DESIGN-BUILD-FLY PROJECTS OF LIGHTER-THAN-AIR SYSTEMS FOR ENHANCED LEARNING OF AIRCRAFT DESIGN PRINCIPLES

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Abstract. This paper shares the experiences of teaching the principles of aircraft design to a group of undergraduate students by assigning “design-build-fly” (DBF) type projects related to Lighter-Than-Air (LTA) systems. In a classical aircraft design course, students are generally made to carry out a paper design of an aircraft that meets some user-specified and regulatory requirements. In some cases, such projects are of DBF type, and mostly related to Gliders, Quadcopters, or UAVs. While this approach has its own merits, one of the key limitations is that success in accomplishing such tasks requires good piloting and/or aeromodelling skills. It’s quite common for student teams to spend many hours in fabricating an aircraft that they have designed, and only a few minutes in breaking it beyond any repair! LTA systems, on the other hand, are quite forgiving and robust, and often pose far greater challenges in sizing, fabrication, system integration and flight testing compared to their heavier-than-air counterparts. This paper provides many examples of such projects successfully completed by student teams, and presents a case for including LTA systems based DBF project to undergraduate students of aerospace engineering.

1 INTRODUCTION

The subject of Aircraft Design is part of the core curriculum in most universities around the world, which run an undergraduate (UG) degree specialization in Aeronautical and/or Aerospace Engineering. Many of these universities teach this subject in a “hands-on” mode, either partially, or fully. In some universities (e.g., at NTU Singapore), the students are divided into teams, and each team is given the task of carrying out a conceptual design of an aircraft meeting some specified requirements, on paper (or, more appropriately, a computer), over a semester. The faculty member(s) that conduct this course try to impart the “design knowledge” via some lectures, instructions and reviews of the design that the various teams work out.
In some other universities (e.g., Virginia Tech in USA), the course is spread over two semesters. In the first semester, primarily, some theoretical and procedural inputs in carrying out a conceptual design are imparted. During the second semester, the student teams are given a choice; some go for design-build-fly (DBF) projects (mostly as part of some competition, e.g., the AIAA Design Build Fly competition), whereas some others take up computer-based designs of aircraft that are not amenable to the DBF mode in a university environment, due to constraints on the facilities and equipment available, and the costs.

The author has been involved in teaching this subject for over two decades at the Aerospace Engineering Department of IIT Bombay. Over the years, the manner in which this subject is taught has undergone many changes, some to keep in line with the developments in this field, but mostly also due to the constraints of non-availability of faculty members with suitable background and training to handle such a course. In the current avatar, the UG students in the sixth semester of an eight semester program, undergo a taught course, in which the history, background, principles, procedures, and special considerations in conceptual design of an aircraft are imparted, using some examples and case studies. However, engineering design is best learnt by doing it, and one needs to get their hands dirty to appreciate and develop a designer’s mind-set, for which the DBF projects come in very handy. Hence, an Aircraft Design laboratory course is also conducted in the seventh semester. In this, the student cohort is divided into groups and made to carry out hands-on design projects which aim to create a physical system meeting certain requirements and expectations. As mentioned above, some teams may decide to undertake theoretical computer-based design projects, especially if they want to address some contemporary challenges in Aerospace Engineering or take part in some competitions, e.g., AIAA Student Individual or Team Design Competitions.

Most of the DBF projects taken up by student teams tend to be related to Gliders or Remotely Controlled UAVs, the most popular one being Quad- or Multi-copters. One of the problems that many students encounter when they attempt such DBF projects is lack of past experience in making things by hand. Part of the blame for this goes to the current UG engineering education system, in which we are slowly moving away from imparting practical skills, and focusing more on computer based skills. On the other hand, society in general is also moving towards more computer (and now hand-phone) based activities, so the students are naturally more familiar with these systems, rather than the machines used for fabrication, e.g., lathe and drilling.

The other problem that novices face is that most aerospace systems are inherently unstable and complex, and it is not easy to make them crashworthy and robust. Moreover, many students do not have the necessary piloting skills and experience in safely operating an aerospace vehicle, and expecting most students to acquire these skills before they attempt an aircraft design exercise is a tall order. In such a scenario, it is a very common occurrence that a student team takes, say, five days to fabricate a remotely controlled aircraft or quadrotor, but just five minutes to break it beyond repair! This leads to a sense of frustration and, in several cases, demotivates the student cohort enough not to attempt any further work. Further, the design and fabrication of systems like Quadrotors is mostly driven by Avionics and Control, and there may be little or no scope for exploring the knowledge gained in subjects like Aerodynamics (and to some extent Structures) in fabricating such systems.
This paper shares the experience of the author in teaching design principles and thinking to teams of UG students, by taking up DBF projects in the field of Lighter-Than-Air (LTA) systems. The next section provides a brief overview and history of LTA systems, and some recent developments. Some DBF projects that have been successfully carried out by UG students and interns are illustrated. Finally, the key challenges and benefits of carrying out DBF projects in LTA systems are highlighted, and a justification for taking this approach is provided.

2 LIGHTER-THAN-AIR SYSTEMS

Lighter-than-Air (LTA) systems are aeronautical systems that derive most of their lifting force to overcome gravity by the principle of buoyancy. This is in direct contrast to Heavier than Air (HTA) aeronautical systems, which use motion relative to the ambient air for generating the aerodynamic forces to overcome gravity. The predominant lift-generating component of an HTA system is its wing or rotors, while that of an LTA system is an envelope filled with an LTA gas, e.g., Helium or Hydrogen. The difference in weight of the air displaced by the envelope and the LTA gas filled within results in buoyant force. The Net Lift $L_{net}$ of an LTA system can be calculated using Eqn. 1:

$$L_{net} = V_{env}(\rho_a - \rho_g)$$

Where $V_{env}$= envelope volume, and $\rho_a$, $\rho_g$ are densities of ambient air & LTA gas, respectively.

LTA systems can be broadly classified into three main categories, viz., Balloons, Airships and Aerostats. Balloons normally uses hot air or LTA gas to generate lift, and are mostly spherical or teardrop in shape, with no propulsive system. Airships consist of an aerodynamically shaped envelope and are fitted with a propulsive device for providing forward motion, and a flight control system to provide directional stability and control. Aerostats, on the other hand, are designed to remain stationary; they consist of an aerodynamically shaped envelope tethered to the ground. Adequately sized fins are mounted on the envelope to allow the envelope to weathercock and provide stability. Fig. 1 showcases the three principle types of conventional LTA systems.

![Fig. 1: Three types of conventional Lighter-Than-Air systems](image)
2.1 History of LTA systems

The history of LTA systems dates back to 220-280 AD when the Kongming lantern became popular in China. These lanterns used the principle of hot air ballooning for generating lift forces and remained afloat, illuminating the sky. In 18th century AD, Joseph and Etienne Montgolfier conducted a series of experiments with hot air balloons and succeeded in the first manned flight in 1783. Around the same time, Jacques Charles and the Robert brothers made the first manned flight using a hydrogen filled balloon. Numerous experiments were subsequently conducted for adding power to hot air and gas balloons which evolved into aerodynamically shaped airships. Balloons have limited applicability for scientific and commercial applications, since they are totally at the mercy of the ambient wind. Current uses of balloons are limited to collection of weather related data or hot air ballooning as an adventure sport. The two LTA systems that are most popular and capable of commercial or scientific exploitation are Aerostats and Airships, and their historical developments are described in the two sub-sections that follow.

2.1.1 Aerostats

The history of Aerostats in military warfare dates back more than two and half centuries. Observation balloons and aerostats have been used in battle since the 1790s; their first reported use was during the French revolution. US military forces have used a network of Tethered Aerostat Radar Systems (TARS) since December 1980, first to help counter illegal drug trafficking, then for border protection by keeping a check on illegal immigration, and later for low-level surveillance coverage for air sovereignty. TARS have also been used very effectively to support the US military in its operations in Afghanistan in 2001 and Iraq in 2003.

2.1.2 Airships

The “Golden Age of Airships” began in 1900 with the launch of Zeppelin which was named after Count Ferdinand von Zeppelin. Zeppelin Airships were the most successful airships of all time and were extensively used for air transportation, as well as bombers during World War I. The United States and Britain also built several Airships during 1920s and 1930s, for example, R-33 and USS Shenandoah (ZR-1) respectively, although these mostly imitated the original design of the Zeppelin. During the 1930s, airships were the luxury liners of the sky, ferrying passengers across the Atlantic in comfort and style, a far cry from the cramped conditions that the vast majority of air travelers today are forced to put up with. Today, however, in the minds of the general public, the very word ‘airship’ today conjures up a vision of a bygone era, and airships suffer from a connotation of being dangerous and unsafe. This is mainly due to a series of fatal accidents between 1910 and 1940, which lead to their downfall. The most noteworthy accidents were the crash of the British airship R101 in France and burning of the Hindenburg, the largest airship ever built, leading to the loss of crew and passengers. After World War II, Airships were deemed to be obsolete due to advancements in HTA aircraft technology, and were sent into a quiet oblivion.
3 PRESENT DAY LTA SYSTEMS

Today, Aerostats are the aerial platform of choice for long duration surveillance applications, when the ambient weather conditions are mostly calm or not very disturbed. Due to the aerodynamically efficient shape of the envelope, as well as provision of adequately sized fins, an aerostat can be designed to remain fairly steady even in strong ambient wind conditions. Depending on the payload, range of surveillance, and operational time, these aerostats can be launched to any desired altitude from a few meters above ground level, to as high as 5000 m above ground level. Of course, the payload-carrying capacity of an aerostat is reduced as its operational height is increased. Aerostats can be easily and quickly deployed at high altitudes, ensuring a long-endurance, and stable surveillance system, with much lower distortion levels. Once they are deployed, there is very little recurring additional expenditure to keep them afloat, mostly in the form of small amounts of LTA gas, just to top-up for the leakages through the fabric over a period of time.

Over the years, technological developments in aerospace engineering have made airships much safer, chiefly due to the availability of Helium as an inert LTA gas, and much superior material and control systems. Many researchers today believe that airships present an effective, low-cost, environment friendly solution for some niche areas of air transportation, such as hauling cargo over remote locations such as Canada and Alaska. This has spawned many studies and technology development initiatives worldwide, and it can be said that airships are now undergoing a revival. Airships can be very effectively used in regions where economic considerations are a key driver towards solving the transportation problems, especially in providing air transport service to remote communities. The costs related to setting up and operating the infrastructure required for operating airships are quite small, compared to that for their heavier-than-air counterparts. Further, the operating costs of airships can also be quite low, primarily due to their low fuel consumption.

In recent times, there has been a significant interest to revisit LTA systems, mostly due to their cost effective and environmentally-friendly deployment for scientific, civil and military applications [1]. With the advancement of technologies like composite materials, durable fabrics and techniques of research, and developments like finite element analysis (FEA) for structural analysis, Computational Fluid Dynamics (CFD), Fluid Structure Interaction (FSI), design optimization, thermal modeling and automated control, modern Airships and Aerostats are getting much more refined and safe and hence, are facing a major revival. They are being proposed for a wide range of applications such as advertising and tourism, surveillance, environmental monitoring, planetary exploration, heavy-lift cargo transport and telecommunication relays.

IMPORTANCE OF DBF PROJECTS

Many institutions all over the world are attempting to incorporate CDIO (Conceive-Design- Implement-Operate) strategy in their UG education systems. In 2001, MIT in the USA took the lead in implementing a CDIO strategy in their UG aerospace engineering curriculum, by arriving at a statement of goals for engineering education. This strategy was updated a decade later in 2011 [2]. DBF projects are an integral component of a CDIO based education strategy in any aeronautical department, and their successful implementation in the
MIT curriculum has been explained by Young et al. [3].

There is a general misconception that implementing a CDIO strategy in UG teaching needs huge amount of resources, and results in much higher operating expenses. In 2003, MIT and three leading universities in Sweden developed a survey that allows an engineering school to benchmark curricula for teaching personal, interpersonal and system building skills, all of which are enumerated in a CDIO syllabus, and all of which are required in a well-rounded aerospace engineer. The results of this survey indicated that no additional resources are needed in following a CDIO approach in UG teaching; it is enough to simply follow a consistent and deliberately designed syllabus [4].

MIT was also the first institution to implement Lighter-Than-Air systems-based DBF projects as part of their curriculum in the freshman year. This exercise has been described in detail by Newman [5], in which she mentions that the lighter-than-air vehicle design competition provides an opportunity to apply the fundamental concepts and approaches of aerospace engineering in the context of the design. This opinion is totally supported by the experience of this author, as described in the next section.

4 DBF PROJECTS ON LTA SYSTEMS AT IIT BOMBAY

In 2001, the Program for Airship Design and Development (PADD) was launched at IIT Bombay, with team members drawn from various national aerospace organizations and private sector companies in India. One of the objectives of PADD was to get updated with the global developments in Lighter-Than-Air (LTA) technology. In the first phase of PADD, techno-economic feasibility of leasing airships for transportation of goods and passengers over mountainous terrain under 'hot and high' conditions in India was investigated. As an offshoot of the PADD program, a Lighter-Than-Air Systems Laboratory was set up in IIT Bombay in 2004.

One of the key outcomes of PADD was the development of a methodology for the design of a non-rigid airship. By using this methodology, one can arrive at the baseline specifications of a non-rigid airship that meets user-specified requirements [6]. The methodology estimates the envelope volume required to carry a user-specified payload and also arrives at the mass breakdown and performance estimates of the various components. Alternatively the payload that can be carried by an airship of specified envelope volume can also be estimated.

4.1 Outdoor Remotely Controlled Airships

The first DBF project to be implemented in LTA laboratory was an outdoor remotely controlled non-rigid airship in 2002, named MICRO [7], in which the abovementioned methodology was modified for carrying out sizing and baseline design calculations of a remotely controlled airship. The design requirements specified for MICRO were very modest; it was required to have a payload capacity of 1.0 kg, while operating at a maximum speed of 30 kmph for 20 minutes, using an existing IC engine developing 0.41 BHP. Due to constraints on storage space, it was required to be less than 5.00 m in length. An extended version of the MICRO, named MINI, was developed in 2003, with an increased payload capacity of 3.0 kg [8]. In 2009, an outdoor airship named MACRO was developed for snow cover evaluation of
lower Himalayas [9]. Recently, a remotely controlled airship named **AUTON** has been developed and flight tested. This airship was meant to act as a test platform for an outdoor autonomous airship [10]. Fig. 2 shows the photographs of these four airships. Their key parameters are listed in Table 1.

![Outdoor airships](image)

**Fig. 2**: Outdoor airships designed and developed at LTA Systems Laboratory of IIT Bombay

<table>
<thead>
<tr>
<th>Year of development Parameter ↓</th>
<th>2002 MICRO</th>
<th>2003 MINI</th>
<th>2009 MACRO</th>
<th>2013 AUTON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>4.99</td>
<td>6.42</td>
<td>8.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Envelope Volume (m³)</td>
<td>6.8</td>
<td>8.6</td>
<td>26.6</td>
<td>24.7</td>
</tr>
<tr>
<td>Payload (kg)</td>
<td>1.0</td>
<td>3.0</td>
<td>6.0</td>
<td>15.8</td>
</tr>
<tr>
<td>Endurance (min)</td>
<td>15</td>
<td>18</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Max. Speed (m/s)</td>
<td>7</td>
<td>10</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Engine Power (HP)</td>
<td>0.41</td>
<td>0.60</td>
<td>2.0</td>
<td>T = 6 kg</td>
</tr>
</tbody>
</table>

**Table 1**: Key parameters of outdoor airships

### 4.2 Indoor Remotely Controlled Airships

Since 2004, several indoor airships have also been developed by students as part of DBF projects. The envelope profile of these airships vary from Oblate Spheroid, Zhiyuan, and NPL. A biomimetic airship was also developed, which mimics the motion of a Rainbow Trout fish. The photographs of four such airships are shown in Fig. 3.

![Indoor airships](image)

**Fig. 3**: Indoor airships designed and developed at LTA Systems Laboratory of IIT Bombay

### 4.3 Tethered Aerostat Systems

Two tethered aerostat systems have also been developed as DBF projects. The first project was to demonstrate aerostats as a relocatable aerial platform for providing communications in remote areas during emergencies. Two field trials were conducted in 2007, in which the
efficacy of the system was established for wireless data and voice communications over a radius of ~ 10 km [15]. In 2014, a tethered aerostat system for aerial surveillance in a college campus was also developed and successfully field tested [16]. Fig. 4 shows photographs of these two systems.

Fig. 4: Two tethered aerostat systems developed under DBF projects

5 CHALLENGES AND BENEFITS OF LTA DBF PROJECTS

DBF projects in LTA systems offer several interesting design challenges in terms of weight management, envelope fabrication techniques, and the need for ground support systems. These projects also impose many constraints, for example, the cost and availability of LTA gas, and the larger space needed to operate the system and then store it when not in use. One major constraint, especially in outdoor LTA systems, is the issue of operational safety in case of system failure; if the system goes out of control, it could possibly drift into controlled airspace and cause interference with commercial or general air traffic! LTA systems are very robust and do not easily get damaged when mishandled. Since airships operate at low speed and are bulky, they respond slowly to control inputs, so students can quickly learn to fly them. Aerostats completely remove the need for piloting skills, although they need a winching and mooring system to operate them.

During the last decade and a half, the supervising teams of UG students for several DBF projects reported that none of the systems were lost, or suffered any catastrophic failure during deployment or testing. While carrying out these projects, students have experimented and solved several design and operational problems, which has made their experience quite enriching. It has also encouraged them to think of novel approaches and learn to tackle new problems. Once such example is the design and field testing of an on-board mounted device for safe recovery of payload in case an aerostat tether is accidentally severed during deployment [17-18], design and fabrication of mooring masts for indoor and outdoor airships [19] and field deployable winch for aerostat are examples of fall-out projects [20].

6 CONCLUSIONS

Based on the experience of over two decades of teaching aerospace design to UG students, and the reasons mentioned above, it is recommended that DBF projects related to LTA systems should be included in the syllabus, because they can go a long way in providing an excellent learning experience, and can inject new ideas into the minds of budding engineers.
REFERENCES


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