



Lighter than air vehicles as aerospace focused projects in a mechanical engineering capstone sequence

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Abstract

Mechanical engineering Senior Design projects often extend to cover aerospace engineering topics. Due to strong student interest, unmanned flight vehicles in the form of the AIAA DFB competition were introduced into Senior Design at the University of Maine, however students encountered difficulties due to their lack of previous aircraft-design specific preparation. In order to respond to both the interest and this difficulty, multi-copters and lighter than air (LTA) airship projects were introduced in AY 2018-19, and have grown in 2019-20 to account for over 44% of all senior design projects, with half of them being LTA vehicles. The mission and design framework for the LTA vehicles is based on the FAI Chapter 4 section 7 sporting code for radio-controlled airships, with a culminating design competition that further motivates student participation.

LTA vehicles are well suited for mechanical engineering students to explore aerospace topics, as flight vehicle lift generation (traditionally not taught or taught in a very limited fashion in a mechanical engineering curriculum) is replaced by hydrostatic lift, with the associated simplification in aerodynamic design (with drag and notions of added mass being the only consideration) and no requirement for knowledge of aircraft performance and stability and control. Rigid body dynamics, fluid hydrostatics and drag, as well as lightweight structures constitute the core knowledge areas required for the design of these vehicles, and are readily available to senior mechanical engineering students from coursework taken as part of the traditional mechanical engineering curriculum.

Introduction

Capstone or senior design courses represent the culminating experience for engineering students, and according to ABET [1] are required to incorporate appropriate engineering standards and multiple constraints, and be based on the knowledge and skills acquired in earlier courses. The courses typically consist of a design-build-test sequence [2], where students are required to follow through the entire design process in addition to building and verifying the intended performance of the project.

Mechanical engineering capstone projects reflect the broad nature of the profession, and as such can originate from many different fields. The overlap of Aerospace Engineering and mechanical Engineering in particular generates a variety of capstone projects that typically are of high interest to the students. However, a requirement for senior design courses is that the content be based on the skills acquired in earlier courses, and this can in turn represent a challenge when incorporating aerospace projects into the broader mechanical engineering discipline. Ensuring

that the demands of the projects are aligned with the previous knowledge of the student is thus imperative to designing successful projects.

The work presented here contrasts the skills required for typical aerospace projects with the skills typically imparted in a traditional mechanical engineering program. It further reports initial findings on the suitability of LTA projects for Mechanical Engineering students.

Methods

The University of Maine Mechanical Engineering Program requires its students to take a 2 semester capstone sequence, where they design, build, and test a complex mechanical system. The Fall semester is utilized for conceptual and detailed design, and the Spring semester for building and testing. The program also offers an aerospace engineering concentration, and students are demonstrating increased interest in the aerospace field; however, due to course requirements and scheduling, it has been difficult for students to begin the concentration prior to their senior year, and thus obtain the necessary background for rigorous flight vehicle based aerospace capstone experiences.

Unmanned aerial vehicle (UAV) projects, and in the context of the typical scope of a 2 semester capstone experience, can be broadly classified as fixed wing aircraft, rotary-wing aircraft and multi-copters, and lighter than air (LTA) airships. Each of these categories requires specific background knowledge, as shown in table 1:

Table 1. Knowledge areas required for UAV projects

Category	Required primary skills	ME taught
Fixed Wing Aircraft	<ul style="list-style-type: none"> • 2D and 3D fixed wing aerodynamics • Aircraft performance and control • Aircraft-specific lightweight structures • propulsion 	<ul style="list-style-type: none"> • no • no • limited • limited
Rotary Wing aircraft and multi-copters	<ul style="list-style-type: none"> • 2D and 3D rotary wing aerodynamics • Rotary wing performance and control • Lightweight structures • Flight control hardware and software • propulsion 	<ul style="list-style-type: none"> • no • no • yes • no • limited
LTA airships	<ul style="list-style-type: none"> • Hydrostatics • Aerodynamic drag • Lightweight structures • Rigid body dynamics • Added mass/maneuvering forces • propulsion 	<ul style="list-style-type: none"> • yes • yes • yes • yes • no • limited

Fixed wing aircraft and rotary wing aircraft require specialized knowledge that is not taught in the traditional mechanical engineering curriculum. Specifically, applied aerodynamics (both fixed wing and rotary wing), as well as performance and control (including stability) are not taught and constitute a core requirement for a successful design. On the other hand, the

fundamental physics of LTA vehicles are taught and are thus well suited for mechanical engineering students. The physical phenomena of buoyant lift, drag, and static stability stem directly from fundamental mechanical engineering knowledge. This higher simplicity of LTA vehicles however does not detract from the scope of the project (always based on acquired prior knowledge); the manufacturing options require many traditional mechanical engineering techniques that range from machining, to 3D printing and rapid prototyping, to composite materials. Electronic controls are readily available, as are propulsion options. An element of novelty is the concept of added mass and the destabilizing Munk moment that is generated by bodies of revolution at an angle of attack. Both are important for the computation of the stabilizer size and can represent a challenge for the students, however guidelines for these are also readily available for the students to explore [3]

Perhaps the only novel manufacturing technique to be learned by the students is the heat bonding of the airship hull. Further, the project requires strict weight optimization, and as such students need to explore the design space and apply numerical techniques to meet the required targets and achieve competitive performance.

The multi-copter projects also represent a viable alternative that does not require knowledge of fixed-wing aerodynamics; however students have difficulty in two key areas of these vehicles: flight vehicle guidance and control, and rotary wing aerodynamics. Both are not treated extensively in a traditional Mechanical Engineering curriculum, limiting the analysis methodologies available to the students and often steering them towards using available (yet “black box” type) online simulations. The result is that students will specify turn-key control and electrical systems and limit their analysis to the structural elements of the multi-copter frame. Thus from an instructor viewpoint, these projects do not offer the same breath of fundamental Mechanical Engineering topics as the LTA vehicles.

LTA activities conducted for the University of Maine Mechanical Engineering Capstone class have been framed in the context of the FAI sporting code, Volume 4, Sections F7 [4], which establishes a simple rule system and competition framework. The capstone projects compete against each other at the end of the year, further reinforcing the attraction of the students through the competitive motivation.

Results and discussion

Project progression:

In response to growing student interest in aerospace related senior design projects, an effort was made in the AY 2015-16 to increase the aerospace project alternatives by introducing the American Institute of Aeronautics and Astronautics (AIAA) Design, Build and Fly (DBF) competition as framework for capstone projects, with immediate interest of 2 student teams (the third aerospace classified team designed and built a wind tunnel). While both flight vehicle projects were successful, it became clear that there was lacking student background in aircraft specific design.

In AY 2017-18, and despite the addition of an aircraft design course to the aerospace concentration, the number of students interested in aerospace projects continued to exceed the number of students with the required background to design fixed wing aircraft. The resulting scenario limited opportunity for students to participate in aerospace projects, as the number of projects had to be limited to allow the increased instructor time commitment to compensate the lacking background, while at the same time some students realizing that their preparation was insufficient, and thus unhappily taking on other projects.

In the 2018-19 AY the instructor team removed the AIAA DBF project from the capstone offering as the AIAA local student branch was given the means to conduct that independently, and instead first introduced multi-copter drones and LTA airships into the project mix. The primary objective for this change was to explore alternatives to purely fixed wing aircraft that would better adapt to current student backgrounds.

The LTA projects, underlying the FAI rules, require the design and construction of these primary subcomponents:

- **Airship hull.** The volume is limited by the FAI rules, and key priorities are to design an aerodynamic shape that provides sufficient lifting capacity while capable of high speeds and adequate maneuverability. There are a number of options that the students consider, that include semirigid and non-rigid hulls, as well as the necessity of control surfaces and gondola attachments. Gertler shapes have been developed in submarine applications, and continue to be used for optimized airship envelopes [5]. Heat sealable balloon foil is used for the envelopes (this is instructor prescribed, as during the first iteration a number of alternatives were tested as unsuccessful), and a variety of methods exist (with excellent available online resources [6]) to manufacture the hulls.
- **Gondola.** While the gondola is not required (and some teams have opted to not include one), the gondola presents an excellent means to increase stability while providing an accessible enclosure for electronics and propulsion. The primary challenge is to design a ultra-lightweight structure capable of withstanding not only the propulsive forces imparted by the motors and guidance system, but also handling and take-off and landing loads. A further critical element is a fail-safe attachment to the hull to avoid loss and recovery complications of the hull in case of detachment.
- **Propulsion.** Propulsion is carried out using commercially available brushless electric motors. The challenge is to develop or select an appropriate configuration; often gimballed twin motors located at the gondola, in combination with control surfaces and/or a stern thruster are used, however internal ducted configurations with counterrotating propellers have also been successfully applied.
- **Control.** Control of an airship can be analyzed at two levels; first a basic rigid body dynamics analysis can be conducted that only considers vehicle inertia and forces generated by thrusters and control surface deflection, and at a more advanced level including all aerodynamic forces and moments such as added-mass and the effect of the Munk moment and tail cross flow [3], [7]–[9]. While mechanical engineering students have the required background for the basic analysis, the more advanced analysis

constitutes a challenge that not every capstone team addresses. However, due to the low speed and volume of the airships, and using a standard tail surfaces configuration, these airships remain flyable albeit not optimized if only the basic analysis is conducted. This area represents a challenge where students can go beyond their already learned background and acquire new knowledge, demonstrating lifelong learning abilities.

Overall the driving criterion is to minimize weight of the system to be able to satisfy the maximum volume constraints offered by the rules. Past airships have exhibited a total mass of less than 1000g.

Student participation and satisfaction:

Over the past two years the introduction of multi-copters and LTA vehicles have yielded an increase of flight vehicle projects from an average of about 10% of all capstone projects, to now 44% (AY 19-20), with LTA projects constituting half of all aerospace projects (Table 2)

Table 2: Progression of aerospace capstone projects 2015-2020

AY	Total number capstone projects	Aerospace projects	% Aerospace projects	LTA projects	% LTA projects
15-16	22	3	13.7%	0	0.0%
16-17	24	1	4.1%	0	0.0%
17-18	16	2	12.5%	0	0.0%
18-19	18	4	22.2%	2	11.1%
19-20	18	8	44.4%	4	22.2%

Student feedback has been very positive, with 2 airships achieving flight in the Spring of 2019 (Figure 1).



Figure 1. Students during test phase of their LTA projects

Students selected two distinct alternatives, one being the more traditional fully buoyant blimp with a bottom mounted gondola, two rotating thrusters that also generated pitch control, and a stern mounted transverse thruster for yaw control. This configuration generated high roll stability due to the low CG, and high speed with excellent maneuverability. The second team explored an unconventional ducted fan type envelope, with two counter-rotating axial fans and multiple

horizontal and vertical control surfaces in the propeller slipstream for yaw and pitch. This novel configuration generated a number of challenges that the students had to overcome before achieving controlled flight; however, both teams successfully completed the time-scaled regatta as prescribed by the rules.

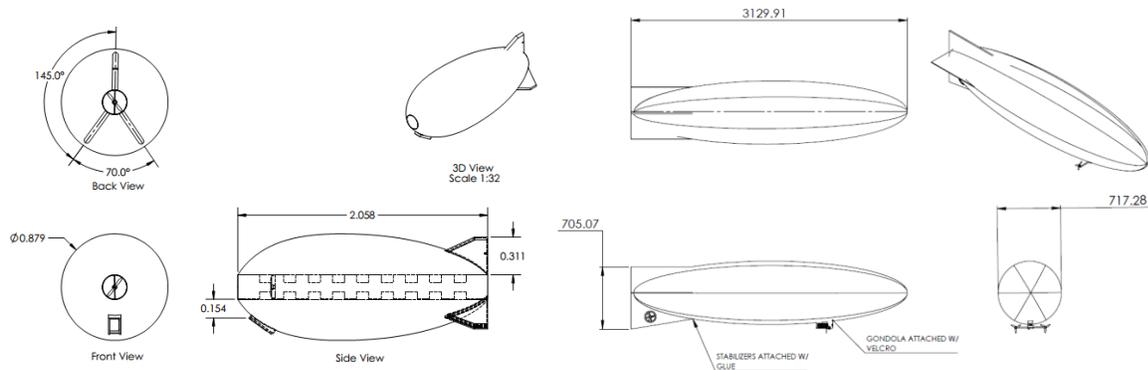


Figure 2. 3 views of 2018-19 airships

Currently (2019-20) there are 16 students participating in the next iteration of the LTA vehicle design within the capstone sequence, with increasing interest and plans to open the competition to outside participants.

Assessment and student feedback

The assessment procedure for the entire capstone course sequence incorporates a combination of individual and team assignments that undergo peer and/or instructor evaluation. The assessment process is outlined in [10], and results for the LTA teams during the 2019-20 academic year indicate excellent achievement of the course learning objectives, with both teams achieving course grade averages of A. However, this assessment of the course learning outcomes does not reflect the instructor observations and continuous informal student feedback offered throughout the course, which indicate strong enthusiasm towards the project. A student stated:

“The project was an excellent introduction to basic aeronautical engineering. It was extremely gratifying to spend the last few weeks of classing actually working on testing and perfecting the design, which not many other capstone projects had the luxury of. Overall the project taught me a lot about solving complex problems on an engineering team and my only regret is not having more time to work on it.”

Course benefits of LTA projects:

In the University of Maine capstone class, design and simulation activities are conducted during the Fall semester, giving the students ample time to in depth analysis of the project criteria. Construction is typically conducted during the first half of the Spring semester, with the second half of that semester dedicated to testing, culminating with the competition. This timeframe is well suited for the scope of the project. Teams begin construction with a construction validation period, where they build one or more small scale hulls to familiarize themselves with the heat-sealing process, and then proceed to build one to two full size hulls for their actual flight vehicle.

In parallel they develop and build the gondola, which often includes 3D printed elements as well as composite and/or balsa elements, and design and install the electronics. To accomplish these tasks within the first 7 weeks of the semester has been shown to be feasible, and teams have not had difficulty (barring late arrival of ordered parts) to initiate flight operations by late March/early April. Flight operations are also simpler (and not weather dependent) than outdoors-type UAV's, with all tests and the final competition being conducted in available athletic venues.

Due to the lightweight structure and limited number of components, the LTA projects have proven quite cost effective when compared to the fixed wing or multi-copter drones. These require equipment and materials oftentimes in excess of \$1000 per team, while the LTA vehicles typically stay below the \$500 threshold.

The primary lesson learned for the LTA projects is the difficulty of sourcing appropriate envelope materials for airships of that size (heat weldable balloon foil has worked well). Due to the time delay and expense associated with experimenting with a range of materials in 2018-19, the envelope material was fixed for the 2019-20 edition of the course.

Conclusion

Due to the strong interest in aerospace engineering in the mechanical engineering students at the University of Maine, a number of aerospace projects have been designed and offered as capstone or senior design projects. The difficulty encountered is that due to the lack of aircraft aerodynamics and performance specific instruction, it is difficult for the students to complete fixed-wing type aircraft projects as only a small minority of the students who have taken the relevant coursework can successfully address these more specialized projects. In order to make the field more reachable for students that have only the traditional mechanical engineering background, both multi-copter drones and LTA airships were introduced, sparking a strong increase in aerospace projects (jumping from an average of about 10% of the projects being aerospace related, to most recently 44% of the projects consisting of flight vehicles, and 22% of LTA airships). In particular the LTA airships have proven to be cost effective, broad scope projects that are well suited for mechanical engineering senior design experiences, and that provide a motivational factor to the student due to their competitive nature.

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