paper study only” type design courses.

A key airframe design decision is whether it is better to design a component with high damage tolerance (but usually more difficult fabrication or higher weight) versus designing for easier reparability (or replacement). Prior to 2009, Kevlar/Epoxy was extensively used in University of Washington UAVs to help minimize damage to the airframe in case of a crash (especially when pitch-up-sensitive aerodynamically nonlinear configurations were being investigated). With growing confidence in the program’s capability to design and fly complex small UAVs successfully the Kevlar outer shell design philosophy was replaced by lighter weight optimized Glass/Epoxy skins, with both Graphite and Kevlar still used for internal structure where beneficial.

As Figure 5 shows, the University of Washington's UAVs are built completely by the students using wet layup into female moulds machined from tooling foam by ATS based on the students' UAV CAD model, or using male moulds built directly by the students. NC water-jet cut metal templates are used as guides to fabricating some sub-components such as pre-contoured dull-depth foam cores for glass-skinned tail surfaces. The hands-on construction experience supported by coupon tests, structural tests of components, and structural tests of the complete vehicle offer the students insight and end-to-end project experience regarding airframe design, composite construction, math modeling techniques and their uses and limitations.

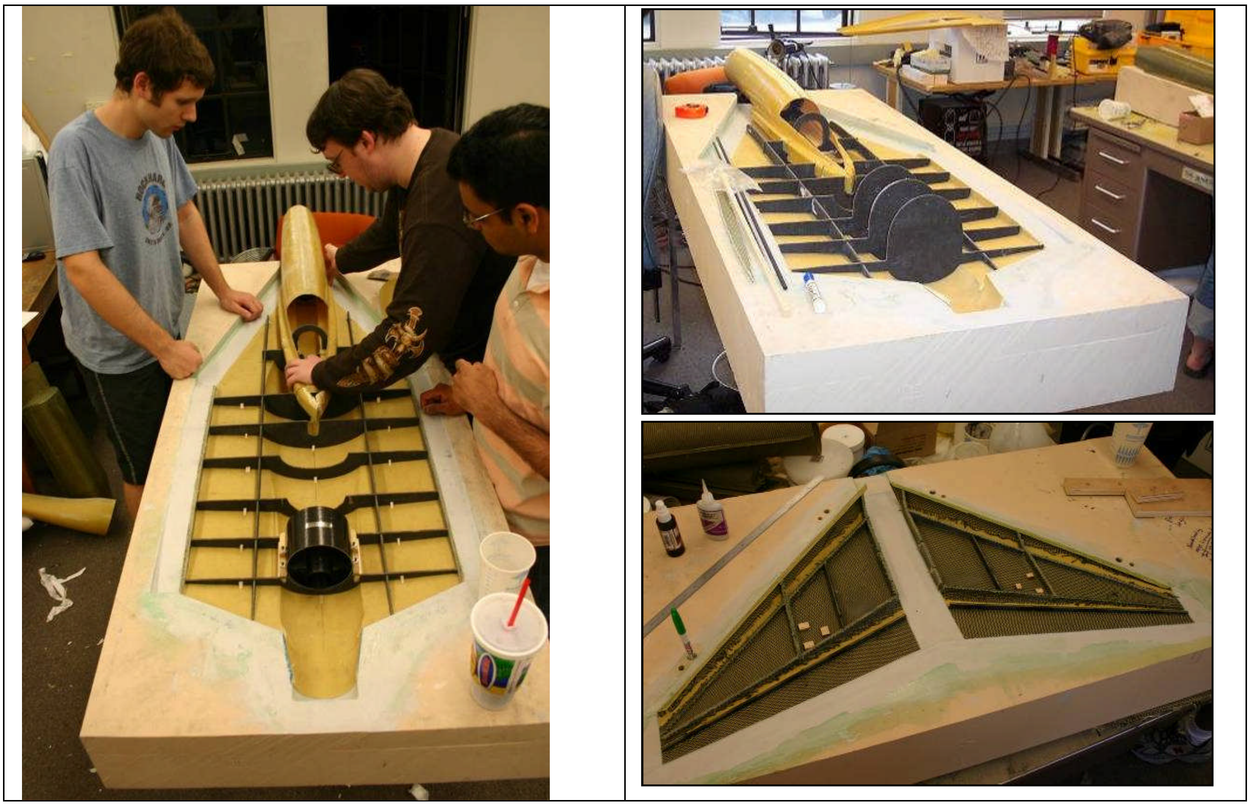


Figure 5: Kevlar/Epoxy and Graphite/Epoxy Construction of the University of Washington's 2006 UAV.

Figure 5 also shows the 120mm sized electric ducted fan used to propel the 2006 UAV. While the configuration selected and developed was a 3-engine airplane, only one large 14-15 lbf thrust EDF was used on the UAVs center nacelle for propulsion. Wind tunnel tests included powered tests with the center engine operating in the wind tunnel and the two wing nacelle inlets domed-over. Motor higher temperatures than expected during operation were reduced by the student team using a set of cooling fins quickly designed, built, attached to the motor, and tested in the wind tunnel.

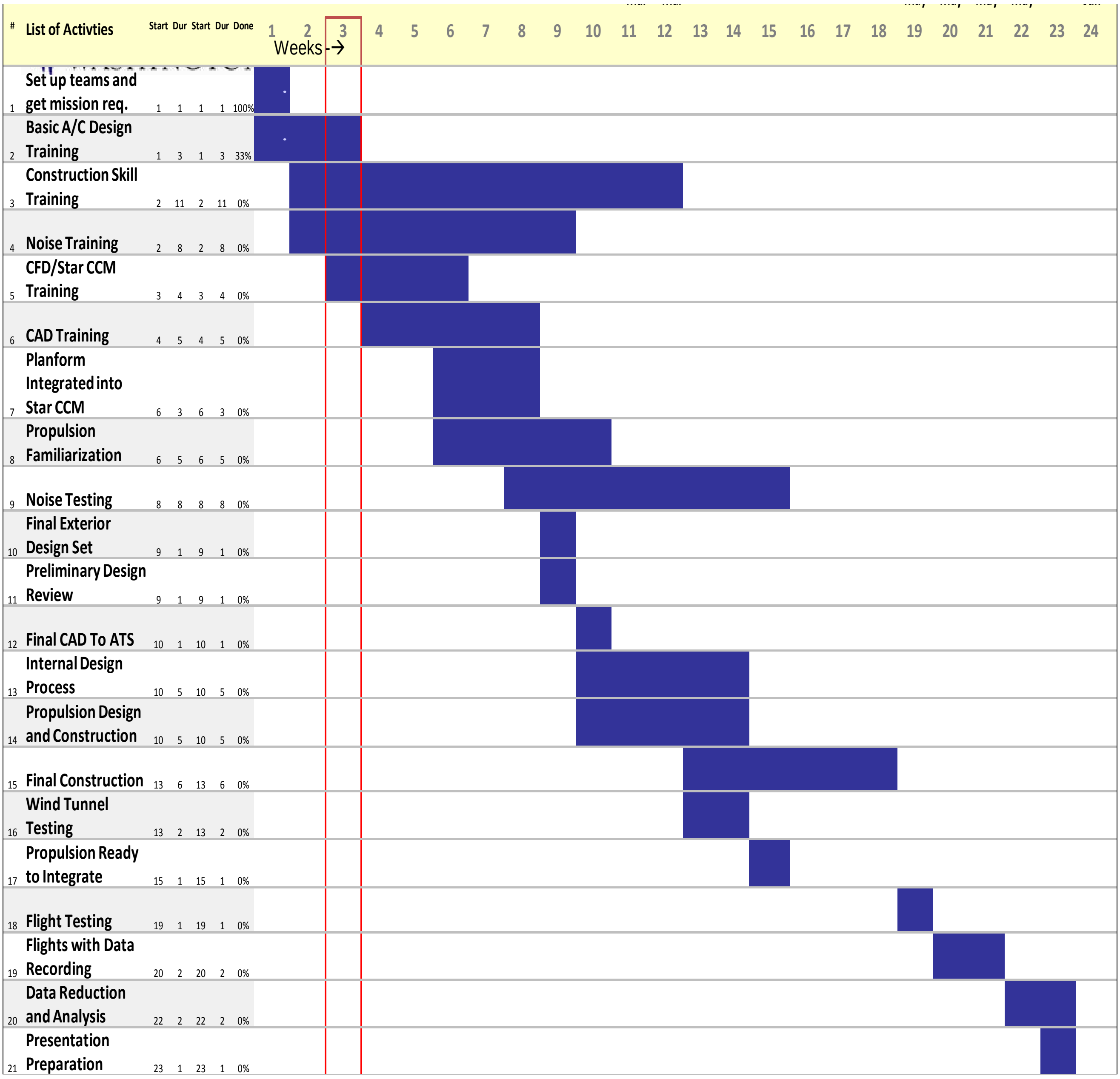
The as-built 2006 UAV is 9.5 ft long, 4.5 ft in span. It weighs 30 lbs and has a thrust to weight ratio of 0.5. Its wing reference area is 7.06 ft^2 and its wing loading is 4.25 psf. It is a 6.76% scaled model of the full configuration.

Figure 6: The 2006 University of Washington's slender SSBJ configuration research UAV

An X-Plane simulation model and the actual UAV in flight are shown in Figure 7. X-Plane is a commercially available desktop PC based flight simulator that has been used effectively in the capstone airplane design course for flight stability and control (S&C) instruction and rapid evaluation of the configuration along its path of development. Uses of this software have expanded as the simulation package has become more capable in later versions, including for pre-flight test rehearsal of the UAVs operation. Piloted simulator use is augmented later in the project by Matlab/Simulink simulations driven by CFD and wind tunnel based aerodynamic data.

Figure 8 shows the nominal class schedule which targets the completion of a flight-ready UAV at the 20 week point. While every effort is made to test fly the UAV before "finals week", the completed UAV roll-out date, weather, test facility availability, and other uncontrollable factors can delay UAV first flight dates beyond the final week (at no grade penalty to the students). Initial tests of the 2006 UAV identified some needed systems modifications but unfortunately occurred too late in the academic year to allow for additional test outings during the course. Needed modifications were subsequently carried out and the UAV was finally successfully demonstrated in 2008.

Figure 7: An X-Plane simulation model of the 2006 UAV and the actual UAV in flight.



#	List of Activties	Start	Dur	Start	Dur	Done
1	Set up teams and get mission req.	1	1	1	1	100%
2	Basic A/C Design Training	1	3	1	3	33%
3	Construction Skill Training	2	11	2	11	0%
4	Noise Training	2	8	2	8	0%
5	CFD/Star CCM Training	3	4	3	4	0%
6	CAD Training	4	5	4	5	0%
7	Planform Integrated into Star CCM	6	3	6	3	0%
8	Propulsion Familiarization	6	5	6	5	0%
9	Noise Testing	8	8	8	8	0%
10	Final Exterior Design Set	9	1	9	1	0%
11	Preliminary Design Review	9	1	9	1	0%
12	Final CAD To ATS	10	1	10	1	0%
13	Internal Design Process	10	5	10	5	0%
14	Propulsion Design and Construction	10	5	10	5	0%
15	Final Construction	13	6	13	6	0%
16	Wind Tunnel Testing	13	2	13	2	0%
17	Propulsion Ready to Integrate	15	1	15	1	0%
18	Flight Testing	19	1	19	1	0%
19	Flights with Data Recording	20	2	20	2	0%
20	Data Reduction and Analysis	22	2	22	2	0%
21	Presentation Preparation	23	1	23	1	0%

Figure 8: A typical planned schedule for the capstone design course (a few activities are omitted for brevity).

Structure and Schedule of the Capstone Airplane Design Course

With the 2006 project in mind as an example, we can further consider the structure and schedule of the capstone course as it has evolved to the present form. At the University of Washington students arrive at the capstone airplane design course at the beginning of the winter quarter of their senior year. The course spans ten academic weeks of the winter quarter followed by ten academic weeks of the spring quarter, from the beginning of January to Mid June (24 calendar-weeks elapsed time). The students bring with them, usually, a diverse mix of prior experiences in the key disciplines affecting airplane design, the design process itself, and the construction, instrumentation, and flying of small UAVs. Some would have some prior R/C model design experience through participation in earlier years in

AIAA design-build-fly competitions (or as individual hobbyists). Most students arrive with no airplane design experience at all, and while students bring with them an academic foundation in aerodynamics, structures, S&C, and performance, they usually lack a solid understanding regarding how these disciplines blend and affect the design through interactions and trade-offs. Often students' mastery of the key aeronautical disciplines is more basic than applied – the result of university education aimed at building strong fundamental knowledge that would give engineers throughout long professional careers the capability to shift focus, adjust, meet new challenges, and tackle unconventional problems.

In the early years of the design course development the three to four first weeks of the winter quarter would be used for a review, from the perspective of airplane design, of applied aerodynamics, structures, propulsion, performance, and stability and control, and the introduction to the fundamentals of airplane design including mission analysis, airplane design objectives and constraints, weight sizing, wing sizing, propulsion system sizing, and control surface sizing. The first week also included discussions of important airplanes, their configurations, and their success or failure stories, followed by a discussion of the airplane design process and the organization of airplane design teams.

The students would then be asked to select the discipline teams they would contribute to, with each student required to be a contributing member of at least two teams including: project management, CAD, performance, aerodynamics (including computational aerodynamics and wind tunnel testing), structures (computational and experimental, including materials, loads and aeroelasticity), stability & control (including X-Plane and Matlab/Simulink, propulsion (including propulsion / airframe integration), systems (including landing gear, control, communication, and flight tests instrumentation and data acquisition), and construction. In years where noise issues were part of the issues the design had to tackle there would be an acoustics team. The project management team would cover schedule and cost aspects of the project and collect from students detailed information about the hours they worked divided into training, analysis, design, test, construction, and management hours. Weight and balance would be covered by dedicated students in either the management or structures teams. They would guide development and update weight and moments of inertia estimates frequently based on structural element property data from previous years, coupon tests, sub-structure tests, and the careful accounting for all non-structural items and their locations. The class would elect two project co-leaders and a team leader for each of the discipline groups.

With fundamentals refreshed and new required material covered and with team, team leaders, and project leaders in place, the class would be ready at the end of four weeks or so for the introduction of the design challenge for the year and the beginning of the conceptual design process. Students, however, seemed to be a bit unhappy with this week by week evolution of the course. With passion for airplanes and after enduring over their freshmen through junior years what seemed to them a set of disjoined courses focusing on details while missing the airplane as a whole, they wanted a design challenge and a beginning of an active airplane design process right at the beginning of the design course. In response, the structure of the course was changed to allow the design-oriented review of fundamentals and introduction to airplane design to run simultaneously with an introduction of a design challenge for the year, the lectures by experts on topics of importance related to the challenge, and the beginning of the conceptual design process. Once this first phase of the course is completed (in about 5-6 weeks) the student team would proceed to conclude the conceptual design and begin working on preliminary design. Simultaneously an intensive training effort would begin for each team to learn and master the analysis, design and development capabilities it would need. This includes FEMAP/NASTRAN training, STAR-CCM+ training (the CFD capability used for the course), Unigraphics (CAD), X-Plane, control, communication, and data acquisition systems used on UAVs from previous years, noise measurement and data acquisition, material, structural, and wind tunnel testing techniques, and more. Progress in the preliminary design process is made while students are still being trained in their respective disciplines. Naturally, of major importance in the early stages of training for the project are CAD and CFD analyses together with systems training that would lead to specification and selection of those systems which have to be ordered early. In some cases, a smaller foam model of the configuration would be quickly built or a UAV from a previous year used to flight test key systems early in the project and well ahead of their installation in the final UAV. The rest of winter quarter would see a shift from conceptual to preliminary design with better mastery of the analysis, design, and test tools used leading to a preliminary design review (PDR) at the end of the winter quarter. A PDR CAD definition of the airplane should also be ready at the end of winter quarter and it would be shipped to the model NC machine shop at ATS for the design and fabrication of the wind tunnel test article for testing to be carried out early in the spring. Spring quarter, in what follows, is devoted to detail design, wind tunnel tests, construction, systems tests, systems integration, structural analysis and tests, final aerodynamic and weights analysis, performance analysis and final stability and control simulations in preparation for flight tests and the final design review at the end of the academic year.

A representative planned schedule for the design project is shown in Figure 8. This particular schedule does not show all activities but it captures overall the pace and planned progress of the course. Quite often plans for flight tests have to be changed and pushed back due to manufacturing delays, changes in the wind tunnel dates, and, unsurprisingly, the unpredictable weather of the Pacific Northwest. All in all, students begin the capstone airplane design course at the beginning of January. By the first week of June, after twenty academic weeks, a complete research UAV of considerable complexity and innovation is ready for flight, almost ready for flight, or has already flown. This is accomplished by between 25 to 30 students under the guidance of the authors and with significant help from ATS and a world class R/C pilot, modeler, and small jet engine expert from the Whidbey Island, WA, chapter of the AMA.

One-year versus Multi-year Undergraduate Airplane Design Projects

The explosive development of radio controlled (R/C) model technology and the growing availability of inexpensive construction materials, propulsion systems, landing gears, as well as controls, communications, and data acquisition systems over the last 15 years have made it possible for student teams participating in design competitions and for engineering education programs to benefit from significant hands-on student experience with R/C models – the “build-fly” of the “design-build-fly” process. Indeed, more and more aerospace engineering departments around the world include design, build, fly experiences in their capstone airplane design courses, and the success, in terms of the number of team participating, of the AIAA design-build-fly (DBF) competitions has been impressive.

But when design challenges of the complexity and scope presented to University of Washington seniors are considered, together with the requirements for thorough industry-level engineering analysis and testing, and when the limited number of academic weeks the capstone design course covers is taken into account, it becomes clear that a tradeoff exists between complexity and engineering rigor on one hand, which mean a longer time required for the completion of the design process and construction of the flight vehicle, and the time left for student flight test experience with UAVS carrying sophisticated systems and avionics.

It may be argued that a capstone airplane design course should end with a completed design ready for flight and that flight tests should be the subject of dedicated courses. And yet, some flight testing experience is important for the education of any designer. And that is not only because of the opportunity to “close the loop” and gain insight by comparing the performance of the real vehicle in all areas to the predictions used as a basis for designing it. Flight testing experience, especially at its first stages, brings to light problems with systems and components, sheds light on issues of reliability, accessibility, and ease of maintenance, and, in general, feeds back important information that should be part of the design process from its start.

To expose seniors to significant flight testing experience with highly instrumented UAVs once completed would require one of the following: (i) Extension of the capstone design course from two to three quarters; (ii) presentation of design challenges to the students that focus on the aerodynamic/structural/control/propulsion/performance improvement of current operational UAVs, allowing the capstone design team to complete its flight vehicle for the year more quickly and fly it taking advantage on the proven systems it already has; or (iii) stretching the design challenges over more than one year by carefully planning challenges and end products each year to allow the continued evolution of complex UAVs from year to year with more time available for thorough flight testing.

The second option – challenging the students to significantly improve an operational vehicle in order to allow more time for testing with full system functionality – was tried the 1990s (see Ref. 1) and led to major student protests. The students, almost uniformly, stated in their instruction evaluation sheets and in personal meetings that it was very important for them to feel ownership of their design, including its development from scratch, and that any "imposition" on them (in their language) of designs conceived by others meant a blow to their dreams about designing airplanes they could consider as their own creations. So great is the sensitivity of airplane design students to this issue that in one of the more recent years, while working on a design of another supersonic business jet configuration, even when given full autonomy to select the final configuration out of the alternatives they generated during conceptual design, many of them protested that too much guidance by the faculty leading this course pushed towards a configuration of particular interest to the faculty.

It is a challenge, then, to balance this passion of airplane design students for creating their own designs with the interests of sponsors and advisers which may be focused on particular solutions. For many years the University of Washington airplane design course presented its students each year with a new and fresh challenge. And through balancing of students desires and passions with the interests of sponsors, based on thorough review of conceptual alternatives and lively class and design team discussions, design work in the capstone design course for many years now has managed to please both students and sponsors.

With the above factors in mind, one can further examine the recent evolution of University of Washington capstone projects since 2007.

The 2007 University of Washington Capstone Design Project

Motivated by the desire of NASA to develop a supersonic cruise test airplane for sonic boom research, and based on initial estimates by Boeing that a modified F16-XL might be an economically desirable option, the design challenge for the 2007 capstone design class was to develop two low-sonic boom airplane concepts based on the F16-XL with a focus on maintaining desirable low-speed performance and stability characteristics. A final candidate configuration had then to be selected and validated based on wind tunnel tests, including comparisons to the original F16-XL configuration. A scaled UAV of the final configuration had to be built and flight tested.

Figure 9: The two finalist competing design for the modification of an F16-XL to a low-boom research aircraft.

In view of the discussion in the last section, much care was taken to make sure students knew they had full freedom to pursue designs they would feel ownership of. Indeed, after considering a number of alternatives two leading competing designs emerged (Fig. 9). Wind tunnel tests included the finalist configurations plus an original F16-XL configuration and involved numerous variations and modifications of the configurations in the wind tunnel (Fig. 10) to achieve desirable longitudinal and lateral-directional stability and control.

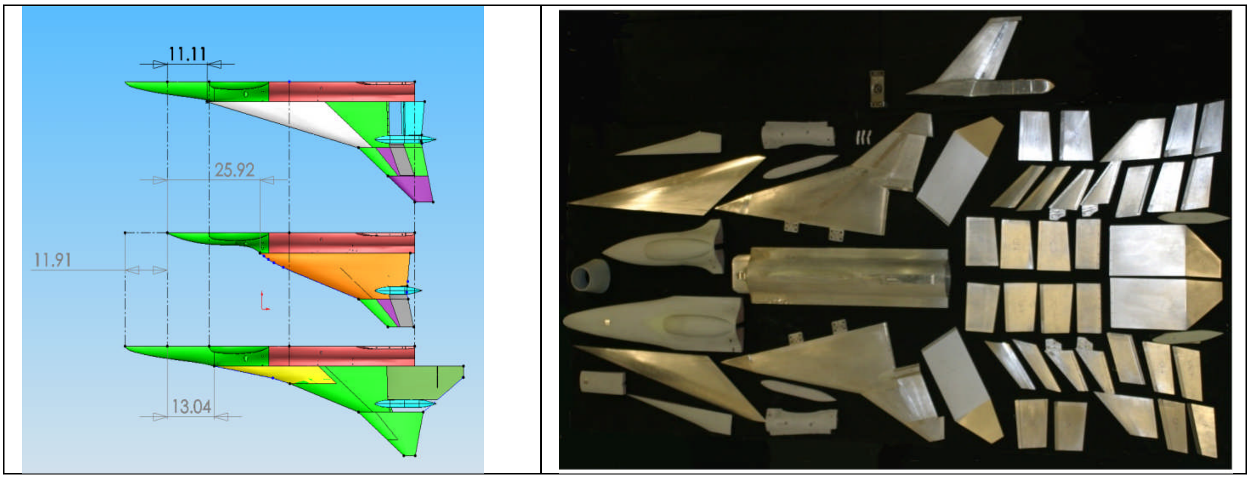


Figure 10: Wind tunnel configurations and models tested at the Kirsten Wind Tunnel for the 2007 capstone airplane design course. Wind tunnel model developed built by Aeronautical Testing Service, Inc., of Arlington, WA.

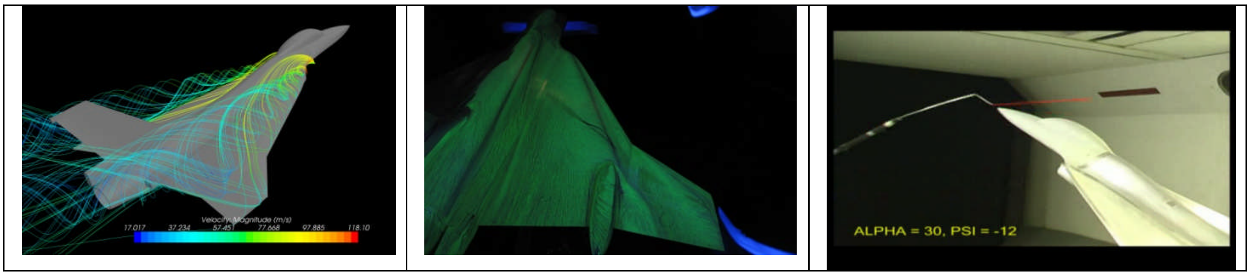


Figure 11: CFD simulations, china clay flow visualization, and smoke flow visualization on a low sonic boom modified F16-XL configuration in the Kirsten wind tunnel, 2007.

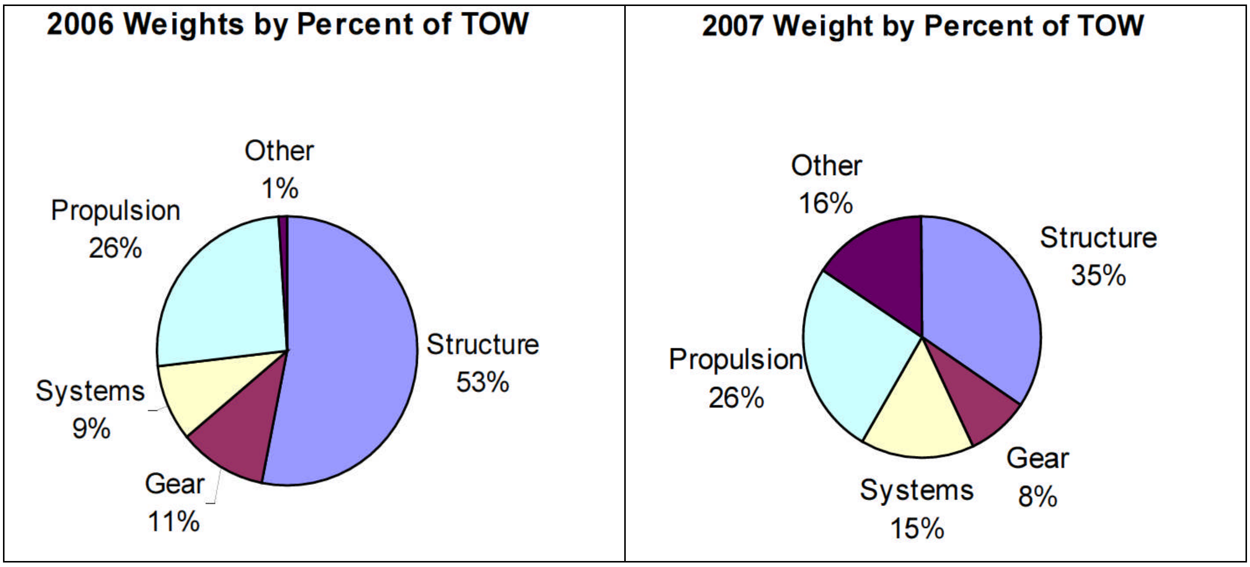


Figure 12: Weight breakdown for the 2006 and 2007 University of Washington UAVs. Note: Kevlar/Epoxy airframe shell construction was replaced in recent years by lighter weight Glass/Epoxy.

As expected, pitch-up and directional stability issues are significant challenges for such a modification of the F16-XL platform, and an extended exploration ensued involving a number of aerodynamic “fixes” in the wind tunnel CFD simulations, and correlation of CFD simulations with wind tunnel tests (Fig. 11). All in all eleven 10-hour shifts of wind tunnel testing (more than 300 runs) covered numerous design variations of supersonic candidate low-sonic-boom configurations.

The 2007 UAV was built, based on students design team decision, around the partial fuselage and landing gear of an off the shelf F16 R/C model. New wings (with Kevlar/Epoxy skins) and major modifications of the fuselage were made. The UAV was propelled by an 8 lbf static thrust electric ducted fan and was instrumented for flight tests. Total take-off weight was 16.5 lbs (T/W=0.485, minimum design requirement = 0.4). The airplane was calculated to have 5 min and 40 seconds endurance at 75% throttle (design requirement was 6 minutes). A weight fractions breakdown comparison of the 2006 and 2007 UAVs is shown in Figure 12.

The 2007 UAV flew in June 2007 (Figure 13), and as expected was moderately stable and controllable at low angles of attack. But at moderate alpha conditions the model would tend to porpoise, and upon a tight turn it lost all stability, pitched up, departed in roll and yaw, and tumbled to a fairly soft impact in tall grass in nearly level attitude. The post flight investigation revealed that, a) changes to the instrumentation battery configuration just prior to the flight resulted in a test CG that was actually behind the aft limit without pitch augmentation, and b) the real-time alpha sensing telemetry which was intended to warn the pilot if his angle of attack was approaching pitch-up boundary was inoperative. This flight provided a major lesson for the students about the importance of check lists, preparation, and careful and thorough procedures before first flight and any flight.

Because of the Kevlar/Epoxy construction of the wings and parts of the fuselage, the damage the vehicle sustained upon impact was minor. Major lessons from the 2007 design project included insight and experience regarding high angle of attack aerodynamics of slender configurations and the stability and control issues involved; the challenge of reliably capturing nonlinear aerodynamic behavior associated with vortex interactions and breakdown using CFD; the schedule and economic factors involved in the development of a research X configurations, and the decision process to determine which components can be taken from existing airplanes and which have to be built anew; the importance of careful planning and strict procedures in flight testing. As in every year, major CAD, structural finite element modeling and testing, stability and control, systems selection and integration, propulsion integration, performance, together with budget and weights simulation and design efforts were carried out.

Figure 13: Take-off of the University of Washington 2007 capstone design UAV.

The 2008 University of Washington Capstone Design Project

Motivated by the growing importance of “green” aviation, the focus of the 2008 capstone design course shifted to “regional jet” sized passenger airplane configurations with low community noise footprints. The challenge to the students was presented, in general terms, as “Develop a UAV to investigate the design issues and characteristics of a conventional airliner configured to provide airframe-shielding of propulsion system noise". The emphasis on "conventional airliners" configured for engine noise reduction tasked the students with suggesting noise reduction improvements while still preserving the known and well proven advantages of conventional airliner designs.

Figure 14 shows the resulting UAV and its CAD definition. The UAV was built with modular engine nacelles (Fig. 15) to allow placing the inlet and exhaust planes of the nacelles at different locations over the wing and the tail. The longest nozzle configuration features a slot to entrain external flow (a low pressure ratio ejector). An increased root-chord wing shifted back on the fuselage, together with a large U-shaped tail and engine nacelles lifted up on the rear of the fuselage are the key configuration features contributing to line-of-sight engine noise shielding on both the inlet and exhaust directions over a range of fly-over angles.

Highlighting aspects of the structural design, analysis, and testing in the 2008 capstone design effort, Figure 16 shows the NASTRAN finite element model and Figure 17 shows the finite element model of a test wing box built early in the design process to build confidence in the team's analysis capability and validate key structural design concepts. The test wing box had Kevlar/Epoxy skins and was divided by spars and ribs into relatively large internal compartments. With relatively thin skins the result was skin panels prone to buckling and with natural frequencies (for the panels) that led to noticeable participation of panel deformations in natural modes of vibration of the test wing box.

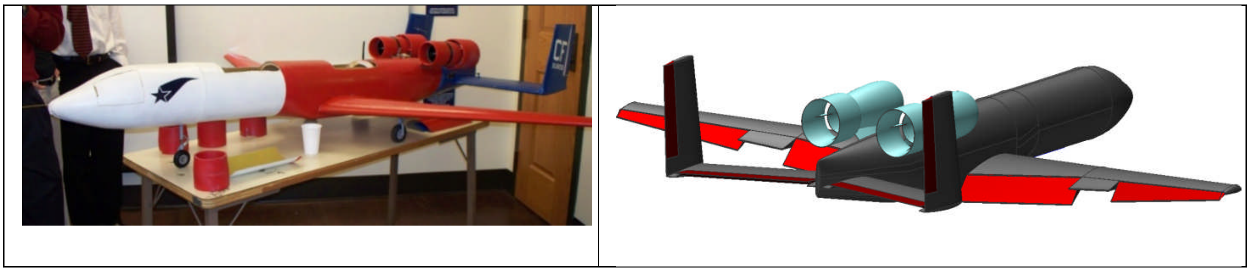


Figure 14: The 2008 University of Washington's capstone design UAV – a conventional airliner configuration modified for reduced propulsion system ground noise using airframe noise shielding.

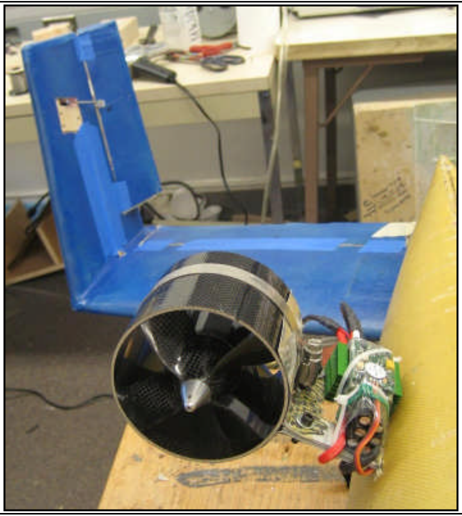


Figure 15 a

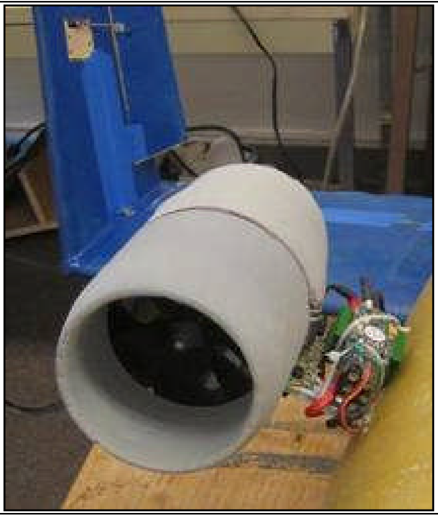


Figure 15 b

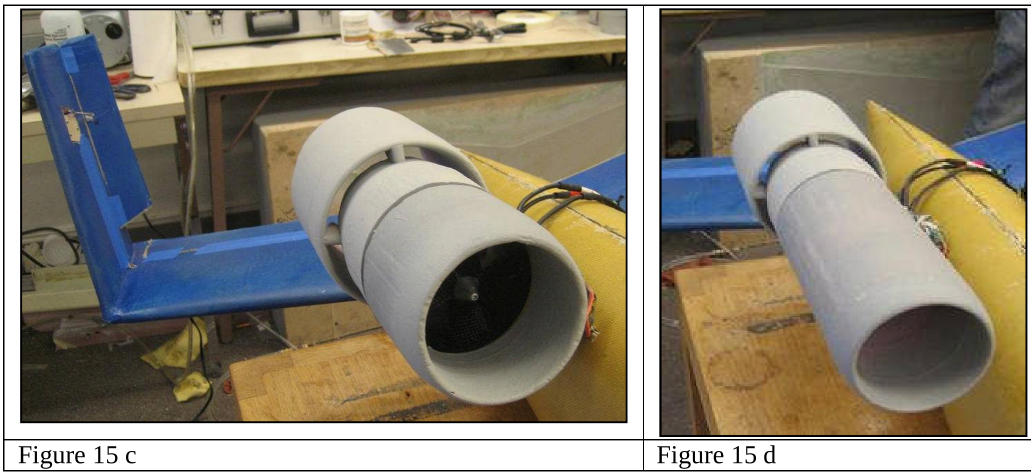


Figure 15 c

Figure 15 d

Figure 15: An electric ducted fan engine for the 2008 University of Washington UAV on its pylon (with the U tail behind it) plus the modular engine nacelle designs, which allow placing the propulsion system intake and exit nozzle at different locations over the root of the wing and the tail.

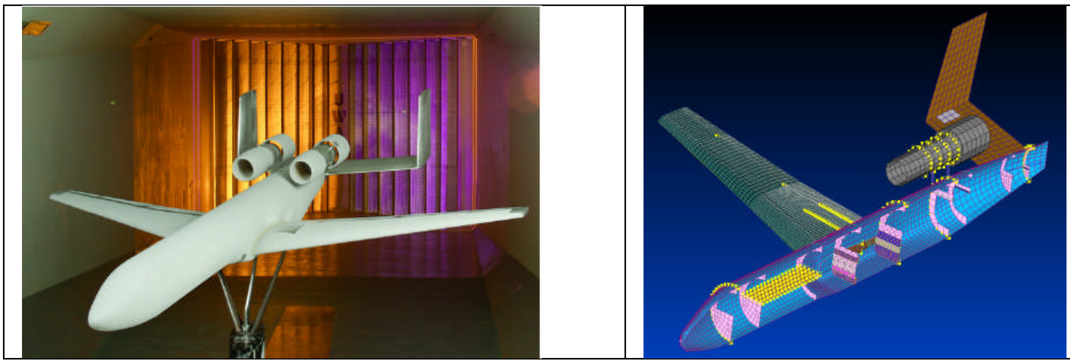


Figure 16: The 2008 UAV: the wind tunnel model in the Kirsten wind tunnel (left) and the NASTRAN model (right) showing mesh details and non-structural masses.

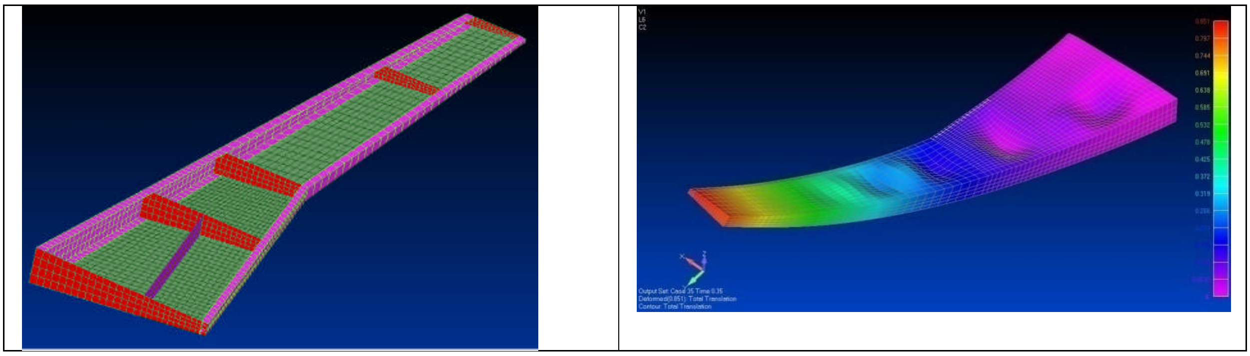


Figure 17: A NASTRAN model of the 2008 test wing box (left) and predicted nonlinear buckling deformation under load (right). Note: the first skin panel to buckle in the root area panel.

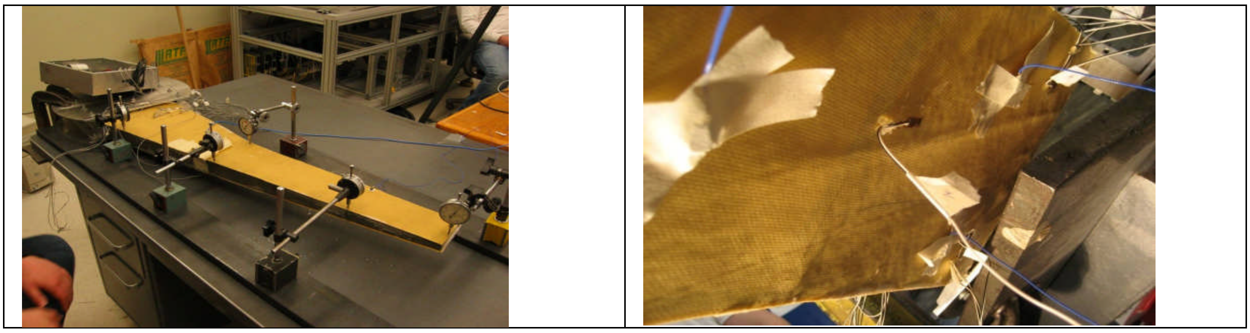


Figure 18: The 2008 test wing box (left) and an accelerometer attached to the root area panel expected to buckle first (right)

Figure 18 shows the test wing box in its testing jig (left) and a small accelerometer attached to the wing root predicted by NASTRAN linear and nonlinear simulations to buckle locally first. The natural frequency of that panel was tracked, using impact hammer excitation of the panel, as the loads on the test wing box were gradually increased, and the resulting reduction of panel natural frequency due to loss of effective stiffness was extrapolated to predict before buckling the load at which it would buckle. Surprisingly for such quite a complex configuration and given the inexperience of the students who were being trained in commercial FE modeling concurrently with supporting the design project, the correlation between numerical predictions and measured behavior regarding the failure of the test wing box was good.

Modal tests using an impact hammer and a Spectral Dynamics data acquisition and modal test system were carried out on the test wing box before it was loaded to failure and the correlation between predicted and measured natural modes was good (Figure 19). The missing measured modes in the correlation with the predicted modes all involve significant local panel motions which could not be measured because of the limited number of accelerometers used in the test. All aspects of the airplane design effort were covered thoroughly in 2008, including CAD, CFD work, wind tunnel tests (Fig. 16), performance, stability and control, systems and system integration, etc. The flight vehicle was ready for flight at the end of the spring quarter and flew flawlessly from Naval Station Whidbey Island in the summer of 2008. This model was successfully used to demonstrate the field recording of fly-over noise and has been used in two subsequent years as a test platform for capstone UAV systems and instrumentation. Although not the sleek machine of subsequent UAVs it remains in flying condition as an instruction asset for future classes.

As expected with such a configuration, stability and control concerns, while important, were not as critical as in the case of the supersonic configurations. The large tails and relatively low-sweep wing, with relatively thick airfoils and a simple trailing edge flap, maintained linear aerodynamic behavior up to normal stall angles of attack. Propulsion system / airframe integration as well as structural design and construction and its weight consequences were the focus of most discussions and team decisions. Different nacelle configurations for wind tunnel tests of the powered model are shown in Fig. 20. The 2008 UAV was the last to be built with a Kevlar/Epoxy shell for the airframe. With confidence in the course’s capability to lead student teams to produce successful UAVs, airframe design and construction in subsequent years switched to Glass/Epoxy skins for lighter weight and better manufacturability and finish.

NASTRAN Modes (Hz)	Measured Modes (Hz)
37.8	37.5
155.8	156.2
163.1	162.5
283.1	–
289.2	–
300.0	–
303.9	–
335.4	343.5
352.2	–
366.2	–

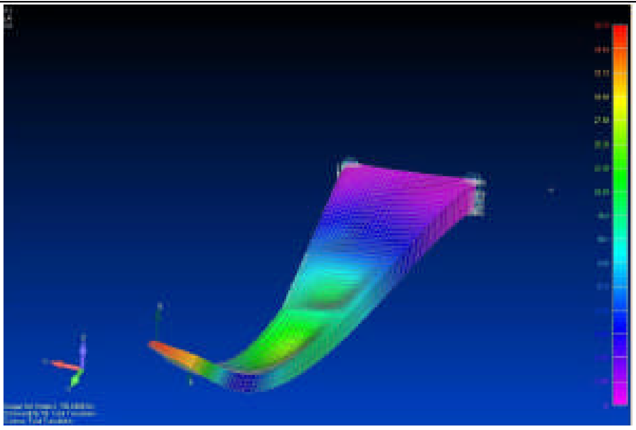


Figure 19: Predicted and measured natural frequencies of the 2008 test wing box (left) and the predicted second mode shape @155.8Hz (right)

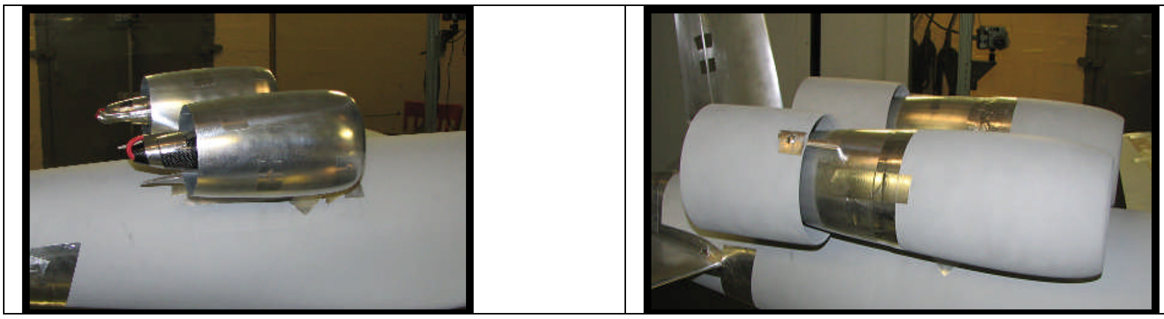


Figure 20: Different nacelles on the wind tunnel model of the 2008 UAV for powered wind tunnel tests.

The as-built 2008 UAV was 21.5 lbs in takeoff gross weight, had a span of 7 ft and length of 7.1 ft. It was propelled by two electric ducted fans with a combined manufacturer's rated static thrust of 16 lbs. The full rated did not materialize in wind tunnel tests of the engines and was significantly affected by the design of the nacelles and installed power system. Yet an airplane static thrust/weight ratio of more than 0.5 was obtained, which proved to be quite a good match for the airframe.

The 2009 Capstone Design Project

Shifting back to supersonic configurations and their low-speed characteristics with added requirements of noise shielding and turbojet UAV propulsion, the 2009 design challenge presented to the students was to design a UAV that would represent a Concorde-sized future supersonic airliner configuration with engine noise shielding by the airframe. The full-scale airliner concept would be consistent with the technology projections covered in recent NASA studies (N+2/N+3 Fundamental Aeronautics Program research). Some degree of departure from "exact scale" would be allowed so long as the following design guidelines were met while maintaining a reasonable representation of a notional supersonic airliner design…

Basic Turbojet UAV Performance:
Approach Speed < 35 kts
Endurance > 5 min
Max speed at least 50% greater than takeoff speed (high-lift leading edge configuration)
Thrust to weight > ~0.35
Take-off length < 500ft

Initial climb out in take off configuration ~7-10 degrees

Other requirements and guidance for the design included a configuration with an aspect ratio between 2.5 and 5, and a front fuselage ogive of 4:1 extending beyond the wing fuselage intersection. Active stability and control, such as a pitch augmentation system, was considered but determined to be an added complication that would not be undertaken on the 2009 year's project (with the exception of a simple yaw-damper). A significant new aspect to the project was the early decision to use fiberglass and carbon composite construction, as opposed to the previously used Kevlar composite as a primary material.

By the conclusion of the conceptual design phase the class had evaluated a number of alternatives, including a variable sweep wing concept, and down-selected to a final configuration having a cranked wing planform with canted "V- tails" with "ruddervator control surfaces". The engine nacelle was mounted on top of the fuselage with its exhaust plane pushed inboard to let exhaust jet flow over an aft deck surface and between the canted V-tails (Figure 21).

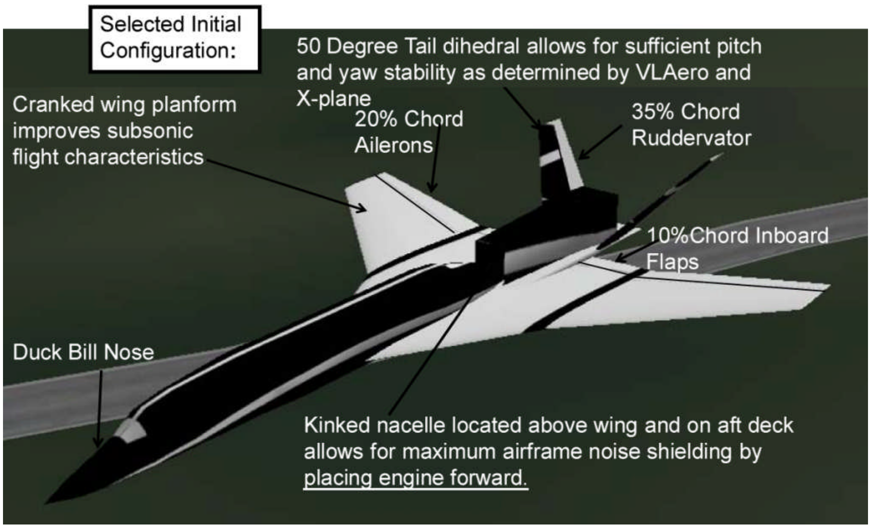


Figure 21: The selected 2009 UAV configuration.

Of major concern during the preliminary design of the 2009 UAV were the pitch-up and lateral-directional stability characteristics of the configuration, flow quality into the engine inlet at high angles of attack, and the thermal environment of the aft deck / tails area affecting the structural design of the airframe in that region.

The initial conceptual design of the planform was guided by high-speed civil transport (HSCT) experience and lessons from the 2006 and 2007 projects, but initial CFD studies of the configuration predicted early pitch-up due to vortex breakdown over the wing. With some skepticism about the early CFD results, which had been obtained in the very early stages of the student team's CFD training on the STAR-CCM+ Navier-Stokes code, the early CFD results were "taken under advisement" and a CDA definition deemed to be of moderate risk was transmitted to ATS to design and build the wind tunnel model. Wind tunnel tests, however, confirmed the early CFD findings and revealed serious stability and controllability problems with the original configuration at high angles of attack. This finding launched a major effort during wind tunnel tests to find configuration modifications that would solve the problems. Solutions proved more difficult than expected. In the end, only a combination of applied aerodynamic fixes, including wing fences, extension of the wing area rearwards in its inboard section, redesign of the strake, extending the V-tail chords, and scheduling full-span leading edge flaps solved the problem. Figure 22 shows CFD results at high angles of attack for the configuration without and with fences. Figure 23 shows the wind tunnel model at the Kirsten wind tunnel and a few of the aerodynamic modifications used to solve the pitch-up problem. Figure 24 shows wind tunnel measured lift and moment characteristics of the configuration before and after it had been fixed. Similar attention was given to the lateral-directional stability and control characteristics of the configuration ensure desirable characteristics and to allow radio-controlled flight without an on-board active control system.

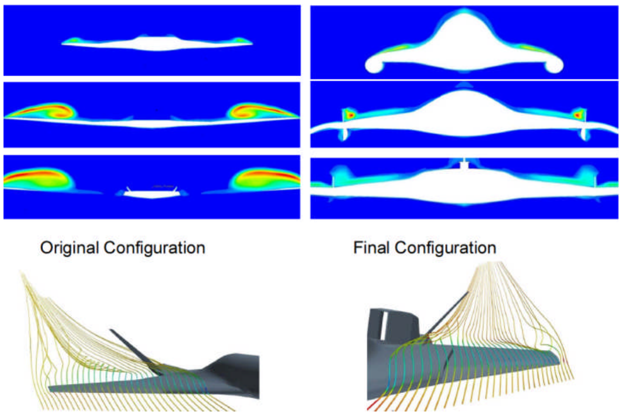


Figure 22: CFD results at high angles of attack for the 2009 configuration without and with fences.

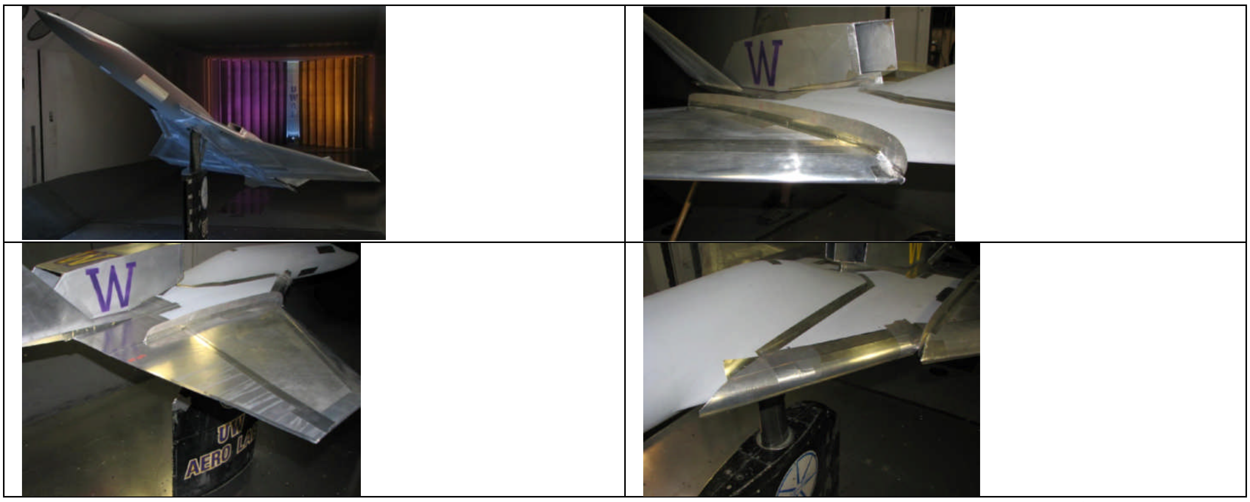
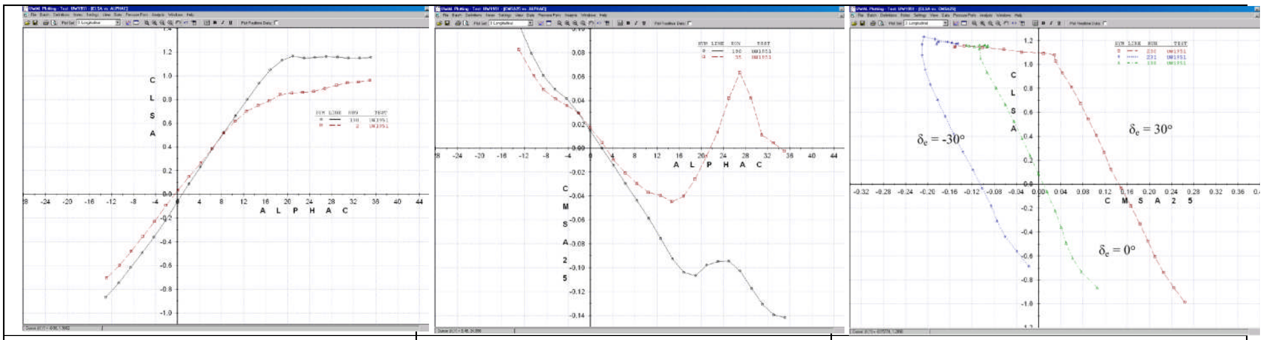


Figure 23: The 2009 wind tunnel model at the Kirsten wind tunnel plus selected applied aerodynamic fixes of the pitch-up problem, including fences, redesigned strake, and rearwards area increase of the inboard wing section.



a) CL vs. angle of attack	b) CM versus angle of attack	c) CL vs CM at different elevator settings

Figure 24: a) and b) Measured Lift and moments characteristics of the 2009 University of Washington UAV before (red) and after (dark) aerodynamic modifications, and c) measured control effectiveness of the final configuration. Zero sideslip-angle.

Another area of importance in the design and construction of the 2009 UAV was the airframe / propulsion integration with a turbojet engine – the first time a small jet-powered UAV was developed by undergraduate students at the University of Washington. The selected engine (based on Thrust/Weight requirements) was a PST-J800R turbine engine shown in its static ground test jig in Figure 25.

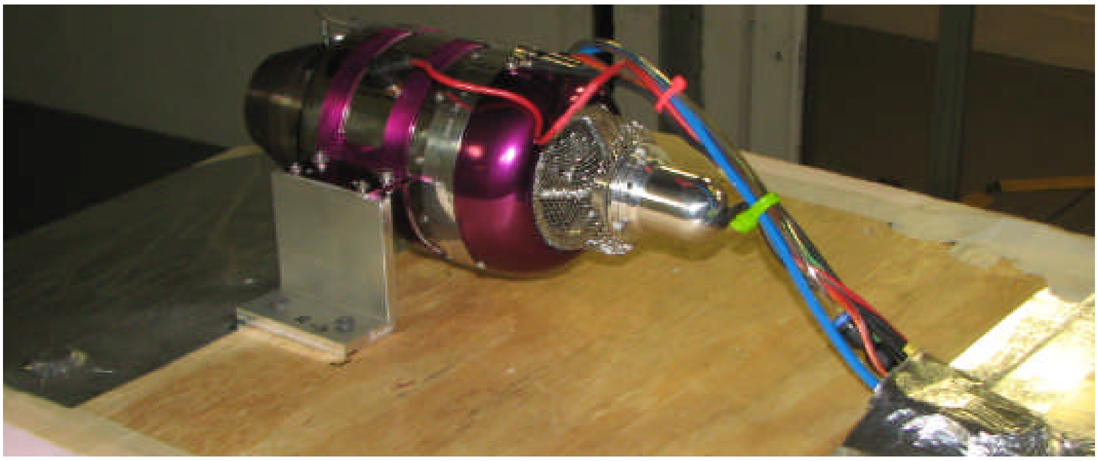


Figure 25: The PST-J800R engine on its test stand.

To meet early needs of the design process an engine/nacelle configuration was tested at the Kirsten wind tunnel to obtain thrust vs. speed characteristics at different angles of attack and yaw angles (Fig. 26). Careful drag and thrust build-up tests were carried out to extract engine, nacelle, and combined engine/nacelle thrust/drag characteristics. As has already been stated, one of the goals of the 2009 configuration development was to study inlet flow quality issues at high angles of attack and sideslip angles with the nacelle mounted on top of the fuselage and wing.

The major influences affecting the selected airframe / propulsion system integration design features are shown in Figure 27.

Another concern was the thermal and acoustic fields at the exhaust /aft-deck areas. STAR-CCM+ CFD simulations were run to assess the width and temperature distribution of the engine exhaust plume field. Ground tests provided experimental temperature field and plume size data that were used to finalize the locations of the tail surfaces and design the structural layout of the tail section of the UAV (Figure 28).

Figure 26: a pylon/engine test article installed at the Kirsten wind tunnel on a pylon which includes fuel and instrumentation.

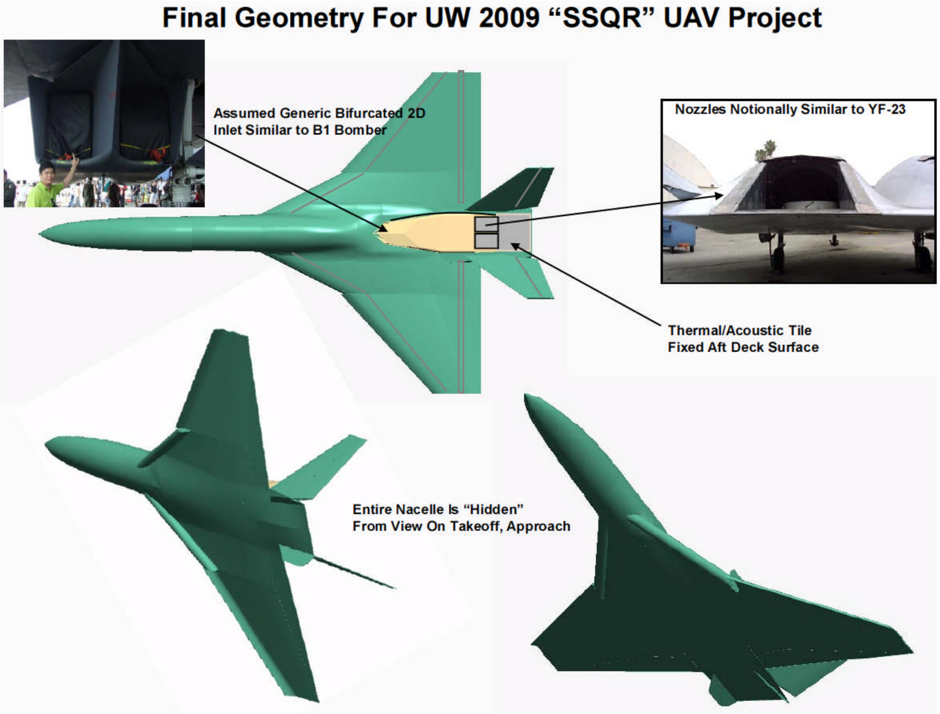


Figure 27: Key airframe / propulsion integration features selected for the University of Washington's 2009 UAV.

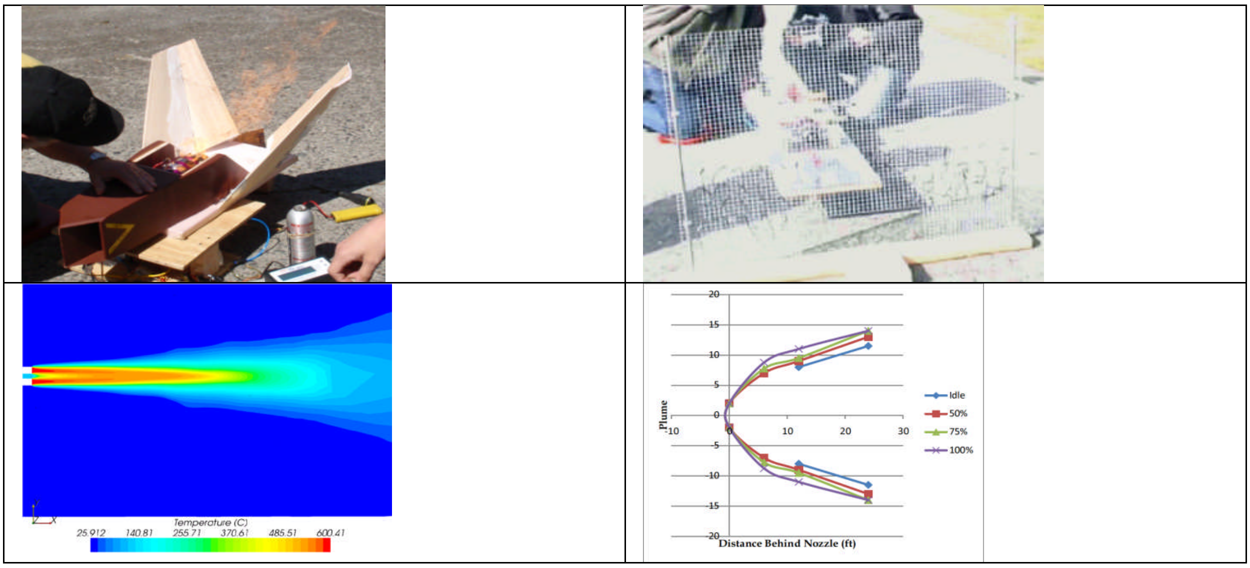


Figure 28: Ground tests and CFD simulations to map the temperature field behind the engine

Engine/airframe noise measurements were carried out over a grass field using a mock-up half-model airframe and later with the actual vehicle. Figure 29 shows the geometry of microphone points below and above the airplane, and the resulting sound pressure levels measured are shown in Figure 30. The significant reduction in sound pressure level under the vehicle is evident.

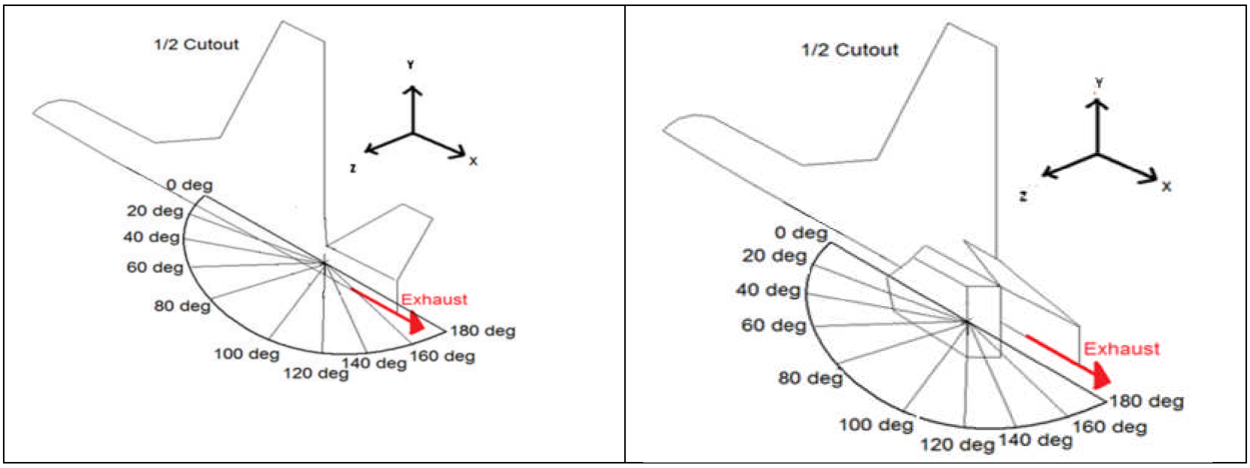


Figure 29: Microphone points below (left) and above (right) the UAV.

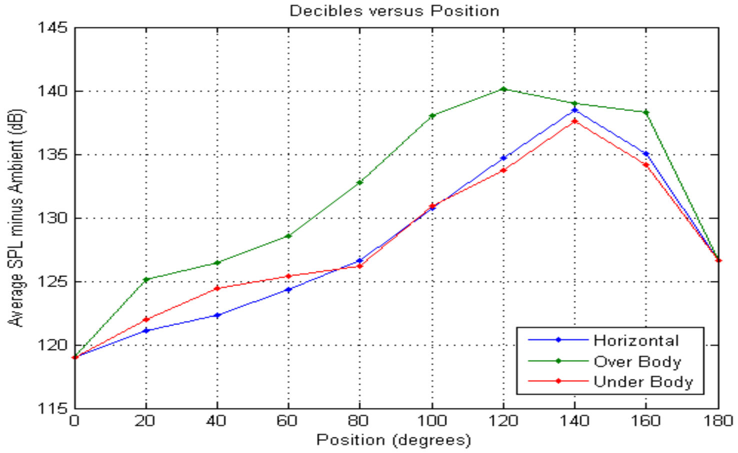
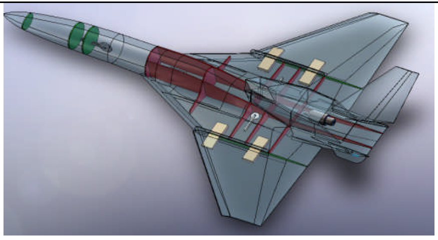


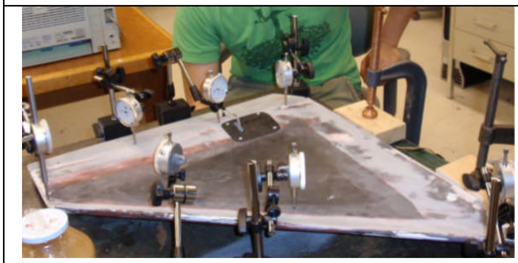
Figure 30: Sound pressure levels measured over the airframe (green), under the airframe (red) and to the side around the airframe (blue)

Detailed structural analysis, supported by static and modal tests of key components, was carried out (Figure 31).

A center of gravity travel diagram, created to account for CG shifts during fuel burning and landing gear extraction and retraction, is shown in Figure 32. The University of Washington’s 2009 UAV was flown successfully several times in the spring-summer of 2009 (Figure 33).



Mode Shape	Experimental	FEA
1	22.5 Hz	24 Hz
2	52 Hz	61 Hz
3	85 Hz	78 Hz
4	120 Hz	121 Hz
5	153 Hz	152 Hz



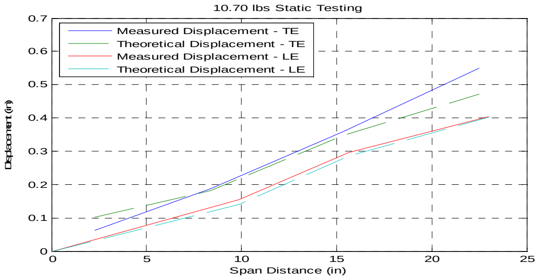


Figure 31: The structural arrangement of the 2009 UAV plus modal and static analysis and test results for the wing's outer panel.

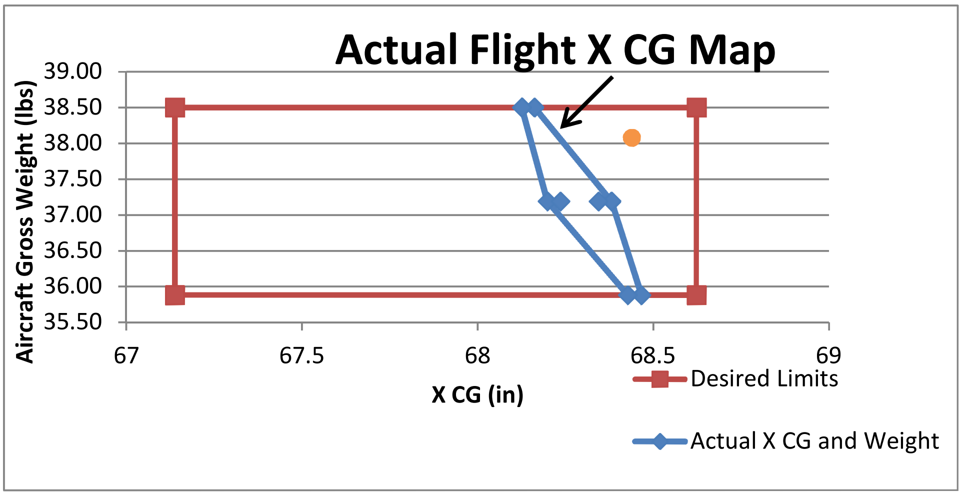


Figure 32: Center of gravity travel for the 2009 UAV.

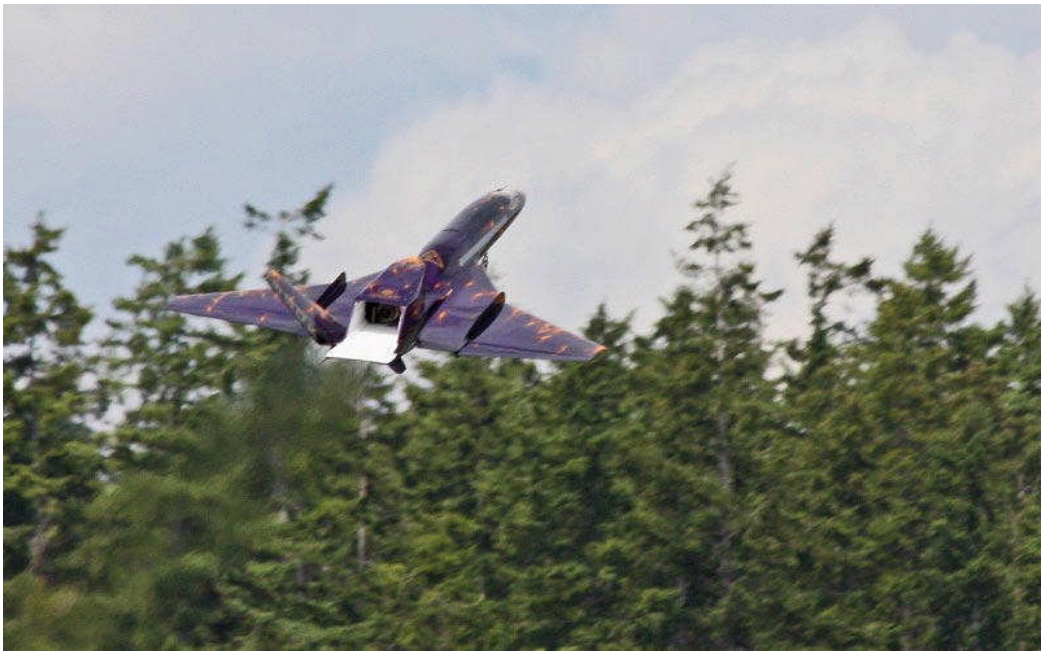


Figure 33: First take-off of the University of Washington's 2009 UAV.

The 2010 University of Washington's Capstone Airplane Design Challenge

Driven to continue the pursuit of engineering information and test results that would contribute to the development of supersonic commercial aircraft technology, the design challenge presented to the 2010 capstone airplane design seniors was, in general terms, to develop a new research UAV of a representative "quiet" supersonic configuration that would serve as a testbed for low-speed handling qualities evaluation and ground noise signature studies. The students were given complete freedom in the selection of their preferred configuration, and, indeed, the conceptual design stage included comparative evaluation of quite a number of supersonic configurations, including an evaluation of leading configurations built in the past or studied over the years by U.S. and international companies and government agencies. Key requirements presented to the students included: Good low-speed flight characteristics in a representative supersonic airliner configuration; enough endurance for meaningful flight testing; elements of engine noise shielding by the airframe; and the ability to carry a flight test data collection payload. The overall challenge was to design and build a research UAV that would be lighter than the 2009 UAV, better instrumented, and that would not require the aerodynamic pitch-up and lateral-directional "fixes" used to achieve desirable flight characteristics at low speeds and high angles of attack on the 2009 UAV.

The development of the resulting configuration involved substantial CFD studies of alternative planforms and airfoils (Fig. 34). During 9 days and 108 hours of wind tunnel tests including flow visualization, covering 425 runs, 46 different configurations (including 14 wing configurations and 13 horizontal and vertical tail options), and after correlating with CFD runs, the final configuration was frozen (Fig. 35). Figure 36 shows the model in the tunnel in one of the configurations tested together with a CFD predicted flow field, and correlation of CFD STAR-CCM+ results with wind tunnel results for drag and pitching moment. The difficulty in capturing the pitch up tendency at about 20 degrees angle of attack is due to the challenge of capturing by computation the complex flow field associated with vortex flow separation and breakdown over slender configurations. This is primarily related to mesh density, mesh topology and turbulence models used. Finer meshes and alternative turbulence models used would improve the CFD results, as had been the case in previous years such as 2007 and 2009 when similar flow fields had been studied. The main educational message to the students here, in addition to the insight and understanding of the configuration / flow interactions involved, is to be careful and thorough in using CFD results which may look graphically impressive and seem correct, but which may still miss important physics. For CFD codes to be used reliably they need to be "calibrated" to the specific class of configuration and flow features encountered.

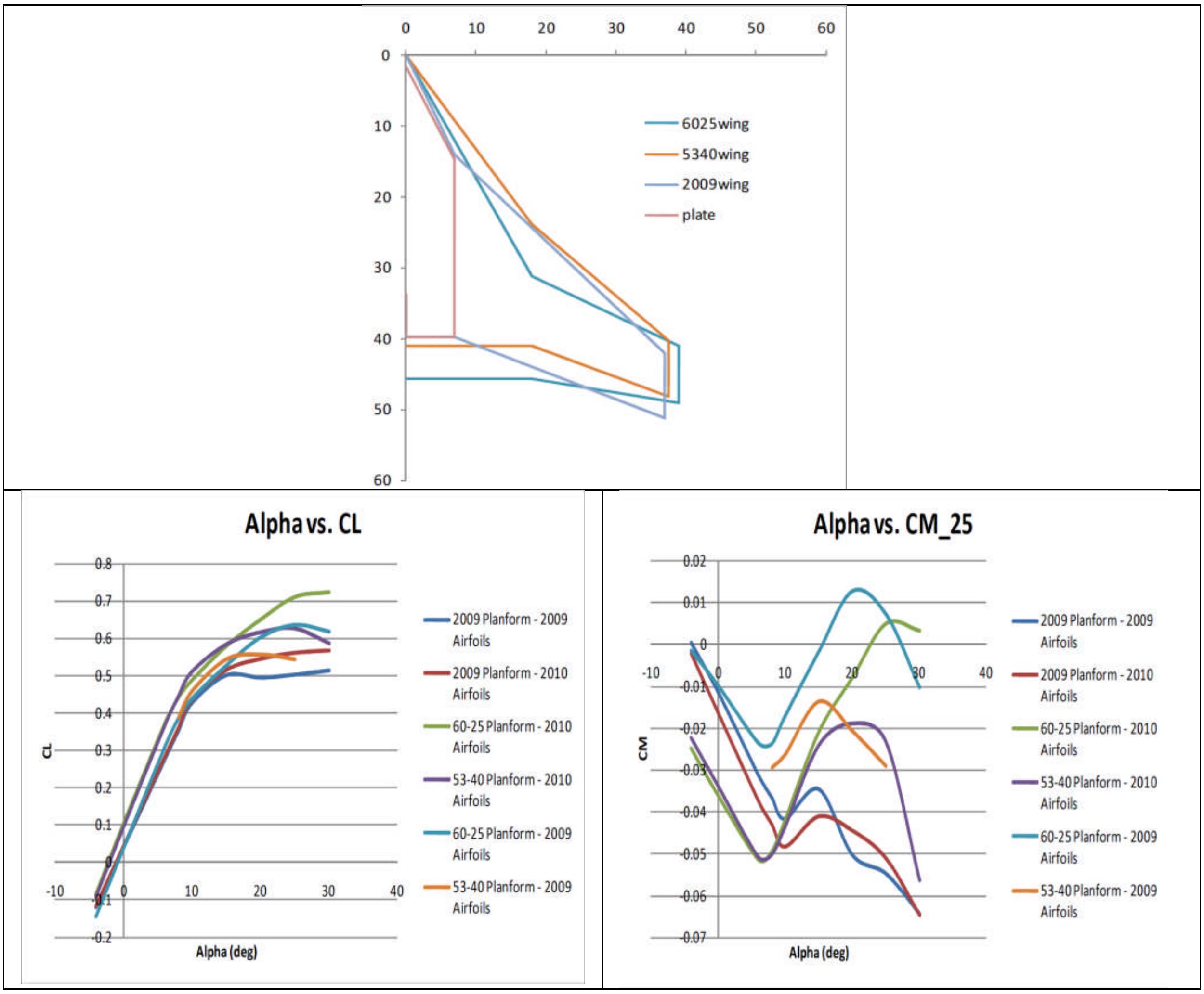


Figure 34: Alternative planforms studied in the conceptual design phase.

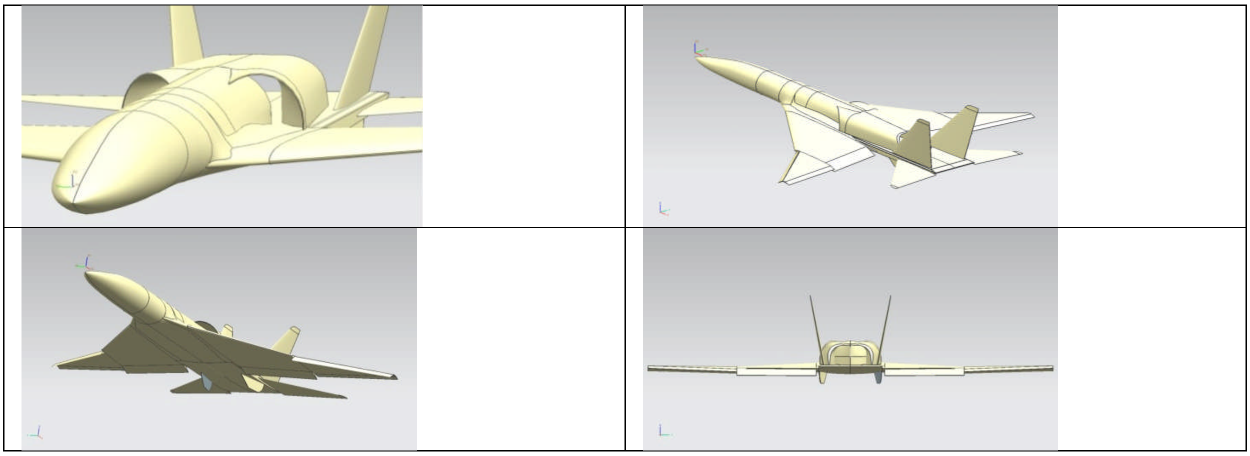


Figure 35: The final University of Washington 2010 UAV configuration

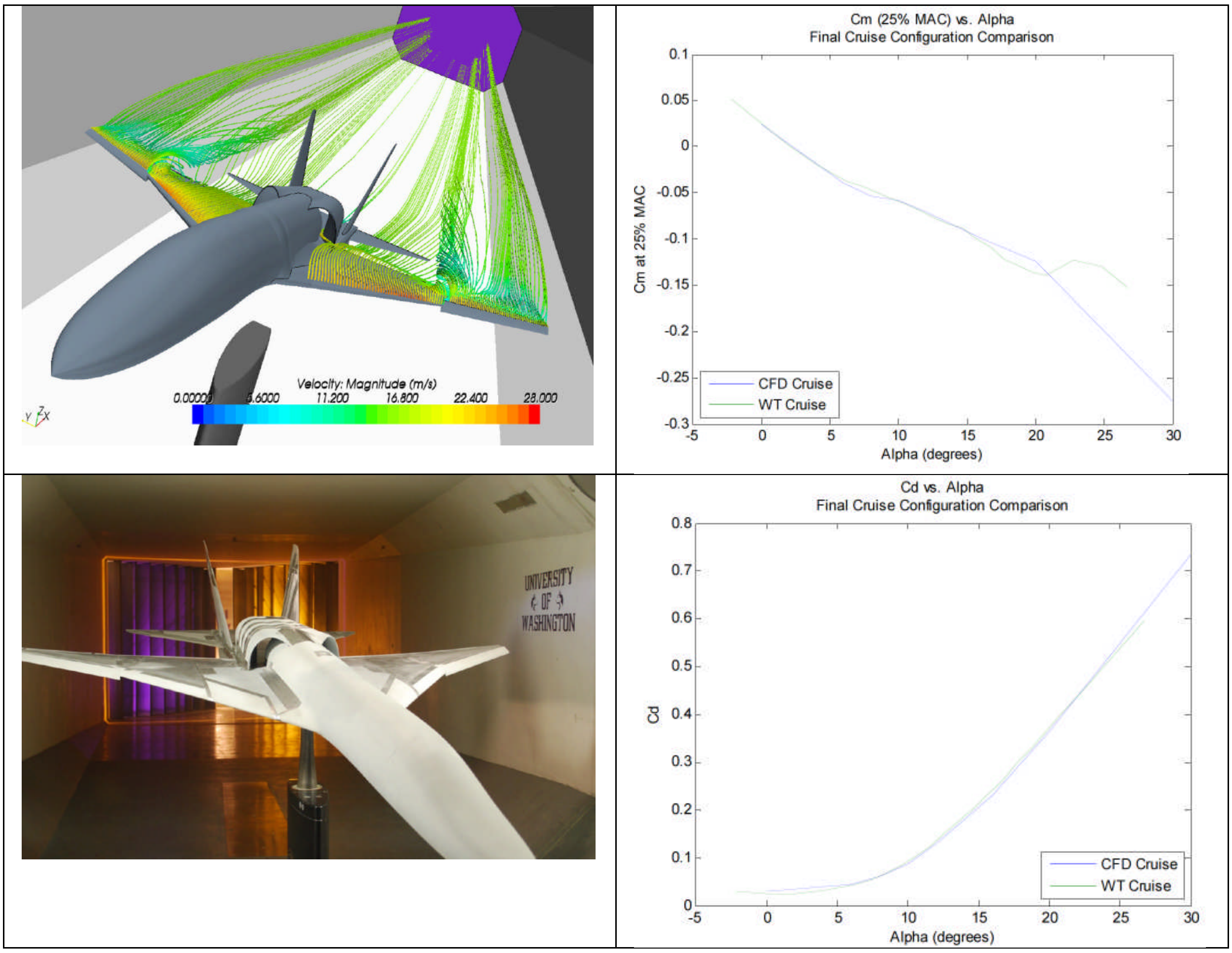


Figure 36: CFD / Wind tunnel test correlation for the 2009 UAV.

Significant structural, stability & control, propulsion integration and engine performance studies were carried out in support of the design effort. Because of the more complex avionics integration planned for the 2010 UAV a foam-built flying testbed was quickly developed and flown before the end of the first quarter to test systems integration and mature the control and data acquisition systems for quick integration with the airframe once it would be done. The “foamie” – a ½ scale pusher-propeller driven version of the selected UAV configuration is shown in Fig. 37. It was powered by a 600W electric motor and carried tufts and a miniature video camera (in addition to its avionics payload) to study the wing’s flow field during maneuvering flight. Materials used for the construction of the complete 2009 UAV and its inner structure are shown in Figure 38.

The final UAV features flight-movable leading edge devices, trailing edge flaps and flaperons, all-flying stabilators, dual rudders, pneumatically operated retractable gear and wheel brakes, nose-wheel steering, provisions for yaw and roll dampers, programmed trim settings for flap and gear movement, and flight instrumentation sufficient for performance and S&C data collection, on-board video cameras, as well as real-time telemetry of air data and engine parameters.

More thorough static noise tests with the completed 2010 UAV were carried out over grass and in fly-over noise tests using microphones at the center of the runway and side of the runway.

Key characteristics of the 2010 UAV:

- Cruise Speed: 52- 70kt
- Maximum Speed: ~113kt
- Stall Speed: 28kt
- Takeoff Speed: 35kt
- Endurance: 8 min
- Range: 12 miles
- MAC = 27.641 in
- Sw= 14.096 ft^2
- Span = 89 in (7.42ft)
- Length = 116 in (9.67ft)
- Static Installed Thrust: 17.7 lbf
- Max Gross Takeoff Weight: 40 lbs

Note that with additions to the flight test system payload and longer endurance the 2010 UAV ended up about as heavy as the less capable 2009 UAV. The 2010 UAV was successfully flown during the summer and fall of 2010 (Figure 41).

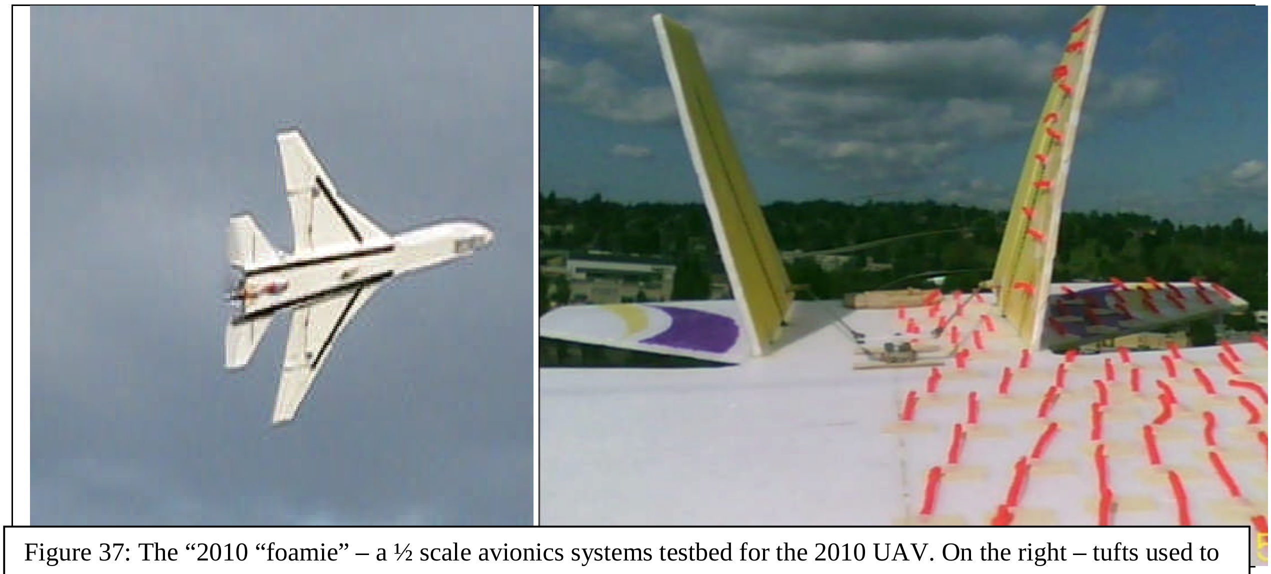


Figure 37: The “2010 “foamie” – a ½ scale avionics systems testbed for the 2010 UAV. On the right – tufts used to study the flow field over the wing during maneuvering flight.

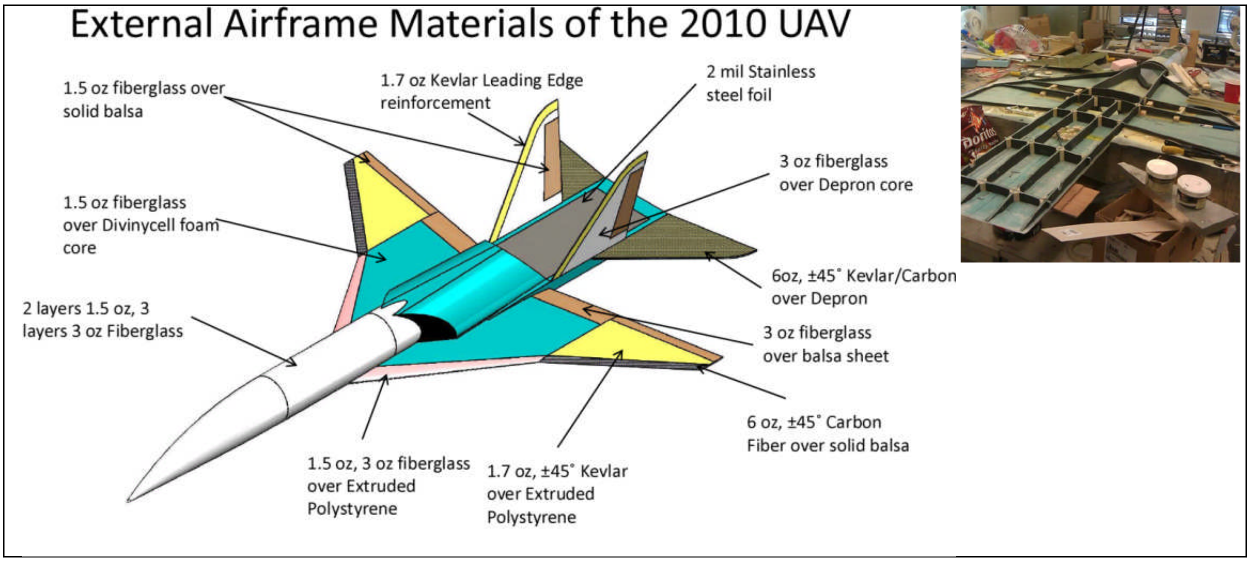


Figure 38: Materials used in the construction of the 2009 UAV. The internal structure is made of laters of 0/90 CFRP with ¼” Divinycell core.

Figure 39: Noise testing over grass 360 degrees around the 2010 UAV at different bank angles.

Figure 40: The 2010 University of Washington’s UAV flying over center runway and side of runway microphones.

Figure 41: The University of Washington's 2010 UAV on its first flight

Direct UAV design, or full-scale design first?

The 2009 and 2010 projects were presented to the students as UAV design challenges directly with minimal effort expected on the corresponding full-scale aircraft concept. Earlier, in 2006, 2007, and 2008, the design challenge focused initially on full scale vehicles to be scaled down later, once their conceptual design was completed, to UAV size, followed by the design, construction, and flight of the UAVs. With 20 academic weeks available for the capstone airplane design course and the ambitious goals and scope of work already presented, it is clear that the addition of a full scale vehicle design to the UAV design is often problematic schedule-wise. On the other hand, in many cases when a new configuration has to be developed and evaluated against other competing configurations, some of which already built and flying, this can be done only in consideration of full scale. For the students to design full scale aircraft concept also means exposure to design considerations and issues they would also see on a small UAV.

With a large group of students both full scale and UAV designs can, conceivably, be pursued during the same academic year, with two groups that work together during the conceptual design phase and then part ways: one group developing the UAV and one group completing an in-depth paper study of the full scale design, with the groups exchanging information constantly.

Experience at the University of Washington has shown that projects of the scope and complexity of the 2006-2010 described above projects can be handled well by a team of 25-30 students over 20 weeks. This size of a student team, in its division into discipline teams for the project, is sufficient for meeting the technical and schedule challenges, even though to do that the students work very hard. It is also the limit, probably, of the size of team that can be managed educationally by one or two professors, if an element of the teaching approach is to develop a personal working relation between professors and each student in the team, to ensure full engagement of every student, to offer personal consultation to each student, to allow early detection of any unhealthy team dynamics, and, in general, to provide leadership and motivate by personal example.

With the design challenge presented to the students of the 2011 capstone design course an effort was made to re-assess our capability to pursue both full scale and UAV scale designs in the same years plus, of course, to help the student benefit from both design experiences.

The 2011 Capstone Design Challenge

Drawing inspiration from recent work at NASA and the aeronautics community on the development of new fuel-efficient “green” passenger aircraft, and responding to interest by sponsors, the challenge in 2011 was to “optimize” a full size civil transport strut-braced wing configuration of high aspect ratio that would hopefully be more fuel efficient than an optimized conventional configuration. The students, then, were asked to scale the resulting braced-wing vehicle down to UAV level followed by the design, construction, and flight tests of the UAV.

During twenty academic weeks from January to June of 2011 a capstone airplane design student team of 28 students, working with the guidance of two lead instructors, supported by experts from Boeing, ATS, Whidbey Island AMA, and the University of Washington’s wind tunnel crew, and using the array of computational, experimental, and construction tools and techniques described in the previous sections, brought their UAV to ground test status. At that point, the class decided to delay test flights long enough to complete a set of improved wings that were still in fabrication. This work was completed during the summer term and remaining 2011 grads flew two very successful test flights of the 14 ft span strut-braced UAV. Schedule pressures allowed completion of the conceptual design comparison between the full scale strut-braced and conventional optimized aircraft, but not the completion of preliminary, more detailed design of the full scale airplane. Also, the time spent on full scale studies at the early phase of the project led to a delay in the completion of the UAV, which, while close to completion at the end of the academic year, still had to undergo final preparations for flight in the summer and flew in early September.

The design challenge for 2011: a) Explore aerodynamic/structural tradeoffs and design synthesis challenges of very high aspect-ratio, thin, strut-braced-wing (SBW) aircraft concepts; b) track potential improvements over a conventional reference; c) Investigate aeroelastics/stability/control aspects of an SBW concept (especially non-linear behaviors not captured by low-order methods); d) Design and build a UAV scale “demonstrator” to investigate/validate design impacts in flight.

A conventional reference configuration and SBW configurations for full scale passenger “concept jets” of the Boeing 737 class were optimized during the conceptual design process (Fig. 42). The down-selected full scale SBW configuration and the scaled UAV configuration are shown in Figures 43-45.

Mission Specification	
Max Range	3,500 nm
Passengers	150
Cruise Mach	0.7
Service Ceiling	41,000 ft

Figure 42: The full size baseline configurations studies in the conceptual design phase of the 2011 project.

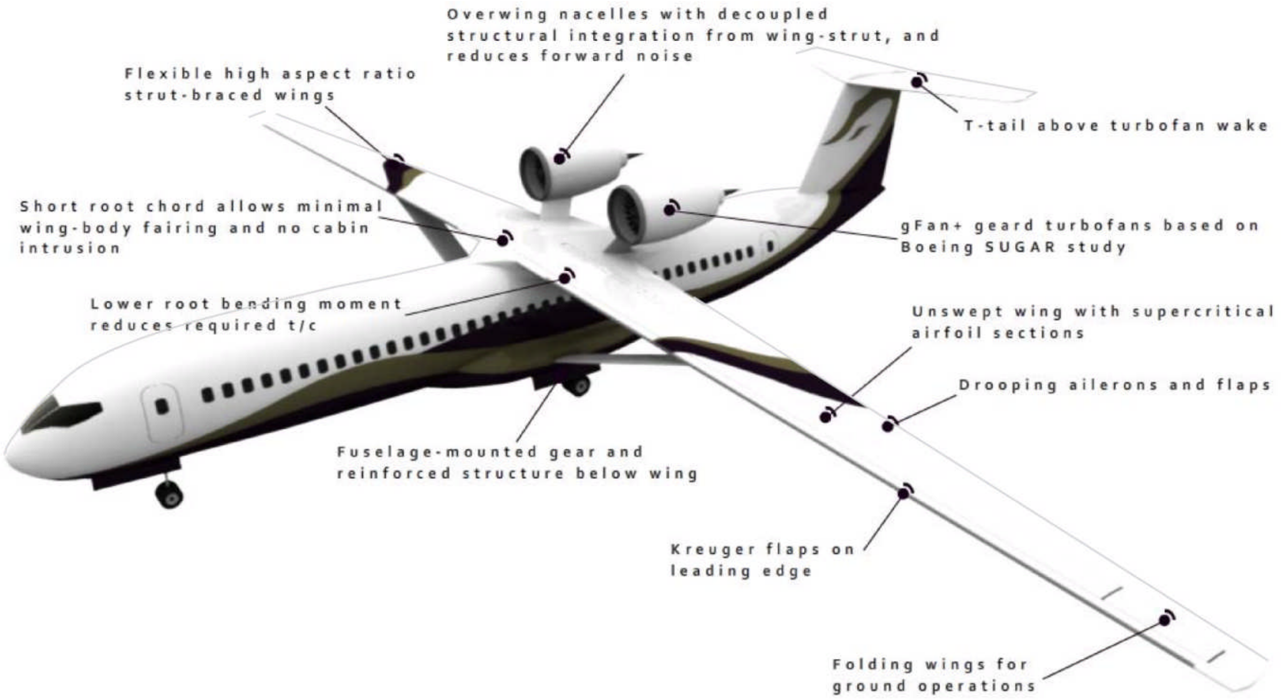


Figure 43: The resulting full scale Strut Braced Wing (SBW) concept 2011 capstone design project configuration.

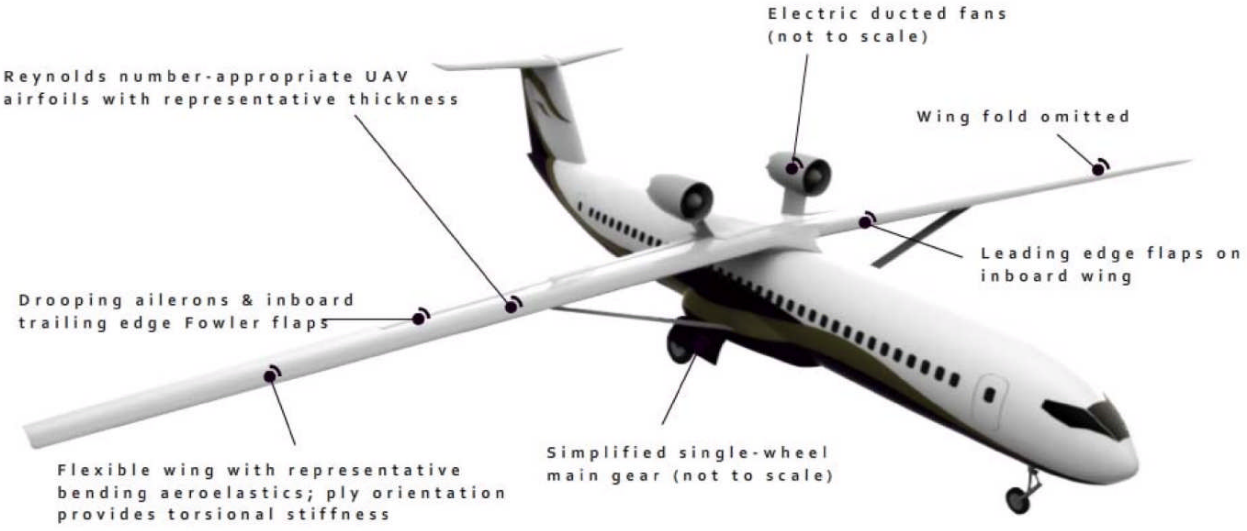


Figure 44: Key elements of the 2011 Strut-Braced-Wing concept UAV.

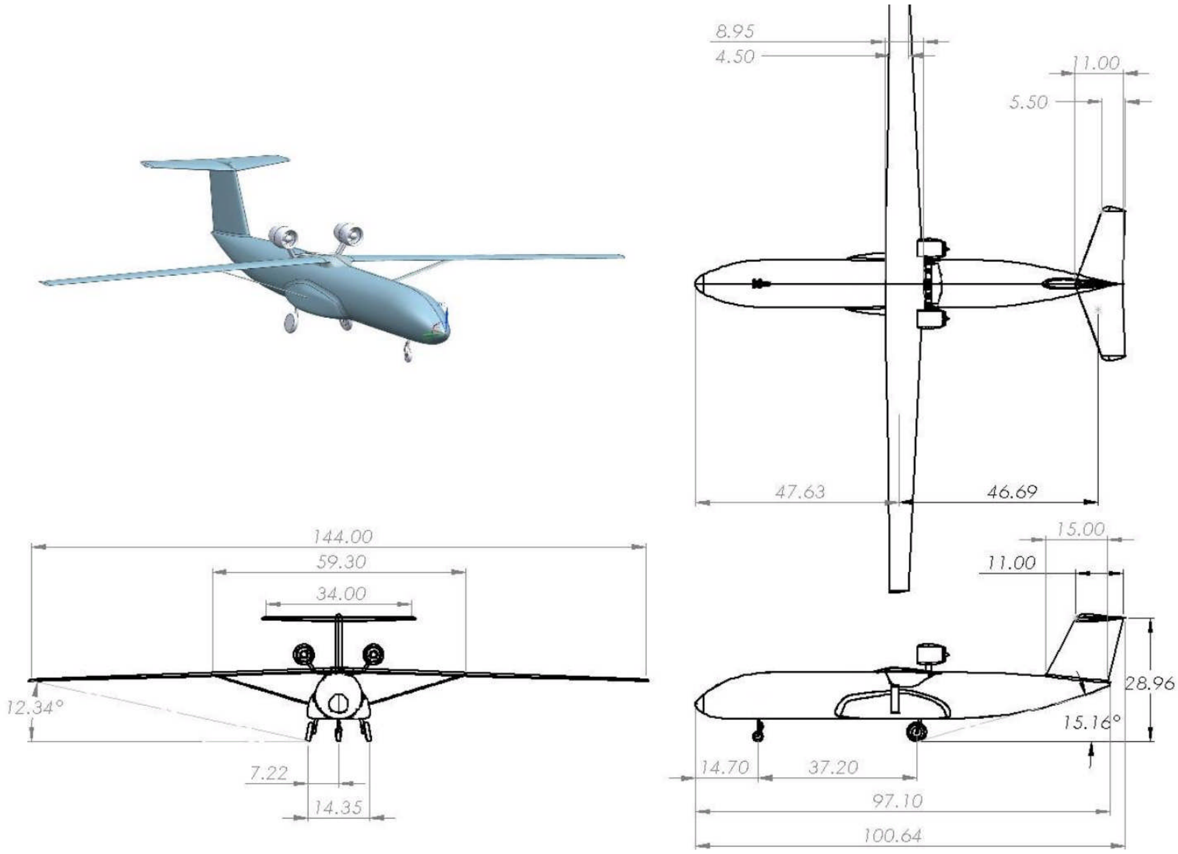


Figure 45: Dimensions of the University of Washington’s 2-11 SBW UAV.

The 2011 SBW UAV is powered by two electric ducted fans of 7.5 lbs static thrust each. They are mounted on the fuselage behind the wing root to decouple them from the structural dynamics of the wing. The UAV carries a more sophisticated flight test instrumentation and data acquisition system than those of previous years (Fig. 46), including miniature video cameras at the wing root pointing outboard and measuring wing tip deformations of the vehicle in flight.

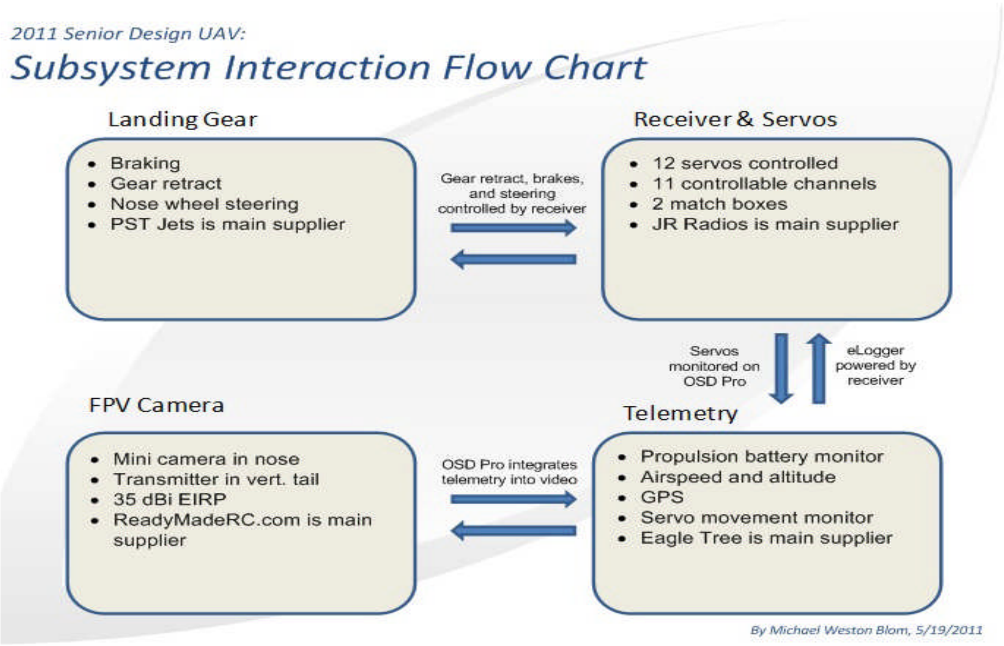


Figure 46: Systems carried by the 2011 University of Washington's SBW UAV.

Of special interest and concern in 2011 was the aeroelastic behavior of the very high aspect ratio strut braced wing which can, under load, exhibit significant nonlinear structural behavior. The UAV was intended to serve as a potential testbed for the ground and flight tests of different strut-braced-wing (SBW) and truss-braced-wing (TBW) configuration concepts. The approach to the development of the UAV was to design an aeroelastically conservative wing/strut system for the UAV for its first flights at the cost of straying away somewhat from the aeroelastic scaling factors required to scale down the full size optimized wing correctly.

Substantial aeroelastic modeling and analysis was carried out using NASTRAN, covering both linear and nonlinear structural behavior. A prototype wing/strut system was car-tested at flight speeds (Figure 47). A wing/strut was also installed in the Kirsten wind tunnel, underwent static force/deformation tests and modal tests, and then was flutter tests at different angles of attack corresponding to positive load factor and negative load factor maneuver conditions (Fig. 48). The vehicle flew successfully from Whidbey Island in September of 2011 (Figs. 49 and 50).

Figure 47: Car tests of a wing/strut system. On the right: wing aeroelastic deformation due to an aileron deflection

Figure 48: Structural static tests (right) and aeroelastic tests (left) of a Strut/Wing system at the Kirsten wind tunnel at different root angles of attack

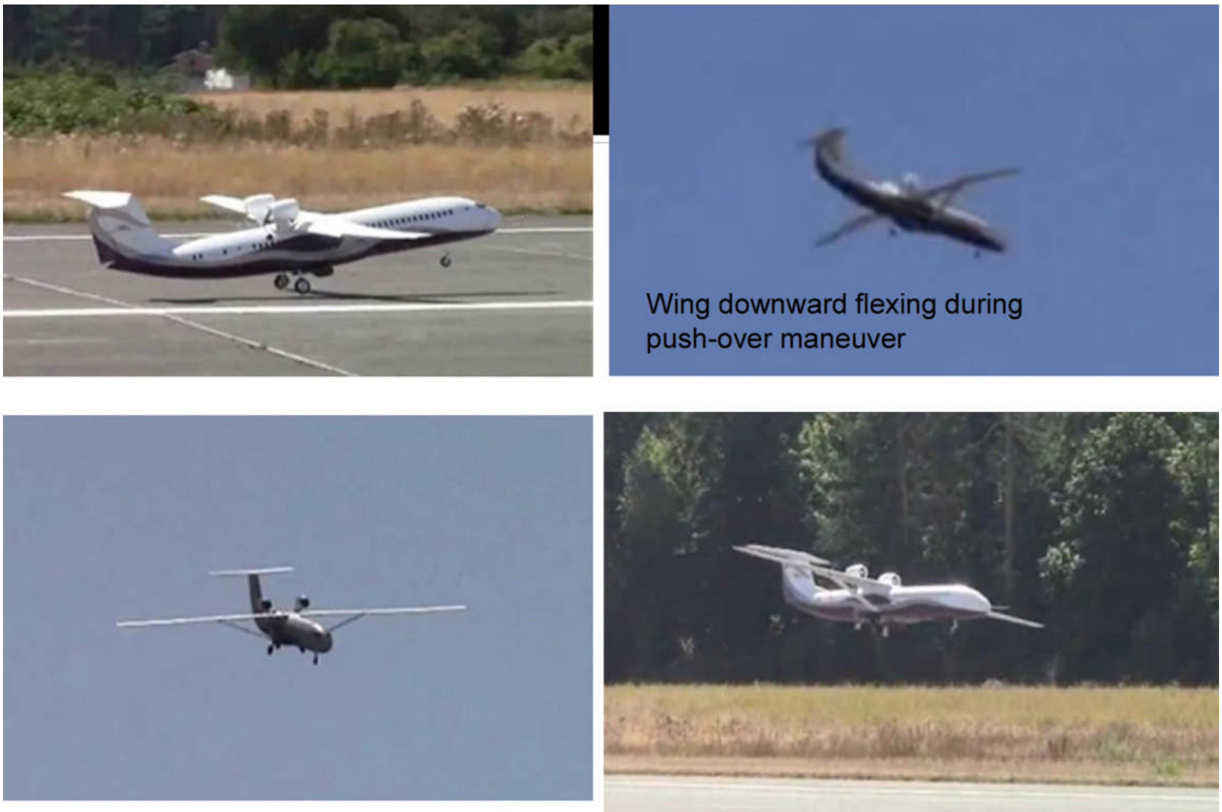


Figure 49: The 2011 University of Washington SBW UAV in flight, Summer 2011.

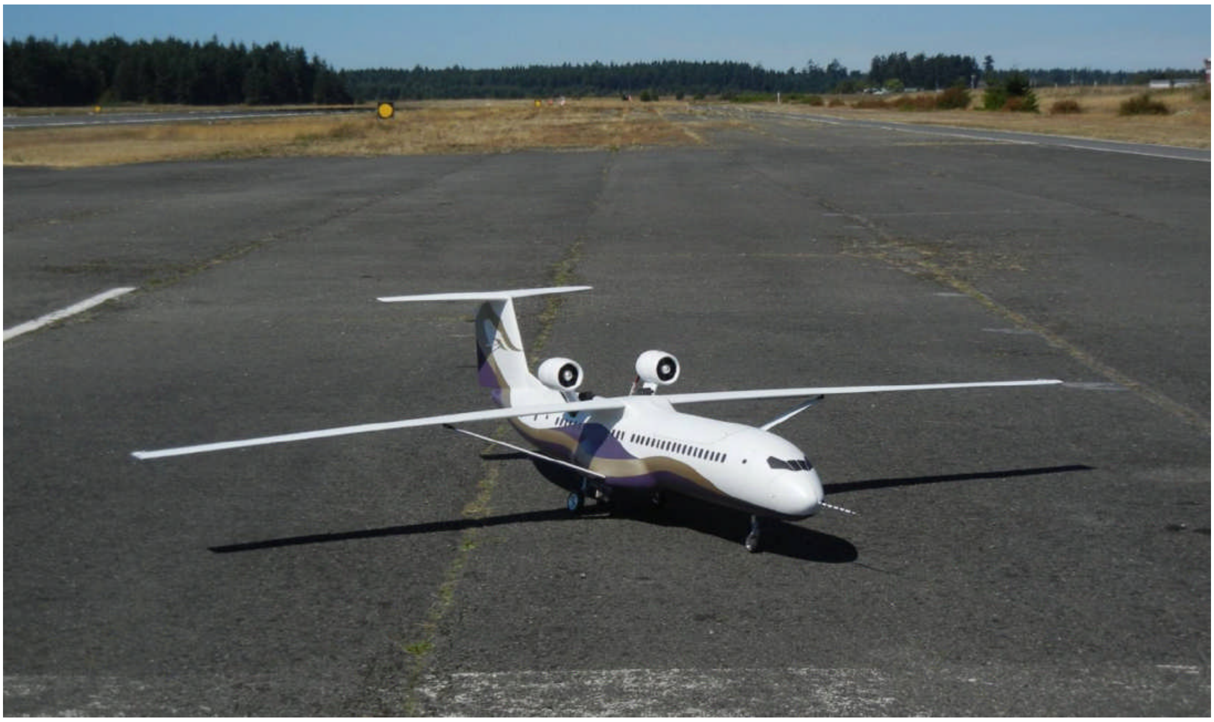


Figure 50: The 2011 University of Washington SBW UAV

Resources

In addition to the university instructional team and the expert consultants advisers from supporting companies and organization, an undergraduate design education program of the scale described here requires significant resources, including design room, shop, lab space, a commercial quality large wind tunnel, engineering software as well as structural, aerodynamic, and systems test equipment, flight simulation capabilities, a flight test facility from which UAVs of the scale developed at the University of Washington can be flown safely, a major computer capability for massive computation allowing the hundreds of clock hours of CFD and nonlinear structural and aeroelastic simulations. Additional resources in the form of materials, constructions tools and equipment, as well as aircraft propulsion, landing-gear, control, communication, and flight test systems are also required.

The budget of the 2010 project is representative of the level of resources required to support the University of Washington's senior capstone airplane design program. Figure 51 shows costs of commercial software (academic pricing), educational materials (reports, books, etc.), construction materials, propulsion system, and other systems, which include control, communication, flight test measurement data acquisition system, and landing gear. The expenses in Fig. 51 amount to about $16,000/year. This amount will increase in years where more software licenses have to be renewed and where more ambitious flight test systems or larger UAV would be built. The cost for software licenses, materials, and systems is between $16,000 and $25,000/year. The addition of on board active flight control system will add significantly to this amount.

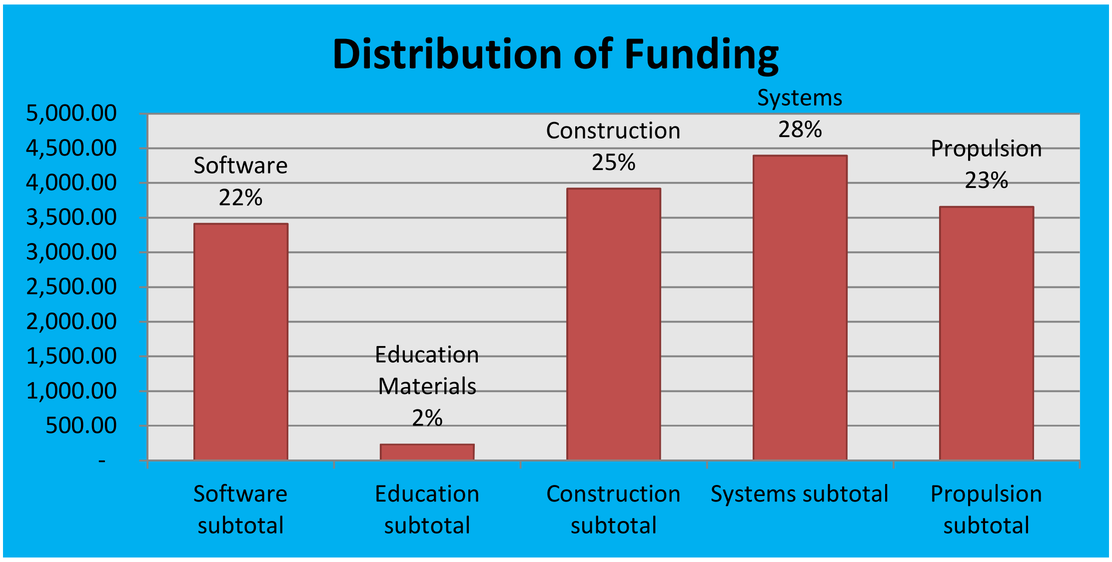


Figure 51: Software (educational pricing), materials, propulsion, and other landing gear and avionic systems cost distribution for the 2010 jet-powered UAV.

Not accounted for, however, in the expenses covered by Fig. 51 are wind tunnel test costs (about $20,000/5-day-week), wind tunnel model of the quality used at the University of Washington (anywhere between $40,000 and $120,000, depending on complexity, size, and number of parts), moulds for composite construction (from hundreds to a few thousand dollars depending on size, material, and complexity), and expert consultants time. We are grateful at the University of Washington to be able to benefit from the generous support of Boeing and ATS, in grant funds and in-kind support, and the support of the Department of Aeronautics and Astronautics and the University of Washington's Aeronautical Laboratory (UWAL) who provide cash support and make the Kirsten wind tunnel available to the students of the capstone design courses. The program also benefits greatly from ATS Inc.'s computer cluster without which the extensive CFD analysis efforts would not have been possible.

It is estimated that to design and build the kind of UAVs described here costs, in cash funds and in equivalent in-kind support, between roughly $120,000 to $200,000 a year, not including the instructional team time and effort. On average, equivalent to a bit over $5,000 per student.

To make the students develop experience regarding not only the schedule but also the realistic cost of the development of small research UAVs the project management team keeps careful accounting of all expenses during the project, including collecting from all members of the design team log-pages with information regarding the hours each student spent working on the project divided into training, design and analysis, construction, testing, and management hours. A team of 28 students in 2010 worked about 9,500 hours over twenty weeks to meet the design challenge presented to them. The number of hours per week per student is not even, of course, and depends on the motivation, capability, initiative, and leadership of each student.

Future Plans

The capstone airplane design program described in this paper has been in constant development for years and will continue to evolve to become stronger. Construction techniques will improve, with access to better manufacturing equipment and methods. More thorough structural analysis, design, and testing capabilities will be developed for nonlinear optimal composite structures, optimization technology will be used more heavily from the early stages of the design process, automatic flight control systems will be added to the avionic systems the UAVs carry and will allow safer flight of more complex and nonlinear configurations as well as more precise execution of flight test maneuvers. There is a definite need to improve our flight test measurement and data acquisition capabilities and our noise analysis and testing capabilities.

A major step that would lead to better integration of education and research is to develop a graduate level design program, research funded, that would link graduate students pursuing graduate level research with the seniors working on their capstone designs. The idea is to tackle research problems by a combined undergraduate / graduate student team so that with the end of the senior year, as another new research UAV is ready for flight, analysis and testing work with that UAV will continue to yield high quality and comprehensive research results for thesis projects, government and industry customers.

Conclusion

The University of Washington's undergraduate capstone airplane design program is unique in resources, scope, focus, and the complexity of the research UAVs is produces every year. The paper presented educational philosophy and education experience regarding airplane design education mixed with summaries of the University of Washington's capstone design projects from the last six years. University of Washington UAV projects involve seniors as a key component of the capstone course, and thus lead to major participation by seniors in meaningful aeronautics R&D. The University of Washington is continuously improving a significant UAV design, test, build, and flight test capability, supported by state of the art computational and experimental resources and by significant engineering work. UAV's developed by University of Washington students are research oriented: unusual configurations, designed to generate data that will be useful to government and industry. Such UAVs can be used to generate data and answer exploratory R&D questions at a fraction of the cost similar work will require if done elsewhere. The resulting UAVs are sophisticated and include instrumentation, allowing students to apply knowledge of flight test discipline, planning, and communications. Typical development cycle from RFP to flying vehicle is 6-8 months. With follow-on graduate work, funded by government and industry, the resulting vehicles (and supporting wind tunnel models) can be used for more in-depth research in areas of need and interest.

Acknowledgements

We are grateful for the support of the University of Washington's airplane design program by the Boeing Company, its engineers and managers. In particular Mark Goldhammer, Duane Oda, Peter Radloff, Mithra Sankriti, Brent Whiting, Steve Precup, and Brian Foist; Aeronautical Testing Service, Inc., of Arlington, WA – applied aerodynamics and airplane design experts and builders of our wind tunnel models and moulds for composite construction (including Paul Robertson, Todd Leighton, Paul Christiansen, and Robert Dick); Mr. Chuck Bower - our world class R/C pilot and R/C technology and small jet engine expert; General Plastics Manufacturing Company, Tacoma, WA; Fiberlay, Seattle, WA; The University of Washington's Department of Aeronautics and Astronautics and its chairmen; The University of Washington's Aerodynamic Laboratory (UWAL) and its manager, Mr. Jack Ross; Colleagues at the Department of Aeronautics and Astronautics and especially Professor Mitsuru Kurosaka, for his help in the noise / acoustics area.

References

1. Livne, E., "The Evolution of the Senior Airplane Design Course at the University of Washington", AIAA Paper 99-0570, AIAA Aerospace Sciences Meeting, Reno, Nevada, January 1999.
2. Roskam, J., "What is needed to teach aeronautical engineering students how to design aircraft? ", AIAA-1990-3257, AHS, and ASEE, Aircraft Design, Systems and Operations Conference, Dayton, OH, Sept 17-19, 1990.
3. McMasters, John H., and Matsch, Lee A.," Desired attributes of an engineering graduate - An industry perspective", AIAA-1996-2241, Advanced Measurement and Ground Testing Technology Conference, 19th, New Orleans, LA, June 17-20, 1996.

4. Nicolai, L.M., “Viewpoint: An Industry View of Engineering Design Education”, Int. J. of Eng. Education, Vol. 14, No. 1, p. 7-13, 1998.
5. Thompson, B.E., “Studio pedagogy for aircraft design and engineering “, AIAA-1998-2794, Applied Aerodynamics Conference, 16th, Albuquerque, NM, June 15-18, 1998.
6. Sullivan, J.P., and Watkins, W.A., “A design/build/test environment for aerospace education”, AIAA-2000-525, Aerospace Sciences Meeting and Exhibit, 38th, Reno, NV, Jan. 10-13, 2000.
7. Hall, C., “Aircraft design at North Carolina State University”, AIAA-2002-959, AIAA Aerospace Sciences Meeting and Exhibit, 40th, Reno, NV, Jan. 14-17, 2002.
8. Curran, R., “Systems Engineering as an Effective Educational Framework for Active Aerospace Design Learning”, AIAA-2009-6904, 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS) , Hilton Head, South Carolina, Sep. 21-23, 2009.
9. McDonald, R., Puig-Suari, J., Esposto, D., and Wright, B., “Senior Design at Cal Poly: A Recipe for Success”, AIAA-2009-1623, 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, Jan. 5-8, 2009.
10. Mason, W.,”Reflections on Over 20 Years of Aircraft Design Class”, AIAA-2010-9065 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, Texas, Sep. 13-15, 2010.
11. Dees, P., “An Industry Perspective on Future Needs for Aircraft Design Education”, AIAA-2010-9015, 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, Texas, Sep. 13-15, 2010.
12. Price, M., Murphy, A., Early, J., Robinson, T., and Soban, D., “Aircraft Design Education at Queen's University Belfast: Philosophy, Framework, and Implementation ”, AIAA-2010-9155, 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, Texas, Sep. 13-15, 2010.
13. Hollingsworth, P., and Crowther, W., “The Philosophy of Design Education at the University of Manchester”, AIAA-2010-9154 , 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, Texas, Sep. 13-15, 2010.
14. Bil, C., Thompson, L., “Aerospace Design Education at RMIT University”, AIAA-2010-9066 , 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, Texas, Sep. 13-15, 2010.
15. Le Corbusier, Aircraft, Universe Books 1988, New York, ISBN 0-87663-677-6. First published in 1935 as “L’avion accuse…”.

YouTube Links to video clips of University of Washington UAV flights

1. http://www.youtube.com/watch?v=xaxDNyH1iw8

2. http://www.youtube.com/watch?v=Bz659FMTd3Q

3. http://www.youtube.com/watch?v=S8WkuBnbLe0

4. http://www.youtube.com/watch?v=6o1yzQOV55o

5. http://www.youtube.com/watch?v=VcTarxYHFZw