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DESIGN STUDY TO SIMULATE THE DEVELOPMENT OF A COMMERCIAL TRANSPORTATION SYSTEM

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UNIVERSITY OF NOTRE DAME

Seven teams of senior-level Aerospace Engineering undergraduates were given a Request for Proposals (RFP) for a design concept of a remotely piloted vehicle (RPV). The RPV designs were intended to simulate commercial transport aircraft within the model of "Aeroworld." The Aeroworld model was developed so that the RPV designs would be subject to many of the engineering problems and trade-offs that dominate real-world commercial air transport designs, such as profitability, fuel efficiency, range vs. payload capabilities, and ease of production and maintenance. As part of the proposal, each team was required to construct a prototype and validate its design with a flight demonstration.

INTRODUCTION

The purpose of this design project is to provide a simulation of the design process for development of a commercial transportation system. The project has been formulated to expose the design students to numerous issues related to the systems design process. Due to the limitations on experience, time, and resources in a single undergraduate engineering course, one appears to have two options in the formulation of the design project: either to select a complex project in which only certain aspects of the design process can be considered, or to select a simpler project in which the design process can be addressed in more depth.

The second of the two options has been selected for this project. Since one of the final products required is a flying aircraft, the nature of the project is limited to those types of systems that can be readily manufactured by the student design teams. Since the area of interest was a commercial transportation system, the problem was modeled in a rather simple fashion. The development of an aircraft system capable of transporting groups of "passengers" to and from a variety of destinations is a complex task involving geographic, demographic, economic, and technical issues. A problem that attempted to integrate a number of these issues was formulated. It should be stressed that the emphasis was placed on the design process, not the final product. The course goals are listed below and the project, as defined in the Request for Proposals (RFP), was intended to help achieve these course goals.

- Introduce the student to system design methodology and, in particular, aircraft design.
- Illustrate the interactive interface between each of the technologies that influence the performance of a system.
- Provide an opportunity to integrate each of the independent technical disciplines at a level where the students understand the technology and can effectively use the appropriate tools.
- Develop an understanding of the planning, coordination, and communication necessary in a team project.
- Expose the students to numerous phases of the system development process, from problem definition to system operation.
- Provide the opportunity to experience the process of translating ideas into an actual product.

Each of these goals is addressed in the context of a team-oriented, mission-directed, aircraft design project. The following section describes the project in some detail and the results of the individual student team designs.

RFP: COMMERCIAL AIR TRANSPORTATION SYSTEM DESIGN

The mission and semester project details were defined in the following RFP. This request placed some additional requirements and constraints on the basic mission specifications. The design teams were notified that certain aspects of the mission were open for modification, given sufficient justification for these changes.

Commercial transports operate on a wide variety of missions ranging from short 20-minute commuter hops to extended, 14-hour flights that travel across oceans and continents. To satisfy this wide range of mission requirements, "families" of aircraft have been developed. Each basic airplane in the family was initially designed for a specific application, but from that basic aircraft numerous derivative aircraft are often developed. The design of the basic aircraft must allow the derivative aircraft to be developed.

Though they may differ in size and performance, all commercial designs must also have one common denominator: They must be able to generate a profit. This requires compromises between technology and economics. The objective of this project will be to gain insight into problems and trade-offs in the design of a commercial transport system. This project simulates numerous aspects of the overall systems design process so that you will be exposed to many of the conflicting requirements encountered in a systems design. Because of the limited time allowed for this single course a "hypothetical world" has been developed and you will be provided with information on geography, demographics, and economic factors. You will be asked to design a basic aircraft configuration and derivative aircraft that will have the greatest impact on a particular market. The project will not only allow you to perform a systems design study, but will provide an opportunity to identify those factors that have the most significant influence on the system design and design process. Formulating the project in this manner will also allow you the opportunity to fabricate the prototype for your aircraft and develop the experience of translating ideas into hardware, and then validate the hardware with prototype flight testing.

Problem Statement

The project goal will be to design a commercial transport that will provide the greatest potential return on investment in a new airplane market. Maximizing the profit that your airplane design will make for your customer, the airline, will be the primary goal. You may choose to design the plane for any market in this fictitious world from which you believe the airline will be able to realize the most profit. This will be done by careful consideration and balancing of the variables such as the number of passengers carried, range/payload, fuel efficiency, production costs, and maintenance and operation costs. Appropriate data for each is included later in the project description.

The "world" market in which the airline will operate is shown in Fig. 1. Additional information is provided to indicate the passenger load between each possible pair of cities each day. This ranged from 20-500 passengers per day. Other useful information about each city including details on location, runway length, and number of gates available to your airline and their size will be provided. The airline may operate in any number of markets provided that they use only one airplane design and its derivatives (your company does not have the engineering manpower to develop two different designs for them). Consider derivative aircraft as a possible cost-effective way of expanding its market.

Requirements

1. Develop a proposal for an aircraft and any appropriate derivative aircraft that will maximize the return on investment gained by the airline through careful consideration and balance of the number of passengers carried, the distance traveled, the fuel burned, and the production cost of each plane. The greatest measure of merit will be associated with obtaining the highest possible return on investment for the airline. You will be expected to determine the ticket costs for all markets in which you intend to compete. The proposal should not only detail the design of the aircraft but must identify the most critical technical and economic factors associated with the design.

2. Develop a flying prototype for the system defined above. The prototype must be capable of demonstrating the flight worthiness of the basic vehicle and flight-control system and be capable of verifying the feasibility and profitability of the proposed airplane. The prototype will be required to fly a closed figure-eight course within a highly constrained envelope. A basic test program for the prototype must be developed and demonstrated with flight tests.

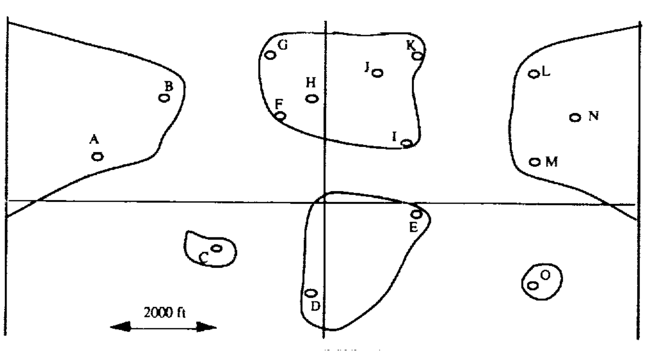

Fig. 1. Geography of "Aeroworld."

Basic Information for Aeroworld

The following information is to be used to define special technical and economic factors for this project. Some are specific information; others are ranges that are projected to exist during the development of this airplane. (Note real time is referred to as RWT, Aeroworld time as AWT.)

1. Passengers = standard ping-pong balls. Remember these are "passengers" not cargo, therefore items like access, comfort, safety, etc., are important.

2. Range = distance traveled in feet.

3. Fuel = battery charge in milli-amp hours (mah) (RWT).

4. Production cost = \$400 per dollar spent on the prototype + \$100 per prototype construction man-hour (RWT).

5. Maintenance (timed battery exchange) = \$500 per man-minute (RWT).

6. Fuel costs = \$60-\$120 per milli-amp hour RWT.

7. Regulations will not allow your plane to produce excessive noise from sonic booms; consider the speed of sound in this world to be 35 ft/s.

8. The typical runway length at the city airports is 75 ft. This length is scaled by a runway factor in certain cities.

9. Timescale is 1 minute AWT = 30 RWT minutes.

10. The world has uniform air density to an altitude of 25 ft and then is a vacuum.

11. Propulsion systems: The design, and derivatives, should use one or a number of electric propulsion systems from a family of motors provided by the instructor.

12. Handling qualities: The aircraft must be able to perform a sustained, level 60-ft-radius turn.

13. Loiter capabilities: The aircraft must be able to fly to the closest alternate airport and loiter for one minute RWT.

14. There are two existing modes of transportation in Aeroworld that offer competition to your market: An average train fare costs \$6.25 per 50 ft + \$50 flat rate; an average ship fare costs \$8.00 per 50 ft + \$65 flat rate.

To satisfy the mission objectives, Design Requirements and Objectives (DR&O) were established by each design team. Development of DR&O for each team was based on the priorities set by each team. The primary items identified in the DR&O were passenger and range requirements, aircraft gate requirements, and certain manufacturing requirements. With these goals established, each group member developed a basic aircraft concept and from the individual concepts, a team concept was selected. The team concept was then used as the baseline configuration and preliminary design studies were performed to develop each concept.

CONCEPT DESCRIPTIONS

The following summaries provide an overview of each of the seven concepts and address specific technical merits and limitations. Included are selected three-view representations of the aircraft. These summaries are meant to give a brief description of each design, and further technical detail on each proposal is available upon request. These are edited versions of the final proposal executive summaries.

Alpha Group: The *Behemoth Apteryx*

Alpha Design Group formulated a design for an aircraft called the *Behemoth Apteryx*. The design is a compilation of efforts both to fulfill requirements imposed by the project definition and to optimize efficiency in both performance and construction. The basic aircraft configuration is a conventional, high-wing monoplane with aft-mounted tail.

We decided to limit the wingspan to 5 ft to be able to utilize all gates in Aeroworld while having a solid, unhinged wing. A SPICA airfoil section with a wingspan of 60 in and a chord of 14 in was selected. This required flying relatively close to $C_{L_{max}}$, the maximum allowable cruise velocity, and α_{stall}. These risks were recognized and it was decided that they could be overcome. With such a short wingspan and thus small area and aspect ratio, the next critical constraint was minimal weight. The small area meant a large wing loading, thus every effort was made to minimize weight.

Considering the two major limiting factors, the design can be summarized as follows: Propulsion is to be provided by an Astro-15 electric motor and a 650-mah battery pack. The fuselage is 44 in long with a maximum width of 7 in and will hold 50 passengers plus 2 crew members. The structure consists of a balsa wood and spruce truss structure for the fuselage and balsa wood spars and ribs for the wing. The entire aircraft will be covered with plastic coating. Control will be accomplished by means of an elevator, a rudder, and ailerons. Given the target commercial market, fleet size, and ticket price, the purchasing airline could make $840 million per year and Alpha Design would make $4,316,800 on the sale of that fleet.

Potential problems with the *Behemoth Apteryx* result mostly from the 5-ft wingspan restriction. To achieve a realistic cruise L/D, the aircraft must cruise at 32 ft/sec or M = 0.91. The takeoff speed is 29 ft/sec, which is also relatively high. However, the design is very versatile in that it can access any airport gate and any runway without additional ground crew handling associated with a hinged wing. It also is extremely easy and inexpensive to build, which keeps the purchase price down, thus making it a very marketable aircraft. This aircraft can beat all existing modes of travel in cost, speed, and convenience. This would make air transportation the ultimate in travel in Aeroworld. We feel that the benefits we receive from our self-imposed restrictions well justify the risks in design.

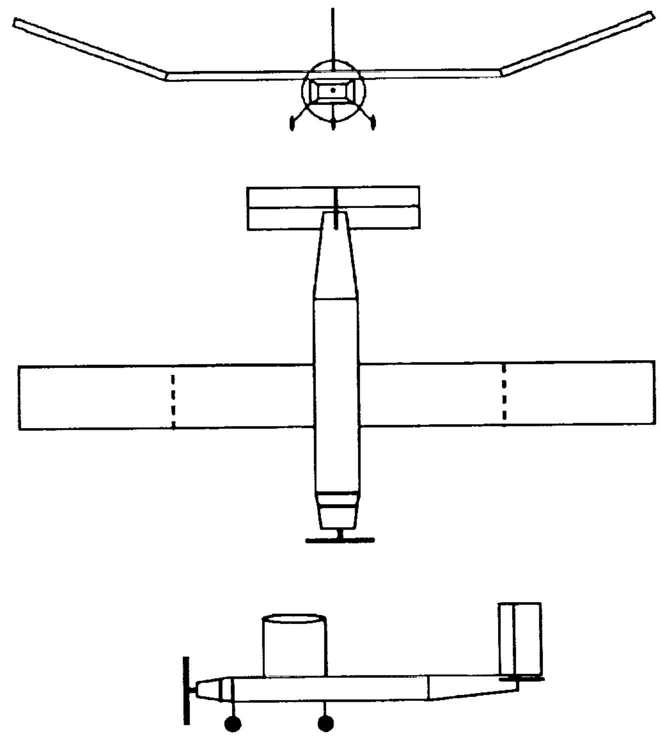

Fig. 2. Beta Group Concept.

Beta Systems: *El Toro*

El Toro has been designed to operate as a commercial transport that can profitably meet the needs of the Aeroworld market for both the manufacturer and the airline. From mission studies conducted of the Aeroworld market, it was determined that an aircraft range of 6000 ft plus loiter time would be able to serve about 90% of the market. It was also determined from these studies that an aircraft capacity of 50 passengers would best meet the needs of the market. *El Toro* meets both of these market requirements with a range of 25,000 ft and a capacity of 51 passengers. The present design for *El Toro* will profitably meet the requirements for operation in Aeroworld with a ticket price comparable to the ticket prices of current transportation. The extended range of *El Toro* allows for numerous flights before the battery pack must be changed. This drastically reduces the operating costs to the airlines, allowing them to charge less for a ticket or to realize a higher profit margin. The unit production cost for the airplane is estimated to be $162,000, including all material, systems, and labor.

The aircraft was a conventional, high-wing design shown in Fig. 2. The airfoil selected for *El Toro* is the SPICA, chosen for its high lift coefficient at low Reynold's number and its ease of construction. The wing is sized for minimum power required at cruise while meeting structural requirements. The wing has a span of 8.33 ft and an aspect ratio of 10. The wing is hinged at 2 ft on either side of the fuselage to allow folding of the wing on the ground to enter any airport gate.

The propulsion system for *El Toro* was sized for takeoff in 60 ft with enough extra power to overcome changes in runway conditions, aircraft weight, and aircraft aerodynamics. The propulsion system consists of a propeller-electric motor combination with the prop mounted at the front of the fuselage.

Maximum passenger comfort and safety established a majority of the stability and control design requirements. Longitudinal stability and control will be achieved with the horizontal tail with elevator. Directional stability and control will be achieved with an aft vertical tail with a rudder. Lateral stability will be achieved with a high wing with dihedral. Ailerons are not used because of the hinged wings.

One of the most critical areas in this airplane's structural configuration is the hinge design of the wing. The feasibility of this technology must be demonstrated in order to justify the airplane design, for without folding wings, *El Toro* would not meet the gate requirements of Aeroworld. One of the primary purposes of the technology demonstrator will be to show that a working folding wing can be constructed.

Beta Systems is confident that *El Toro* will be a successful and profitable airplane in Aeroworld for both the manufacturer and the airlines. This success will continue into the future with a family of derivative aircraft. Possible derivatives will have extended or shortened fuselages, larger or smaller engines, or capabilities to be converted for cargo or military applications.

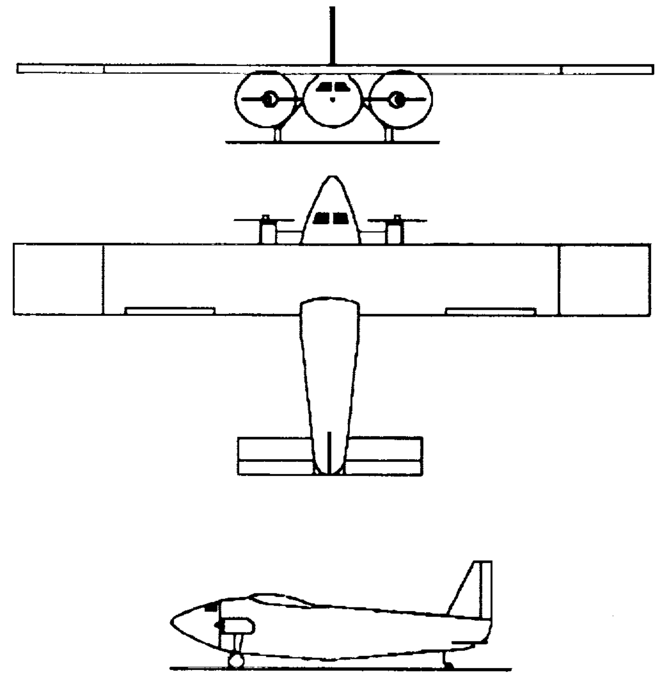

Fig. 3. Delta Group Concept.

Delta Group: The *Nood Rider 821*

The *Nood Rider* aircraft provides a fast, efficient, and relatively inexpensive alternate mode of transportation to the people of Aeroworld. In addition, the *Nood Rider* is able to expand with the growing needs of the market. The Nood Rider offers safety far superior to that of its competitors. A number of the routes the aircraft will be used on will be over large bodies of water. With its twin engine configuration, the aircraft can remain safely airborne while diverting to the nearest airport. Although the aircraft cannot take off with one engine out, it can be brought to a stop safely with adequate control.

The *Nood Rider* cruises at a velocity greater than or equal to that of our competitors. At a cruise velocity of 34 ft/sec, the *Nood Rider* will be able to move passengers to their destinations with a large time savings. Since the passenger is paying a premium for air transportation, we felt it important to maximize this time savings. With the absence of a drag penalty for flying at Mach numbers close to one, there is no disadvantage with flying at this velocity.

The passenger payload of 50 and the foldable wingspan of the *Nood Rider* gives a greater flexibility in our departure schedule (Fig. 3). The on-ground wingspan of 5 ft allows the Nood Rider to use all the gates available in Aeroworld. The relatively small passenger payload allows multiple daily departures from every city in Aeroworld. Flexibility in planning an itinerary is paramount in every traveler's needs, and the *Nood Rider* is able to satisfy them.

Maintaining the aircraft was always an important consideration. The engines, mounted on pylons extending from the fuselage, are easily accessible. This allows easy routine maintenance or replacement of the engine if necessary. The structure of the entire aircraft is of the simplest design. The wing is a three-spar structure with ribs and stringers. The empennage is a two-spar configuration of similar construction. The fuselage consists of circular bulkheads with longerons running between. All this allows easy maintenance and repair.

With a cruise range of 4200 ft, the *Nood Rider* is able to remain competitive with the other modes of transportation in Aeroworld. The selling price is $368,000. The per-flight operating cost of the aircraft is $70,843. Charging the passenger a ticket price of $12 per 50 ft (15.24 m) plus a flat fee of $100, allows the operator to recoup all the operating costs, which include depreciation for yearly replacement of the aircraft, even when flying at a passenger load factor of 0.70. This makes the *Nood Rider* a viable alternative to trains or boats.

Gamma Group: The *Pale Horse*

The *Pale Horse* is a conventional RPV that will operate in Aeroworld as a 30-passenger aircraft. The major design concerns were cost, range, and passenger comfort. Economic analysis concludes that approximately 150 aircraft flying 8 missions of an average distance of 2150 ft per mission will comfortably accommodate the needs of Aeroworld. A rate of $12 per 50 ft plus a $50 flat rate will be profitable to the airlines and will be competitive with the other modes of transportation in Aeroworld.

The Pale Horse uses the SD7062 airfoil. The rectangular wing, with an 8-ft span and 10.5-in chord, will be mounted high on the fuselage with 10° of dihedral for increased roll stability. The wing will be hinged 1.5 ft from each wing tip to utilize the 5-ft as well as 7-ft gates at Aeroworld airports. The hinge enables the wing tips to be folded upward during loading and unloading in the airport gates.

Passengers will be seated in two rows of 15, with a center aisle for safety and comfort. Aft of the passenger cabin will be space for a restroom as well as a galley. Beneath the passenger area will be a luggage storage hold that will also house the control system and linkage.

An Astro-15 electric motor will be used to power the *Pale Horse*. Connected to the motor will be a Tornado 10-6 propeller, and driving the motor will be thirteen 1.2 V/1.2 ah batteries connected in series. This propulsion system enables the aircraft to be maneuverable with a desirable rate of climb and a takeoff distance less than 38 ft. The flight range for one battery pack is over 20,000 ft; therefore, a fully charged *Pale Horse* can fly its 8 daily flights including taxi and delay times on a single charge. This reduces Aeroworld gate times, thus allowing quicker turnovers between flights. In addition, this reduces maintenance costs, which allows the airlines to pass the savings on to passengers.

Concerns in the design include the hinge design and structural failure resulting from the inexperience of the manufacturers. Prototype studies give encouraging results for the effectiveness of the hinge. Throughout the design, large factors of safety have been included to reduce the apprehension for the latter concern.

Kappa Group: The *Initial Guess*

This aircraft is designed to generate profit in the market that is currently dominated by the train and boat transportation. The main priority of the design team was to develop an extremely efficient aircraft that could be sold at a reasonable price. The *Initial Guess* offers a quick and safe alternative to the existing means of transportation at a competitive price. The cruise velocity of 28 ft/sec allows all flights to be between 20 and 45 min, which is a remarkable savings in time compared to travel by boat or train.

The *Initial Guess* is propelled by a single Astro-05 engine with a Zinger 10-6 propeller. The Astro-05 is not an extremely powerful engine, but it provides enough thrust to meet the design and safety requirements. The major advantage of the Astro-05 is that it is the most efficient engine available. The fuel efficiency of the Astro-05 is what puts the Kappa Aerospace aircraft ahead of the competition. The money saved on an efficient engine can be passed on as lower ticket prices or increased revenue.

The *Initial Guess* has a payload of 56 passengers and a wingspan of 7 ft. The 7-ft wingspan allows the aircraft to fit into the gates of all of the cities that are targeted. Future endeavors of Kappa Aerospace will include fitting a stretch version of The *Initial Guess* with a larger propulsion system. This derivative aircraft will be able to carry more passengers and will be placed on the routes in greatest demand.

The fuselage and empennage are made of a wooden truss configuration, while the wing is made of a rib/spar configuration. The stress-carrying elements are made of spruce, the non-stress-carrying elements are made of balsa. The wing is removable for easy access to the fuselage. The easy access to the batteries will keep maintenance costs down.

The *Initial Guess* will cost $246,000 to produce. The ticket price will be $75 flat fee and $12/50 ft. This ticket price will generate profit at the most expensive fuel price and, assuming that the plane flies at capacity, the production cost will be made back in 49 flights. The *Initial Guess* provides an extremely rapid return on investment and will be competitive with the already existing modes of transportation.

Theta Group: The *Hotbox*

The *Hotbox* is a 40-passenger commercial aircraft designed to have a minimum range of 5500 ft and cruise at a velocity of 30 ft/sec. The aircraft is designed to serve the longer-range, overseas market in Aeroworld. The driving force behind the design was to generate the greatest possible return on investment and profit for an Aeroworld airline. This goal, at least in an underlying sense, influenced all aspects of the design. Because of the seven-week engineering timeframe, ease of construction and simplicity of design also had a primary influence on the design. In addition, space restrictions (disassembled aircraft must fit in a $2' \times 3' \times 5'$ box) imposed significant limitations on aircraft design.

From these primary design goals, a set of secondary drivers evolved. First, in order to serve all the airports in the overseas market, the *Hotbox* was required to be able to use a 5-ft gate. A weight requirement was set at 4.5 lb in order to maximize aircraft efficiency. Finally, a single-engine system was chosen because it minimized system weight, complexity, and cost. From these primary and secondary design goals, the *Hotbox* was born.

The *Hotbox* is estimated to cost $152,000 Aeroworld dollars (AD) and will sell for $200,000 AD. A ticket price of $38 flat rate plus $9.70 per 50 ft is recommended. This ticket price is, on an average flight, 15% higher than the ticket cost of a ship. Because of the time savings involved with air travel, this excess cost is considered acceptable. A market consisting of 27 routes and 316 flights per day is estimated to generate a $42.3 million AD net income and a 53.8% annual return on investment.

The propulsion system for the *Hotbox* consists of a nose-mounted Astro 15 electric-powered motor and a Top Flight 12-6 propeller. Early in the design process, studies indicated that the Astro 15 motor would provide sufficient power for all phases of the mission and better cruise performance than other motors considered. After ordering this motor, however, weight considerations became an increasing concern in the design of the *Hotbox*. The Top Flight 12-6 was used because it allowed minimum battery weight and was the only propeller considered that met the 60-ft takeoff requirement.

A SPICA airfoil was selected for the *Hotbox* based on the ease of construction of its flat bottom and its positive lift and drag characteristics. In order to provide acceptable wing loading, the *Hotbox* has a wing area of 7.33 ft^2. Aircraft aspect ratio is 8.72. To simplify construction, no sweep, taper or twist was incorporated into the wing design. The wing consists of a spar and rib construction with a plasic sheet skin. In order to fit into the 5-ft gates of Aeroworld, the *Hotbox*'s 8-ft wing must be hinged. The primary hinge mechanism will be enclosed in the wing and located at the quarter chord and 26.75 in from the fuselage centerline.

A fuselage of rectangular cross section will contain the propulsion system, control system, and a passenger bay with 2×20 seating. The center of gravity (c.g.) is located at 30% chord

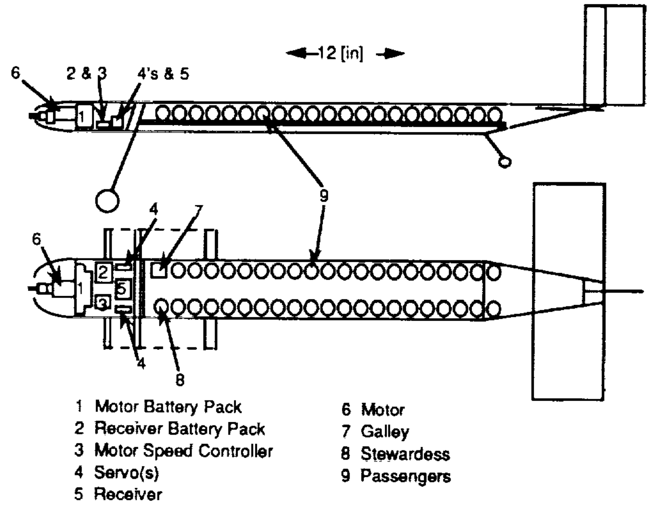

Fig. 4. Theta Group Concept - Internal Layout.

with the aircraft fully loaded and at 21.5% chord without passengers. Figure 4 is a schematic illustration of the internal arrangement.

The final design of the *Hotbox* provides for takeoff distance of 26.5 ft and normal cruise range of 17,000 ft. Maximum range and maximum endurance for the aircraft are 20,600 ft and 14.3 min respectively.

Zeta Group: The *Valkyrie*

The *Valkyrie* is a flying wing concept designed to serve as a high-volume commuter transport in Aeroworld (Fig. 5). The technology demonstrator seeks to validate the flying wing design as a superior alternative to the conventionally configured aircraft used in the modern airline industry. The 5.02-lb *Valkyrie* has a wingspan of 84 in (7 ft), which results in an aspect ratio of 4.9. The root and tip chords measure 23 and 11 in, respectively, forming a taper ratio of 0.48.

The *Valkyrie* employs the NACA $2R_212$ airfoil section. A 2° reflex in the trailing edge of this airfoil provides a zero moment coefficient about the aerodynamic center over the applicable range of angles of attack. Furthermore, the rear 20% of the chord across the entire span comprises the elevator and ailerons. This configuration, along with a judicious positioning of the c.g. location, allows the *Valkyrie* to trim during cruise at an angle of attack of 8°. Although reflexing the trailing flap to trim does increase the drag generated by the wing by raising the C_{D_0} to 0.0314, the overall drag produced by this configuration remains small compared to similarly sized conventional designs with drag-inducing fuselages.

A leading edge wing sweep of 13.2° and a 2° dihedral have been incorporated to provide lateral stability. Ailerons have been designed to provide adequate roll control power. Yaw stability is provided by triple vertical stabilizers. Yaw control is achieved through the use of a rudder on the center vertical stabilizer. With this configuration, it is possible to land in a crosswind of 10 ft/s.

The *Valkyrie* is a semimonocoque structure manufactured from spruce and balsa wood covered in plastic mylar skin. The internal ribs are spaced 3.5-in apart to provide comfortable seating for the maximum carrying capacity of 100 passengers. The NACA $2R_212$ airfoil, with its 12% maximum thickness (t/c) provides sufficient volume to comfortably carry the maximum passenger load. In addition to adequate passenger space, the *Valkyrie* must have sufficient usable volume to house the fuel and control system. Two large, solid balsa wood ribs form the central corridor of the aircraft, housing the motor, batteries, and avionics.

The AstroFlight Cobolt 25 electric engine will power the *Valkyrie*. It is designed to take off in less than 20 ft. To eliminate the difficulties associated with rotating the aircraft at takeoff, the wing is mounted on its landing gear at the takeoff angle of attack of 8°. A velocity of 26.7 ft/s is required to generate sufficient takeoff lift. Once airborne, the *Valkyrie* climbs to the cruise altitude of 20 ft, then flies at 32 ft/s on a closed, figure-eight loop. In turns, the *Valkyrie* can either increase its speed or deflect it's control surfaces to maintain the cruise altitude. On landing, the aircraft must touch down at a speed of approximately 26 ft/s to maintain trimmed conditions.

Finally, the *Valkyrie* provides a greater payload-to-weight ratio than a conventionally configured aircraft of comparable weight. Considering the requirements, the *Valkyrie* is the most efficient design for the specified mission.

DESIGN ISSUES

The following brief sections address issues in the major areas of weights, structures, propulsion, aerodynamics, stability/control, economics, and production, and describes the concept technology demonstrators and their flight validation.

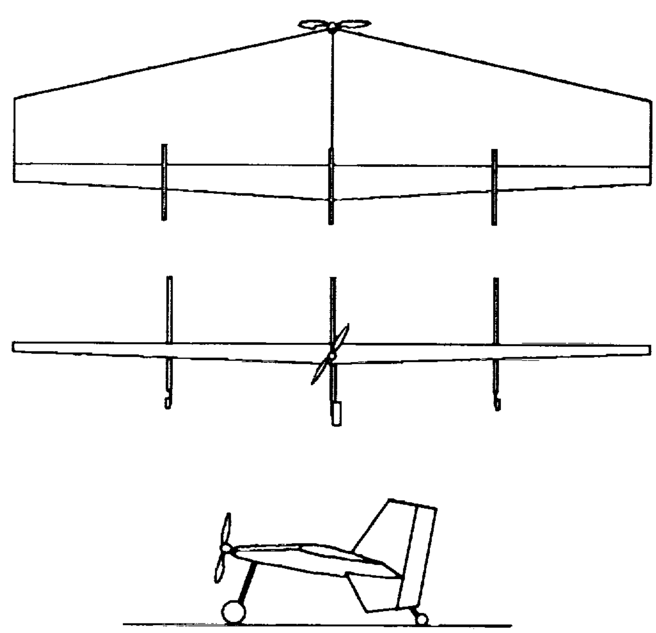

Fig. 5. Group Zeta Concept - the *Valkyrie*.

Weights

Each team was concerned about keeping overall weight to a minimum. Previous design studies have provided a reasonable database for component weights, but accurate initial estimates are difficult because they significantly depend on manufacturing techniques. Payload weight was not a significant issue, though payload volume was. C.g. control was usually achieved by positioning of the relatively heavy motor batteries.

Structures

Manufacturing considerations imposed the greatest constraints on the structural design. Certain unique features such as a circular fuselage, multiple-engine configurations, and, in particular, folding wings provided challenges in structural design. Because of limited manufacturing expertise, the design teams were often cautious in adopting nontraditional structural concepts. Since total time required for the fabrication phase was a significant cost factor, manufacturing constraints were present in the structural designs.

Propulsion

For safety and other reasons related to development of the technology demonstrators, electric propulsion systems were required. Integration of the battery storage, electric motor performance, and propeller selection proved to be critical in determining the success of the concepts. Takeoff power requirements exceeded the low-speed, steady-cruise requirements. Various computer-based methods were developed to provide performance predictions since analytic models of the electric motor performance are available. Performance predictions for the propellers operating in this low Reynolds number regime are difficult and the flight validation indicated that a number of the propeller selections were inappropriate. The size of the propulsion systems ranged from the 035 to the 25 and unfortunately weight and cost were not directly proportional to power available. The twin-engine concept developed by Delta Group presented a technical risk. The engines were readily accessible and simultaneous control appeared to be effective. During flight test, asymmetric thrust developed either because of differences in the motors or the propellers. Resolution of this problem would have required additional testing.

Aerodynamics

Wing design was driven by the conflicting requirements of gate dimensions and the desire for high aspect ratio to achieve optimum cruise performance. Only one group attempted to develop the minimum span wing (5 ft). Others selected either rigid wings that met the larger gate requirement or folding wing tips. Certain aerodynamic considerations such as taper, twist, or complex airfoil geometries were often eliminated from consideration by anticipated problems with fabrication. The Mach number limit did not carry with it a penalty for approaching the limit and was therefore only invoked for safety considerations associated with the indoor flight tests. Most groups attempted to achieve cruise near L/D_{max} but the preliminary drag predictions are difficult in this low Reynolds number regime.

The primary payload, citizens of Aeroworld, was relatively lightweight, but occupied significant volume. Space/comfort requirements for the passengers as well as baggage and required services were not well defined, leading to different interpretations by individual groups. Fuselage size was influenced by the design passenger load. The influence of fuselage design on the drag did not appear to be a critical design issue since cruise drag was not a design driver.

Stability and Control

Concerns were primarily those of maintaining adequate static pitch stability and the roll control necessary to perform the closed course maneuvers. This was usually accomplished with two channels of control, elevator and rudder, in order to eliminate the weight and complexity of the additional control for ailerons. A number of the groups did effectively integrate aileron control, but pilot response did not imply that these designs handled any better than the two-channel systems. Previous designs developed to fly in the same constrained airspace had demonstrated the feasibility of the control concepts and, other than issues related to control surface sizing and actuator installation, few significant problems were encountered.

The *Valkyrie* flying wing design was a unique development that presented a certain technical risk. C.g. control in this design was particularly difficult and a number of post PDR changes had to be made to the design prior to flight validation. This aircraft may have performed more like a fighter than a transport.

Economics

In light of the overall design goal of generating a profit, a direct comparison of each concept would be desirable. Because of the limited time allowed and rather liberal interpretation of some of the initial guidelines, this direct comparison is not possible. Most of the design groups interpreted fuel cost, production time, and production costs as primary cost drivers. Since each used similar total battery capacities and the total fabrication times were comparable (each group fabricated the technology demonstrator in about two weeks), system cost predictions yielded similar values. This implies that the aircraft carrying the greatest number of passengers might be the most profitable, if flights were full.

Complete system economic studies were beyond the scope of this project, but it did make the groups aware of certain economic drivers in the design process.

Production

Since each group has limited manufacturing experience and a very short time to construct the technology demonstrator, many early decisions are based upon perceived problems in production. Airfoil complexity, wing taper, fuselage cross section, type and placement of the control systems, and internal structural arrangement are all influenced by the manufacturing requirement. Available tooling and materials also affect the design process. The time constraints make it more difficult to incorporate new technologies or materials.

The requirement to produce a product in a finite time, with a limited budget, is probably the most important design driver. Every decision appears to be influenced by this factor.

Technology Demonstrators

Each design team constructed its prototype during the last three weeks of the project. They were issued Futaba Attack 4 radio systems, as well as their respective engines. All construction took place in the Notre Dame Aerospace Design Lab, where simple construction equipment was provided. After a construction period of approximately two weeks, a series of taxi tests were performed to test the systems and to check the aircraft for basic flight worthiness and controllability. All seven aircraft experienced problems, especially in the areas of c.g. placement, tuning of the control surfaces, landing gear stiffness and alignment, propeller selection, and propulsion system battery performance.

On May 3, 1991, the flight demonstrations were held. All seven aircraft successfully performed takeoff and sustained, controlled flight. All the aircraft handled very well under the control of an experienced pilot with the exception of the Delta Group plane, which experienced significant thrust asymmetry as mentioned above. The Theta Group aircraft appeared to handle exceptionally well even at very low cruise speeds. The Zeta Group flying wing design provided the most dramatic flight, though its performance may not have been particularly characteristic of a commercial air transport. Considering the lack of experience of the builders and the time constraints placed on the teams, this flight demonstration was considered a great success and showed the students the difference between a conceptual success and success in the real world.

CONCLUSIONS

The purpose of this course is multifaceted. Students entered the course with the knowledge required to complete the mission. The learning process involved the ability to incorporate that information into a design. They were shown the design process from start (the RFP) to finish (the prototype). They were immersed into many real-world problems faced by engineers. These included working in a team and integrating seven engineers' ideas and work into one design. They were given the opportunity to experience the construction process, and how to bridge the gap between a concept on paper and a flightworthy aircraft.

The attempt to simulate numerous issues related in commercial transportation system design through the use of an RPV system appeared to be successful. The limited time available to address so many complex issues precluded attention to great detail in any area.

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