Aerospace Engineering Initiative at the University of Maine

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Masoud Rais-Rohani is Richard C. Hill Professor and Department Chair of Mechanical Engineering at the University of Maine. He earned his Ph.D. degree in aerospace engineering from Virginia Tech in 1991. His academic experience includes a long tenure in the Department of Aerospace Engineering at Mississippi State University. He has taught undergraduate and graduate courses in the areas of design optimization, aerospace structures, structural mechanics, and composites. He has made extensive use of experiential learning and computer applications in his courses, including the development of two websites, one devoted to analysis of aircraft structures and the other to statics. He has also led or contributed to the development or redesign of several courses in aerospace and mechanical engineering.

Dr. David S. Rubenstein, University of Maine

David Rubenstein has twenty-five years of industrial and research experience in aerospace guidance, navigation and control (GN&C) system design and modeling and simulation development. He has worked for a variety of major aerospace contractors including Martin Marietta (now Lockheed Martin), Raytheon Space andMissile Systems Design Laboratory and Draper Laboratory in Cambridge, MA. Dr. Rubenstein received his B.S. in Mechanical Engineering from Washington University in St. Louis and the M.S. and Ph.D. in Aerospace Engineering from the Pennsylvania State University in the area of spacecraft dynamics and control. His areas of expertise include math models for simulation, parameter estimation and system identification, GN&C system design and analysis, estimation, sensor fusion and Kalman filtering algorithms as well as numerical optimization techniques. While in industry, Dr. Rubenstein provided algorithms for a wide variety of systems including satellites, unmanned rotary and fixed-wing aerial (UAV) and underwater (UUV) vehicles, guided parachutes and parafoils, missiles, projectiles, and even a flying saucer as well as an unmanned reusable launch vehicle. Since founding Maine Aerospace Consulting in 2003, Dr. Rubenstein has worked on GN&C of a small autonomous helicopter, optimization of missile loiter patterns, Kalman estimators for parachute deployment and to integrate eLORAN range with GPS measurements. Currently, Dr. Rubenstein is designing sensor fusion algorithms for a medical devices application to support surgical VR training, and is also working on GN&C for an autonomous vehicle capable of personnel and cargo transfers to low-Earth orbit. In 2009, Dr. Rubenstein became Adjunct/Research Faculty of Aerospace Engineering within the Department of Mechanical Engineering at the University of Maine. In this capacity, he has developed an Aerospace Engineering Concentration at the University through the creation and teaching of four aerospace courses.

Dr. Wilhelm A. Friess, University of Maine

Dr. Friess holds a Ph.D. in Aeronautical Engineering and a B.Sc. in Physics from Rensselaer Polytechnic Institute (1997), and currently is Associate Professor of Mechanical Engineering with the University of Maine and Director of the Brunswick Engineering Program. Previously he has spent 5 years in Dubai as inaugural faculty of RIT Dubai and Dubai Aerospace Enterprise University. Dr. Friess' industrial and academic career spans a variety of consulting and entrepreneurial activities in Europe, Asia and Africa. Dr. Friess' research background includes fluid mechanics, composite materials, performance optimization, and global engineering education. Current research interests focus on engineering education, in particular curriculum integration and innovative pedagogical methods.

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Abstract

The growing interest in aerospace engineering and related technology in the state motivated the aerospace engineering initiative within the Department of Mechanical Engineering at the University of Maine. Through the hiring of multiple full-time faculty and development of undergraduate and graduate courses in aerospace engineering, the department has increased its capacity by offering an undergraduate concentration and a graduate certificate program in aerospace engineering. Various aspects of this initiative, including the host of courses, laboratory, student activities, related research, and future directions are presented and discussed.

Introduction

There are nearly seventy ABET accredited undergraduate aerospace engineering degree programs around the country, with a smaller number offering master's or PhD degrees. Whereas some of these programs are offered by stand-alone aerospace engineering departments, others are part of a combined department, most often with mechanical engineering. Attempts at keeping the existing aerospace engineering degree programs successful [1], starting a new bachelor's degree [2] and master's degree program [3], or overcoming challenges in creating new aerospace engineering minors [4] point to the importance of increasing the educational opportunities in this field, particularly in light of the expected rise in retirements in the aerospace industry.

The Department of Mechanical Engineering at the University of Maines offers an ABET-accredited undergraduate program in mechanical engineering as well as MS and PhD degrees in the same field. The aerospace engineering initiative was undertaken as a joint effort between the department and the College of Engineering in 2009 in response to the growing aerospace industry and technology in the state and the region.

Aerospace companies, such as Lockheed Martin and Pratt & Whitney are continuing to invest in and expand their production capabilities in the state. Germany, Canada, Japan, and the United Kingdom were the largest importers of the state's aviation industry in 2016. [5] The Aerospace Alliance in the state includes more than 80 companies, many of which make component parts. As with all other states, Maine has an active NASA Space Grant Consortium which provides funding in support of students, educators, and researchers in the state.

After the initial hiring of a part-time faculty with a PhD in aerospace engineering and extensive experience in guidance, navigation, and controls, the department gradually hired three additional full-time faculty with expertise in computational fluid dynamics, aircraft design, and aerospace structures. The expansion of aerospace engineering education activities included the development of multiple undergraduate- and graduate-level courses, promotion of aerospace related capstone projects, establishment of student chapters of Students for the Exploration and Development of Space (SEDS) and American Institute of Aeronautics and Astronautics (AIAA), and creation of an AIAA design-build-fly competition team.

This initiative has so far resulted in the establishment of an undergraduate-level Aerospace Engineering Concentration and the Aerospace Graduate Certificate Program. Efforts to expand the initiative are ongoing, particularly at the graduate level. Aerospace related research activities in the college of engineering are also growing with investigations involving analysis and testing of inflatable aerospace structures, fluid-structure-acoustic interactions associated with flapping wings for bio-inspired micro air vehicle applications, lighter-than-air unmanned aerial vehicles for long-endurance, low-altitude remote sensing, and wireless leak detection in inflatable space structures. Details related to the various elements of this initiative are presented and discussed.

Curriculum development

The initiative was introduced with the development of four new courses (MEE 445, 446, 547, and 548) as listed in Table 1. The 400 and 500 designations refer to senior-level and graduate-level courses, respectively. The latest addition to the list is MEE 448 - Fixed Wing Aircraft Design, which was introduced in fall 2017. A course in the area of aircraft structures is currently under development for a planned initial offering in spring 2019. Other graduate-level courses with relevance to aerospace engineering are also listed in Table 1. A brief summary of the top five courses as listed is provided below.

Table 1. List of aerospace engineering and supportive courses

Course Number	Course Title
445	Aeronautics
446	Astronautics
547	Flight Dynamics and Control of Aircraft
548	Spacecraft Orbit and Attitude Dynamics and Control
448	Fixed Wing Aircraft Design
560	Computational Methods in Fluid Dynamics
562	Advanced Fluid Mechanics
564	Fluid Structure Interaction
573	Advanced Vibrations I
546	Finite Element in Solid Mechanics

MEE 445 – Aeronautics

This course provides an introduction to the dynamics and performance of aircraft flight. Topics include basic aerodynamics and wing design theory, the primary in-flight aerodynamic forces and torques, stability and trim concepts, aircraft control surfaces, actuation and propulsion basics. Course material is discussed in the context of several key examples including fixed-wing aircraft, steerable parachutes, the reentry (atmospheric) phase of a reusable launch vehicle and unmanned aerial vehicles (UAVs), a critical, state-of-the-art technology in the modern-day aerospace and defense industry. Modeling and simulation of a selected UAV system provide an exciting and comprehensive application of the skills developed in the course.

Students are required to integrate much of the course material, including basic aerodynamics, standard atmosphere and attitude modeling, as well as project specific topics such as rudimentary aerodynamic angle and heading control concepts, into a Matlab-based simulation tool. In the past, this project has involved the modeling and control of a guided parafoil airdrop system. This project is well-suited to this skill level, with application of fairly simplified but key aerodynamic models and an introduction to the notion of controlling an autonomous system. Specific experiments (test cases) are required as are qualitative assessments of the results.

Other focus areas include airspeed measurement methods and subsonic and supersonic wind-tunnel design. Also, as a thorough understanding of reference frames and coordinate transformations is a critical skill in all avenues of aerospace, both MEE 445 and 446 dedicate a fair amount of time to direction cosine matrices and vector time derivatives in rotating frames.

MEE 446 – Astronautics

This course provides an introduction to the design and operation of spacecraft systems. Topics include kinematics and relative orientations of different coordinate systems as well as fundamental orbital mechanics – orbit design, maneuvers and transfers. Rigid-body dynamics, torque-free and forced motions due to external disturbances acting on the spacecraft, are discussed in addition to basic propulsion concepts related to orbital design. Course material is integrated into the development of a spacecraft simulation project, demonstrating a critical method of satellite system design and analysis. Specific examples, including the Global Positioning System and the NASA Space Shuttle, are described as applications in the context of the course material.

Students conduct a project that typically involves design, modeling and simulation of a mission to low-Earth-orbit, including a launch phase and an orbital transfer phase. The project entails development of a pre-simulation parameter computation script which is used to populate the simulation workspace as needed. Students must incorporate critical course topics such as timed velocity change for purposes of orbital maneuvers and basic orbital mechanics into a true vehicle simulation including numerical integration of the two-body equations of motion and data reduction, plotting and analysis.

Additional areas of focus in this course include attitude representation, using Euler angles and rates, direction cosine matrices and rocket propulsion basics. Homework assignments seek to fortify course material as well as Matlab skills, critical for the semester project. For example, students are asked to design, code and test a Matlab-based simulation of a simple spherical pendulum, utilizing a Matlab provided Runge-Kutta integration utility.

MEE 547 – Flight Dynamics and Control of Aircraft

This course provides an introduction to the flight dynamics, modeling and fundamental stability and control aspects of aircraft. It covers aircraft roll, pitch and yaw static stability and control basics and develops the full nonlinear equations of motion. The concept of numerical simulation of these equations is also introduced. Finally, with the dynamic models in-hand, open -loop response to actuation of the control systems is analyzed and the concept of closed-loop aircraft control system design is presented. Both MEE 547 and 548 generally build directly on the undergraduate 445. Utilizing the fundamental understanding of aerodynamics, reference frames and simulation, the course focuses more on control, stability and full six-degree-of-freedom rigid-body modeling of aircraft.

The simulation project is a very important and highly prioritized element of both graduate courses. In MEE 547, the project typically involves design, development and test of a longitudinal simulation of an autonomous fixed-wing UAV. Aerodynamic models are provided in terms of force and moment coefficients as a function of angle-of-attack and control surface deflection. Thrust data is also provided to facilitate construction of a simple propeller system. The project also requires the incorporation of a linear control system to stabilize the vehicle about trim and to enable altitude changes. This project introduces a number of key elements of aerospace design, including linearization of equations-of-motion as well as implementation of powerful control design tools such as the Linear Quadratic Regulator algorithm. Students formulate the simulation structure, with appropriate initialization scripts, subsystem models, linearization and control system implementation, integration (done using Matlab ODE45) and post-processing and plotting functionality. The project generally brings together many of the key elements of both MEE 445 and 547, allowing students "hands-on" experience with implementing and integrating these concepts in a real vehicle simulation. This is an extremely effective means of allowing students to fully understand, assimilate and unify many complex notions which are typically presented as individual course topics.

MEE 548 – Spacecraft Orbit and Attitude Dynamics and Control

This course covers the orbit and attitude dynamics, modeling and fundamental control aspects of space vehicles. Rotational kinematics and dynamics of rigid-bodies as well as passive and active attitude control and stabilization methods are introduced. Additionally, Keplerian and non-Keplerian orbital motion, orbital transfers and orbit determination topics are covered. Finally, an introduction to spacecraft navigation systems is presented. As with MEE 547, this course builds directly upon the fundamental lessons of reference frames, energy and momentum principles and orbital mechanics provided in MEE 446.

A number of interesting homework assignments are required that, as in MEE 547, seek to bring together key lecture topics and to increase skill and confidence in using Matlab, in preparation for the semester design project. An example of such an assignment requires students to plot the resulting orbital inclination for a given launch site, over a range of launch azimuth angles. This work entails the computation of the momentum vector resulting from the combination of launch position and heading, and as such, it provides students with a very meaningful perspective on launch-to-inclination restrictions, incorporating Matlab coding and plotting requirements. Additionally, students are asked to use Matlab numerical optimization functionality to solve for the optimal allocation of velocity changes for a Hohmann transfer with an inclination change. Another assignment involves the implementation of the Clohessy-Wiltshire equations for relative motion and rendezvous in a Matlab simulation, computing required velocity changes associated with executing the rendezvous, which entails a significant element of implementing complex mathematical models in Matlab.

The semester project for MEE 548 has typically involved the design, coding and test of a simulation of an interplanetary mission to Venus. This project, as in all the aerospace projects, seeks to integrate many of the critical elements from the undergraduate and graduate course topics in a challenging, fun and rewarding individual task. Students are required to design and integrate each phase of the mission, assembling and saving the overall state history for post-processing, plotting and analysis. The students are asked to utilize the two-body representation of the orbits initially, using patched-conic design for simulation. Then they are asked to perform the same mission simulation utilizing the four-body equations and compare results. Also, Lagrange coefficients are used to solve for a section of key nodes in the orbits. As in MEE 547, this project requires assimilating many of the key concepts from MEE 446 as well as 548, in a single, focused, enjoyable application while simultaneously extending critical Matlab skills.

MEE 448 – Fixed Wing Aircraft Design

This senior-level technical elective was first taught in fall 2017 and covers the design principles for subsonic fixed wing aircraft. The course steers students through the different phases of the conceptual design process including costing, trade studies, and constraint analysis, and exposes them to the breadth of topics related to aircraft design, such as 2D and 3D aerodynamics, structures, propulsion, control, and performance.

The delivery of the course is highly interactive, with students developing their design tools in multiple individual and group exercises, culminating in a 6-week-long team design project. Further, field trips to the airport are conducted to familiarize students with physical aircraft and to inspect and discuss design decisions. During the first iteration of the course, the design project required the students to design an amphibious light sport aircraft for recreational flying in the state of Maine. The course serves as preparation for more advanced coursework and for aeronautics related projects in MEE 478 – Capstone I and 488 – Capstone II as well as the AIAA Design-Build-Fly competition.

Methods of instruction

Web-based

The principal courses (MEE 445, 446, 547, and 548) are taught live remotely using Adobe Connect Pro software, although students require only the appropriate web link. The resulting virtual classroom features electronic whiteboard (controlled via a writing tablet), a full access chat window, a webcam window (for the instructor primarily), audio access for instructor and students as needed, live document sharing and download, and video and graphics sharing pods.

Students historically are extremely comfortable and quite skilled at using the chat feature, for asking questions, answering questions, and simple social conversation. In fact, the chat window tends to encourage students who otherwise may be timid of interaction or attempting to answer questions in a standard classroom format. The white boards are partially populated beforehand, with key typed bullet points, drawing and figures, pictures, etc. Then, during the live lecture, additional mathematics and descriptions are added “around” the existing pre-prepared material in a contrived, specifically designed manner.

In addition to being delivered live, the lectures are all recorded. The recordings are uploaded to Blackboard shortly after each lecture and made available for all students to view at any time, in any location that they choose. They can fast-forward, pause and rewind the recordings at will, during their reviews. This feature is a very powerful asset of the online aerospace courses, enabling students to view and review the material as often as desired and minimizes the necessity for meticulous note-taking.

The lectures, as well as all homework and project assignments are made available on the course Blackboard page. Students upload their completed homework to Blackboard. Each student is also provided with a “Private Student Folder” on Blackboard. This folder is used for returning graded homework, projects and exams in a manner that permits only the specific student to access. Exams are administered in a typical fashion on campus with a proctor. The completed exams are collected and mailed to the instructor for grading. Off-campus students and working professionals—many of whom have taken these courses because of the very flexible and accessible online aspect, including the recordings—are responsible for finding a proctor to perform similar functions and to return the finished exams to the instructor.

Face-to-face

With the exception of the four courses noted above, all other aerospace engineering related courses are taught using a face-to-face approach. Fixed Wing Aircraft Design (MEE 448) is taught in a design studio format. A collaborative learning classroom (see Fig. 1) is utilized, equipped with round tables and individual monitors near each table. The delivery format combines lecture and group work, with student groups reporting out their work to the class utilizing the collaborative technology of the room.

Figure 1. Students in a collaborative learning classroom.

A typical 75-minute class session begins with a brief reading quiz, followed by a short lecture (~30 minutes), followed by a group activity or discussion with a report-out requirement (30 minutes), and closing with another short lecture. The course requires significant out-of-class reading and research, and reading quizzes are utilized to motivate these assignments. In addition, peer evaluation is utilized for the team projects to ensure a fair distribution of the team grades. Informal student feedback indicates a high level of student satisfaction with this format, with high levels of perceived learning rooted in the reading assignment and subsequent discussion.

Aerospace engineering concentration

Undergraduate mechanical engineering students can declare this concentration by successfully completing three aerospace engineering courses (MEE 445, 446, and 547 or 548). The list of students taking the aerospace engineering classes in general, includes not only mechanical engineering but also Physics, Engineering Physics, as well as Electrical and Computer Engineering. Since its inception, the total enrollment in the four courses has reached approximately 280 students.

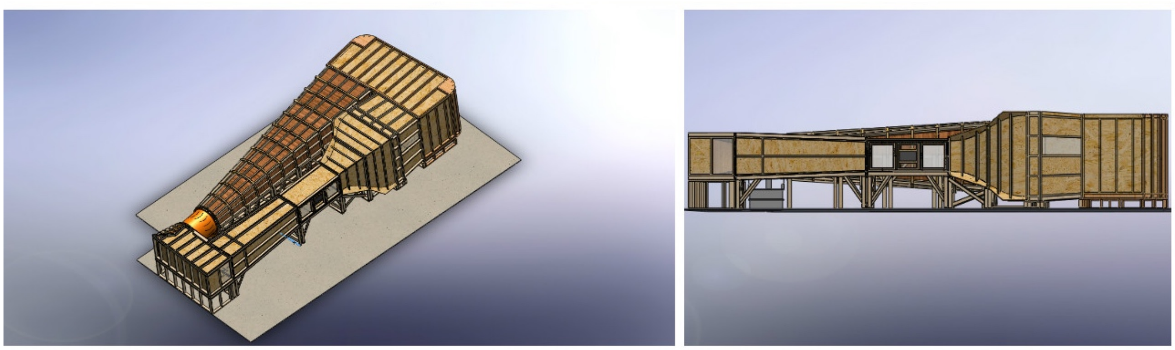
The fact that the four specified courses are typically taught over a two-year cycle makes it challenging for students to complete the concentration if they decide to pursue it too late (e.g., 2nd semester junior year or later). By introducing additional aerospace engineering courses while keeping the course requirement to a total of three, we anticipate the interest in the concentration will continue to grow and more students will be able to complete it in a timely manner.

Aerospace engineering graduate certificate

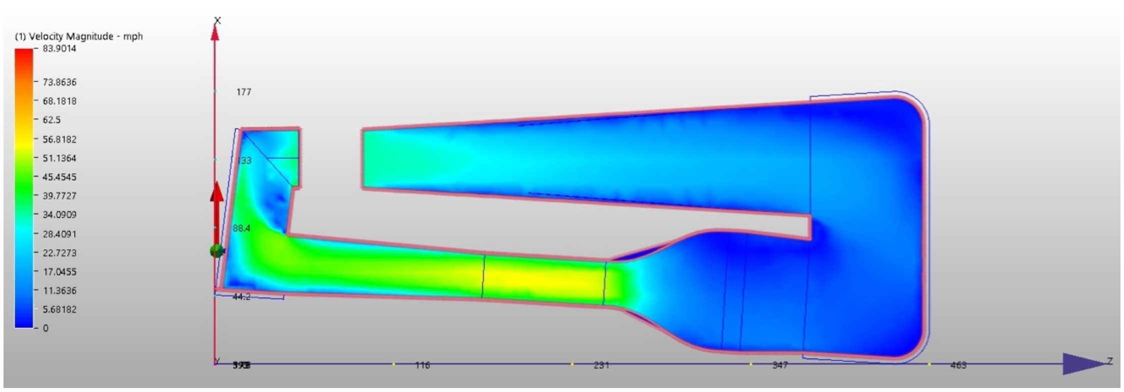
In its present form, the certificate is awarded to graduate students, in mechanical or other engineering majors, who complete four aerospace engineering courses (i.e., MEE 445, 446, 547, and 548). We see an opportunity to make the certificate more flexible by expanding the number of graduate-level aerospace engineering courses offered in the near future.

Laboratory capabilities

In 2015, a closed-circuit subsonic wind tunnel with a 75 cm x 75 cm test section and a top speed of approximately 130 km/h (80 mph) was designed and constructed by a group of senior students as a capstone project. Figure 2 shows the wind tunnel's Solidworks CAD model and CFD simulated flow field, whereas Fig. 3 shows photos of its wooden construction and assembly.



(a)



(b)

Figure 2. Subsonic wind tunnel (a) Solidworks CAD model and (b) CFD simulated flow field.

(a)

(b)

Figure 3. Subsonic wind tunnel (a) diffuser under construction and (d) final assembly.

The tunnel is equipped with a hot wire anemometer and pitot-static probes. An LDV system is currently being updated for non-intrusive air flow velocity measurements. Since its completion, the tunnel has been used successfully for mechanical engineering lab experiments and offshore energy research (see Fig. 4). Current activities include the design and implementation of a gust generator to study the effect of wind gusts on infiltration through building envelopes. Planned wind-tunnel projects include hybrid lift airships, energy efficiency, and the expansion of the instrumentation with a force-balance sting.

(a)

(b)

Figure 4. Setting up and testing (a) for a mechanical engineering lab experiment and (b) of an offshore platform truss.

Student organization and projects

A student chapter of AIAA was established in 2016, which has sparked interest in students forming teams to design, build, and fly their own remote-controlled aircraft in preparation for entering the annual AIAA sponsored design-build-fly (DBF) competitions as shown in Fig. 5. To date, four teams have completed the DBF projects, and currently two teams are developing entries for the upcoming competition. Furthermore, club activity includes networking with other regional sections of AIAA, as well as student trips to aerospace related events and industry.

The DBF project initiated interest in AIAA upon its first inclusion in capstone (MEE 487-488) in AY2015-16. Two teams developed entries to (albeit not attending) the competition as a capstone project, triggering so much student interest that a formal AIAA student chapter was formed in the same year. Since then, the AIAA section has participated in three more capstone projects, and is currently working towards participation in the national competition.

Another capstone team conducted a project in support of the ongoing NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD) research, culminating in a small-scale test rig for torus deflections. In 2015 a local chapter of SEDS was established, with the members participating in the NASA Student Launch Initiative in 2016. These varied aerospace activities have paved the way for several students doing internships at NASA over the past 3 years.

Figure 5. AIAA students engaged in a DBF project.

Select aerospace related research

Examples of Aerospace related research at the University of Maine include two NASA funded projects: the HIAD and an inflatable lunar habitat (ILH). HIAD is a multi-year collaborative project between NASA and a group of faculty and research staff in the college of engineering at UMaine.[6] HIAD system consists of an assembly of inflatable torus-shaped tubes that would be mounted on the nose of a spacecraft to decrease its speed as it enters the Martian atmosphere. Among other activities, the research at UMaine has included the analysis and testing of inflatable tube structures as shown in Fig. 6.

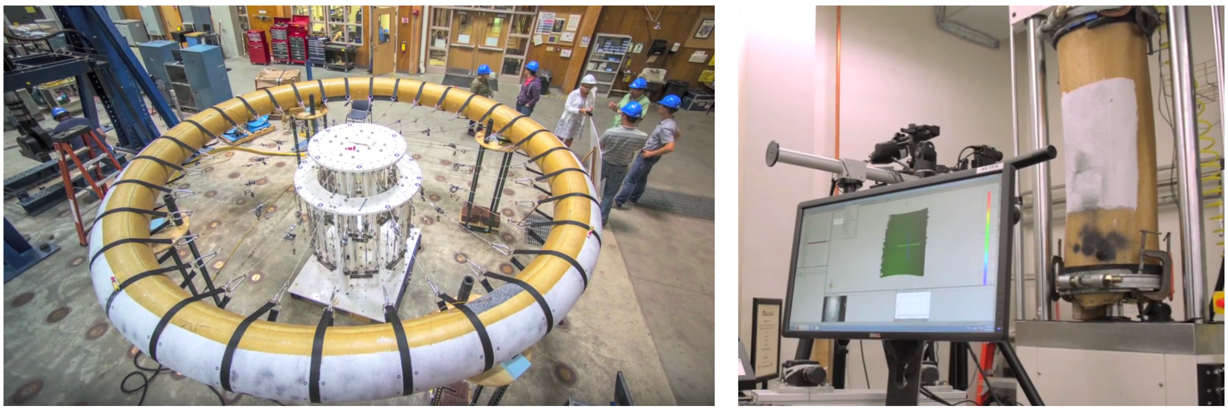


Figure 6. An inflated ring of HIAD being tested at UMaine's
Advanced Structures and Composites Center
https://composites.umaine.edu/defense-and-aerospace-composites/.

A group of faculty and staff in the college of engineering has worked with researchers at NASA to explore the viability of an inflatable structure as a lunar habitat (ILH). Research has included examination of structural integrity of chemically rigidized fabrics under conditions simulating the harsh lunar environment and design of battery-free, wireless sensors for measuring the vibration of the test structure during inflation. [7, 8]

Figure 7. ILH model at UMaine's Wireless Sensing Laboratory
https://umaine.edu/news/blog/2011/01/20/umaines-lunar-habitat-wireless-sensing-laboratory-opening-friday/.

Other projects with close association to aerospace include the analysis and testing of large (56 m) composite blades for offshore wind platforms as shown in Fig. 8. Tests have included static proof loading, fatigue, natural frequency and damping measurements, digital image correlation for surface buckling, and ultrasonic inspection of adhesive joints.

Figure 8. Strength testing of a 56-m long wind turbine blade
https://composites.umaine.edu/key-services/wind-blade-testing/.

Current research includes developing design algorithms for lighter than air (LTA) small UAV's for remote sensing missions. Efforts in providing appropriate aerodynamic coefficients for these LTA drones, in particular addressing the gap between hybrid and fully buoyant lift, are underway using CFD modeling of a range of configurations, as are related simulation engines to develop guidance, navigation and control algorithms eventually leading to autonomous flight.

Reflections on the initiative and future direction

Since the initial offering of the first aerospace engineering course in fall 2009, the aerospace initiative at UMaine has gained considerable momentum. Student feedback on the aerospace courses has been predominantly positive, and demand is high and growing. In particular, having faculty on site and developing student projects in aerospace serve as motivating factors that attract students. Traditional courses such as Advanced Strength of Materials and Mechanics of Composite Materials, that originally did not have an aerospace perspective, now aim to integrate this area, and new courses in aerospace structures and design are being developed.

The current two-year rotation of offering the current principal four courses (MEE 445, 446, and 547 or 548) prevents many undergraduate students from completing the concentration and interested graduate students from receiving the certificate in aerospace engineering. A core difficulty has been the disconnect between the aerospace course offering and the normal mechanical engineering curriculum timeline, which concentrates all technical electives in the senior year. It is, thus, almost impossible for students to complete the concentration without adding extra time to their degree program. The creation and offering of additional aerospace courses will begin to address this challenge.

It remains a challenge to integrate the wind tunnel into the teaching of the aerospace sequence, but as the instrumentation and equipment for the facility grows, this will be accomplished. An additional course in Experimental and Computational Fluid Dynamics, specifically with the goal of increasing experimental components is currently under discussion, and computational capabilities have very recently been introduced with the acquisition of ANSYS CFD (CFX and Fluent) packages for academic and research use in the department.

To further grow the initiative, we are developing a plan to extend the aerospace engineering concentration into a minor and to establish aerospace engineering specialization at the master's level. A preliminary study shows that there is significant opportunity to grow the aerospace engineering program, and we intend to direct more attention and resources to this effort in the future.

Acknowledgment

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