# EVOLUTION OF MIT'S "INTRODUCTION TO AEROSPACE ENGINEERING AND DESIGN" COURSE

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## ABSTRACT
Since the 1990's, MIT's Aeronautics and Astronautics Department has offered a freshman-level project-based learning class. The projects have included, parachutes, model rockets, LEGO Mindstorms, and radio-controlled lighter-than air vehicles. There was a major upgrade of the projects, based on ideas developed in the early days of the CDIO initiative, and the projects have continued to evolve since that time. This paper describes the evolution of the design projects, and, in particular, how CDIO principles have influenced that evolution. Increasing attention was paid to specifying design parameters that could be varied, allowing students to predict the behavior of their design projects, compare predicted with observed behavior, and try to explain the differences. The parachute project was modified so as to introduce the students to the importance of design drawings as a method of communication in engineering. Model rockets were eventually dropped from the curriculum because of an insufficient number of design parameters over which students had control. LEGO Mindstorms was introduced to emphasize to students the importance of software in aerospace systems. New scoring elements such as cost and robustness were added to the lighter-than-air vehicles in order to more closely emulate real-world design considerations. The talk will be illustrated by slides and videos, and design project specifications will be available.

### KEYWORDS
Project-based learning, Projects, Lighter-than-Air, parachute, LEGO

### 1. GOALS OF "INTRODUCTION TO AEROSPACE ENGINEERING AND DESIGN"
"Introduction to Aerospace Engineering and Design" a course offered by MIT's Department of Aeronautics and Astronautics in the spring of each year, is designed to give students a general background in aerospace engineering and in principles of design, through lectures and projects. The course is intended for freshmen and is not a required course either at the departmental or institute level. The students taking this class comprise three groups. The first are freshmen who are so excited about aerospace that they cannot wait for their sophomore year, when they will start their aerospace engineering major courses. The second group are freshmen who have not decided yet on a major and want to see if Aerospace is what they want. The third group, smaller than the first two, are students who are not majoring in aerospace engineering or, in some cases, in any type of engineering. These students look at this course as a way to get a relatively painless exposure to what aerospace engineering is all about. They tend to be upperclass students rather than freshmen. Since this course is an extra elective for all students, the workload is scaled appropriately. The lectures primarily deal with rockets and space flight, airplanes and air transportation, and safety. Only a few problem sets are assigned, and they are kept relatively simple, designed to give students a chance to use the equations presented in class. The remainder of this paper is devoted to presenting the projects that comprise the heart of 16.00. We note that although the projects follow CDIO principles, they do not actually engage the "Conceive" function, since the concept of the projects is given to the students, and they are just responsible for the Design, Implementation and Operation phases.

## 2. AERODYNAMIC DECELERATOR PROJECT

This project is presented on the first day of class, together with a short introduction to the concept of aerodynamic drag. The *Learning Objectives* of this project are:

- Importance of engineering drawings as a tool of communication
- Basic concepts of equilibrium – stable and unstable
- Concepts of center of gravity and center of pressure
- Basic use of the Aerodynamic Drag Equation

Students are given a basic set of materials**:** balsa wood sheets and stringers (long, thin pieces with square cross sections), plastic wrap, glue, and tape. Each student must design a "drop object", make a clear drawing of the object, and add whatever instructions might be necessary to build the object. The object must carry a weight of 15 grams (~ ½ ounce). In order to control the maximum size, each "drop object" must completely fit in a cubic box with 30 cm. edges. The goal of "drop object" design is to maximize the fall time after dropping the object off a 10.8-meter high balcony under the MIT dome, as is shown in Figure 1.

Figure 1. Dropping and Timing the "Drop Object" from the Balcony under the MIT Dome

Each student writes a short description of the behavior they expect their "drop object" to exhibit as it falls through the air. On the next class day, each student gives the drawing and instructions to a partner. During the next few days, everyone goes to the lab to construct the object designed by their partner. Total construction time is not supposed to exceed one hour, and students are asked not to consult their partner while building their "drop object". Students then write a short description of the behavior expected to be exhibited by the object they have just built. They also evaluate the completeness and clarity of their partner's instructions and drawing. On the third class day, all students drop the objects they designed, as built by their partners. For the final project report, students must evaluate the quality of construction of their "drop object" by their partner. Did the object look like they thought it would? They must describe the results of the "drop test" for both their and their partner's objects, including both the drop times and stability behavior, indicating any differences in the observed and predicted behaviors, and offering explanations for the differences. Finally, they must indicate what they would do to improve the performance of their "drop object".

Although a short explanation of drag is given at the beginning of this assignment, no mention is made of stability. The idea of having the center of mass below the center of aerodynamic pressure is left to the students to figure out. Some do and some don't, and many parachutes flip over after being dropped.

When this project was first initiated, no weight was required to be carried, and there were no specifications on how the provided materials should be used or on the size of the "drop object". One clever student presented a square inch of plastic wrap as his "drop object", and it had the slowest descent of all objects. The following year, we specified that balsa wood must form part of the object as well as plastic wrap, and we required that a ~15 gm. washer be carried as a payload. Some students then started making larger and larger parachutes, so we instituted the requirement that the completed "drop object" fit into a cubical box 30 cm on a side. In response, the following year, several students developed "folding" parachutes that would fit into the box but expand when dropped. We expect that this give and take of requirements and innovative design will continue. It is a good way to introduce students to the idea of what it means to "meet requirements" and to the importance of precision in writing requirements.

The main goal of showing students the importance of drawings as a means of communication in engineering has remained constant over the years. Another constant principle of all the projects is to predict the behavior of a system as one designs it, then test the system and compare the actual to the predicted performance. The most common deviation from predicted behavior of the "drop objects" involves stability. Many of the "drop objects" turn out to fall unstably or turn over and fall stably while inverted. Some students complain that they should have been introduced to the idea of having the center of gravity below the center of aerodynamic pressure before the project was assigned, in the same way that basic concepts and formulas for drag were presented. However, we believe that letting students discover some principles on their own is a valuable experience. Students are often surprised at the difference between what they thought they had designed and what their partners actually built. This is a valuable lesson in how precise drawings are an important type of engineering communication.

## 3. MODEL ROCKET PROJECT

Since the course is an introduction to aerospace engineering, the idea of building and launching model rockets seemed natural and was included as the second class project for many years. Teams of three to four students were given basic model rocket components as well as formulas to calculate aerodynamic stability and rocket performance. Calculating aerodynamic stability involved determining the center of mass of the rocket by a simple physical balancing process. The center of pressure required measuring the dimensions of the rocket body and fins and applying the formulas that were given out at the beginning of the project. Before any rocket was

cleared to launch, it was given a “swing test”, in which a string was attached at the center of mass and the rocket was swung in a circle. If it swung with the nose first, it passed the test. If the tail went first, it was unstable and had to be modified before being cleared for launch.
Launch day provided an opportunity for a discussion of larger scale launch operations and range safety. Students always enjoyed launching their rockets, despite the fact that in late February in New England it was often quite cold out on the athletic field! (Figure 2)

Figure 2 – Model Rocket designed for maximum height (February weather in Massachusetts)

The *Learning Objectives* of this project were:

- Predict the performance of a model rocket under zero-drag conditions
- Explain the effects that drag & wind will have on a rocket’s flight path and performance
- Predict the center of mass and center of pressure locations of a model rocket design
- Assess the stability of a model rocket design
- Explain and follow range safety procedures
- Successfully launch a model rocket

The major pedagogical shortcomings of the model rocket problem were the limited number of variables under the students’ control and the difficulty to accurately predict the behavior of the rockets. Students were given the choice of a small or a large nose cone, and they could vary both the length of the rocket body and the size and shape of the fins, but these had far less impact on overall behavior than the rocket motor performance and the wind blowing during launch. When the project was first started in the early 2000’s, the rockets were launched vertically and were rated on how high they went. Students soon learned that the best way to get altitude was simply to minimize weight, and we ended up with three-inch long rockets. In order to give the students more latitude in their designs, we changed the procedure and launched the rockets at a 45-degree angle, challenging the students to come as close as possible to a downrange target. This new goal of hitting a downrange target meant that simply maximizing range by minimizing weight was no longer a winning strategy, and predicting the actual rocket performance became more important. We still faced the problem of a limited number of variables that the students could control, as discussed above. Most important, however, was the inability to accurately predict the behavior of the rockets. First of all, there is variability in the impulse provided by the Estes rocket motors (size A). Also, calculating the aerodynamic drag was problematic, because once the rocket motor had burned out, the angle of attack of the rockets was seriously affected by wind, which varied the frontal area in a way that the students could not control. The 45-degree-launched rockets had no parachutes, so we were able to introduce an additional challenge to the students by offering them a second launch if their rocket survived the landing impact. This added robustness as a design variable and also gave the students experience with “field maintenance”.

While they enjoyed the challenge of launching their rockets and seeing if they survived to fly again, the students were frustrated by the large dispersions in performance compared to what they predicted. In discussing the reasons for the difference between predicted and observed performance, many students could do no more than speculate about the effect of wind gusts or under/over performance of the motors. Since comparing predicted and observed behavior is one of the prime pedagogical goals of the 16.00 projects, we eventually decided to delete the model rocket project and replace it with a LEGO Mindstorms project.

## 4. LEGO MINDSTORMS PROJECT

2012 was the first year that a LEGO Mindstorms project was included in the course (replacing the model rocket project), so we only have two years of experience. A prime motivation for added a LEGO Mindstorms project was to remind students of the increasing importance of software in aerospace systems. The challenge to the students is to build a “Mars Rover” that can collect and store onboard as many “Mars Rocks” (small marbles scattered around the collection field) as possible in a given time. The collection area was bounded by a white tape strip, and the rovers had to recognize this strip and stay inside the collection area. Furthermore, several large “boulders” (1-gallon milk jugs) were placed inside the collection area, and the rovers had to be able to navigate around them. Each team has four students, who have to figure out how to divide up the software and hardware work, reporting the task assignments as part of their final report. Teams have to document problems encountered during design, construction and testing and report how these problems are resolved.

Despite being given several opportunities to test their rovers, many teams were surprised by the behavior of their rovers in the final competition. During test runs, teams were only given a few “rocks” to work with, and many rovers had difficulties in storing larger numbers of rocks. Some rovers did not properly recognize the boundary and were penalized for going outside the collecting area. Many rovers lacked sufficient robustness and broke when hitting the “boulders”. The best part of this project was the wide variety of designs the students came up with. The problems that they ran into were fairly easy to understand, so they could do a good job in writing up the differences between predicted and observed behavior as well as making suggestions for future improvements. In summary, the first two years of the LEGO Mindstorms project were successful, and we plan to continue to include this as part of the course, in lieu of the model rocket launches.

## 5. LIGHTER THAN AIR VEHICLE PROJECT

The Lighter than Air (LTA) vehicle project is the oldest and most well known part of the Introduction to Aerospace Engineering and Design course. The goal of this project is, as a team of six, to design and construct a lighter-than-air (LTA) vehicle, often referred to as a "blimp". This project is used as a microcosm to represent many aspects of real world project design, construction, test and operation in the real world. The goals are both technical and societal. Most first-year engineering students nowadays have never built a major hands-on project, so it is an excellent introduction to aerospace engineering, especially since a lighter-than-air vehicle is much easier to control than an airplane, given that its lift does not depend on its velocity, so students just have to deal with thrust, drag, and weight. Aerospace projects are almost always team efforts, and this project is an excellent introduction to teamwork. It also duplicates many aspects of the design/build process used in industry and government: preliminary and critical design reviews, opportunities for test flights and evaluations, and a competitive "fly-off". The preliminary and critical design reviews give the students experience in oral presentations, building confidence in their ability to stand up in front of an audience and talk about technical material. The project also entails two written reports, one on the test flight activities, where the students learn about the Cooper-Harper rating system, and then a full project report on the entire experience. Taken in totality, this gives the students a lot of oral and written communication experience.

The *Learning Objectives* of this project are:

- Design, Build, Test and Operate a lighter-than-air vehicle.
- Calculate lift and drag for blimps to evaluate aerodynamic designs.
- Learn how to design a radio-control system
- Gain an understanding of the tradeoff between maneuverability and stability in aerospace systems
- Gain experience in working as part of a team

Numerous changes have been made in the LTA project since its origin in the 1990's. Some of the most significant are listed here.

Scoring: Originally, LTAs were rated just on speed, as measured during a lap around MIT's indoor track. To more closely mirror aerospace design metrics in the real world, payload capacity was added as a scoring factor in the late 1990's. Cost was added early in the 2000's as an additional scoring factor in the LTA project, in addition to speed and payload capacity. Again, the motivation was to give the students a more real-life experience. The cost was calculated according to the number of balloons, motors and servos that were used. We continue to experiment with the formula used to calculate the success of the project. In the early days of the LTA project, most teams used three or four weather balloons for their LTAs. As weather balloons and helium became more and more expensive, and when we introduced an additional flight day (see below) we used the scoring formula to encourage students to use fewer balloons and make their LTAs more maneuverable. In 2006, the last year that weather balloons were used, two teams were able to design their LTAs to use only one balloon. A feature at the end of race day during the early years of the LTA project was a "demolition derby", when teams flew their LTAs into one another, and the "last LTA standing" was the winner. While many students enjoyed crashing their vehicles into one another, we felt that with all our emphasis on reusing balloons, this destructive activity would send the wrong message to students.

Flight Opportunities and Test Flight Criteria: Originally, students had an initial flight day to test out their vehicles and gain pilot experience. They then had a week to make repairs and changes prior to the race day a week later. We introduced a third LTA flight opportunity in 2005 and have retained it as a permanent feature of the LTA project. This gave us the opportunity to introduce concepts of test flight into the LTA project. Taking advantage of the extra flight day, we created special slalom courses to test the horizontal and vertical maneuverability of the vehicles. In a lecture before this test flight day, the students are introduced to concepts of test flight, including Cooper-Harper ratings. The students have to write test flight reports for their vehicles, including CH ratings for horizontal and vertical maneuverability. Student response seems extremely positive.

New Balloons: A large change occurred in 2007, when the class TAs came up with a method of sealing off the opening of a large, translucent plastic trash bag around a wooden dowel, leaving only a small opening for filling, which could be tied off after the fill. Photos below show the old and new configurations. With the new technique, we no longer needed to use individual weather balloons. The plastic trash bags are reusable, are almost impervious to bursting, and small tears can be easily repaired. When we fill the balloons, we hang a standard weight of 700 gm. from the wooden dowel. When the balloon plus weight are neutrally buoyant, the filling is stopped and the bag sealed off. Each LTA vehicle is weighed before being attached to its balloon, and however much less it weighs than 700 gm. is counted as the payload capacity. The team then attaches the vehicle to the balloon and adds ballast to achieve neutral buoyancy. Figure 3 shows both the old weather balloon system (3a) and the new single-balloon system (3b).

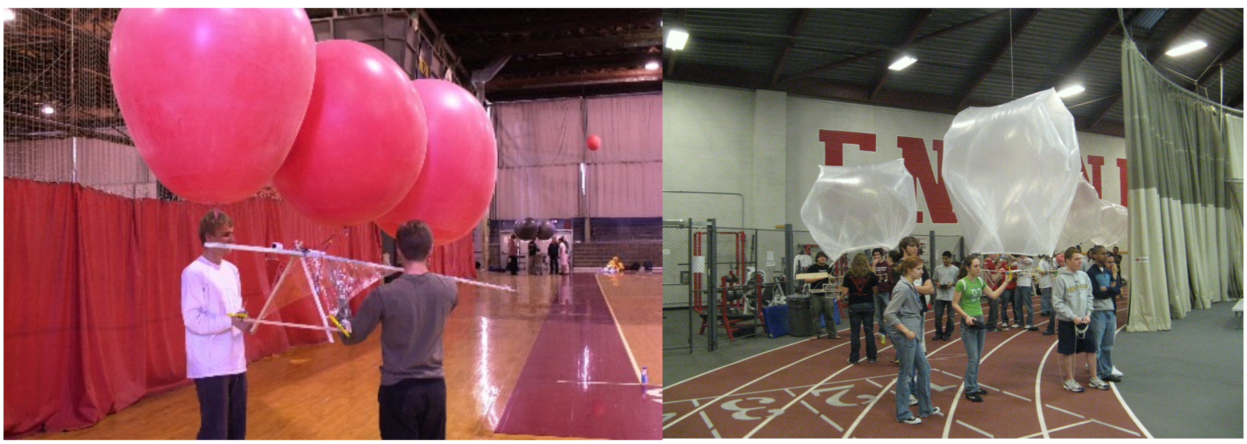

Figure 3a Multi-Weather Balloon LTA System (in use through 2006)

Figure 3b Single Balloon LTA System (in use since 2007)

Students are often surprised at how much slower their LTAs move around the race track than they calculated just on the basis of thrust and drag. They eventually come to realize that excessive controllability limits their ability to fly in a straight line, and the back-and-forth motion of the LTAs actually results in a longer course. This teaches an important lesson about the tradeoff between stability and controllability as a critical design and performance issue. Some teams achieve lateral control using differential thrust of two motors mounted on an extension perpendicular to the main axis of the LTA. Others use thrust vector control by mounting a motor on a movable platform attached to one or two servos, for vertical or horizontal control or, sometimes, both. Others use aerodynamic surfaces, which need to be mounted close behind the propellers to provide adequate slow-speed control. Figure 4 shows four examples of different control schemes.

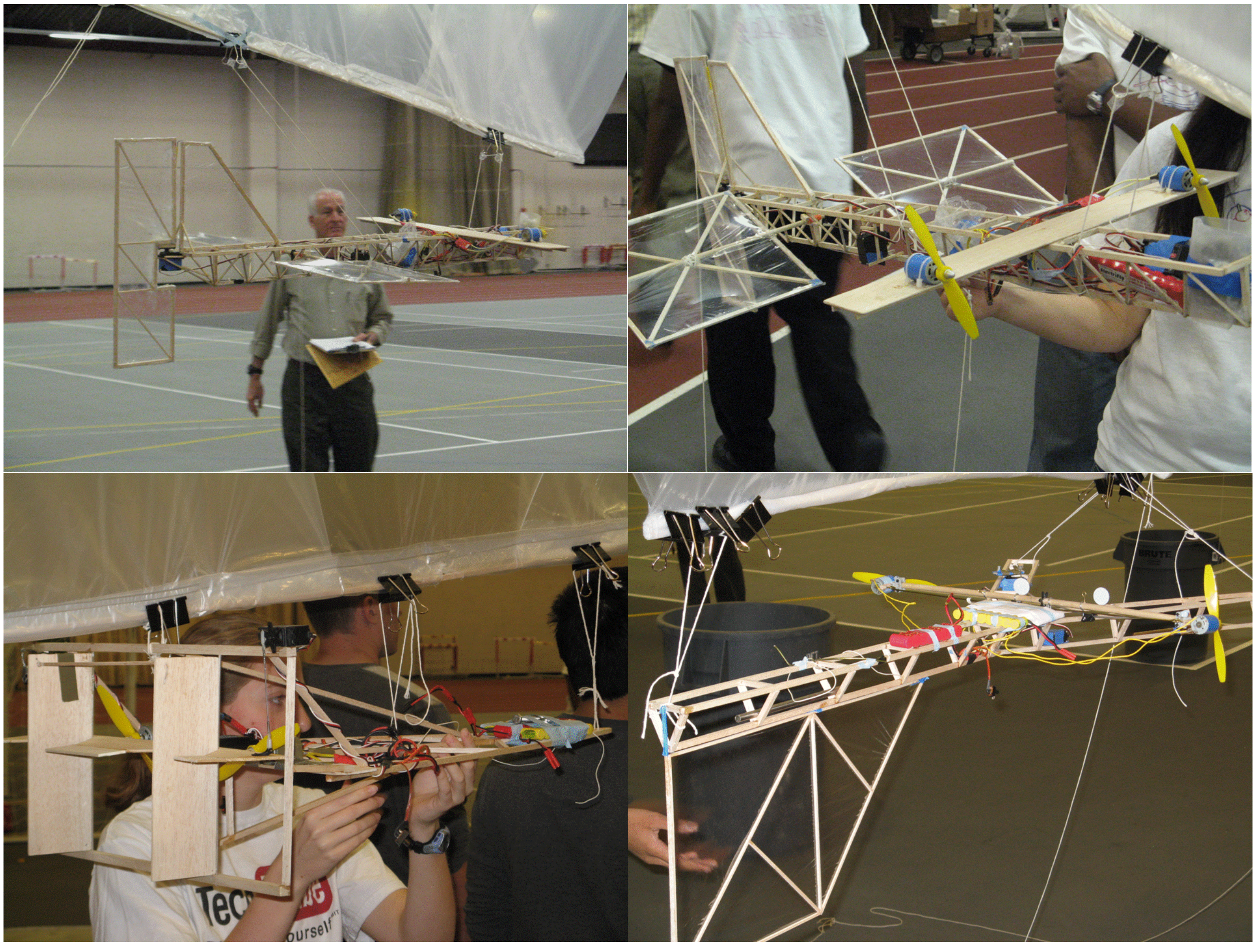

Figure 4 – Different LTA Control Schemes
(Differential Thrust, Thrust Vector Control, Aerodynamic Control Surfaces)

Besides the technical challenges, teamwork is critical in this project. Given the importance of teamwork in aerospace engineering, this is excellent preparation for real-world internships and jobs. Students fill out peer reviews towards the end of the project, commenting not only on one another's performance but also on how their teams functioned.

In summary, the Lighter Than Air vehicle project continues to provide an excellent "capstone" project for MIT's freshman introductory aerospace course. The LTA project is simple enough to allow students with little experience in hands-on work to design, build and operate a working aerospace system but is complex enough to challenge the students for the entire latter half of the semester. Detailed student instructions and specifications of the RC system are available on request for faculty desiring to introduce a similar project in their classes.

## BIOGRAPHICAL INFORMATION

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