AC 2009-2458: BUMBLEBEE

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Bumblebee

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The primary goal of capstone projects is to familiarize students with the design process. Through student interaction and peer reviews students are able to gain valuable knowledge that cannot be taught in the traditional lecture. This particular capstone project focuses on the design of an autonomous UAV that is capable of loitering above a field for 10 hours while collecting pollen samples for post-flight analysis. The report highlights the educational value of decision making within the context of a group as well as the hands on experience that comes from designing an aircraft. The requirements pertaining to this project consist of a maximum gross weight of 40 lb, maximum stall speed of no greater than 35 knots, the capability to recover from 12.5 foot per second gust, and a maximum take off and landing distance of 300 feet. The aircraft must also be easily assembled and fit in a 5 x 3 x 3 foot box for easy hauling. Based on the aircraft specifications trade studies were performed in order to identify a fully functional design that is optimized. A blended-wing configuration has been chosen for the aircraft. Laminar flow technologies are used to minimize viscous drag of the aircraft. The engine chosen is the Zenoah G26, capable of providing 2.4 HP, which is sufficient power to takeoff and fly at maximum gross weight. In order to obtain fully autonomous flight the Twog V1 autopilot from the Paparazzi Project is used. This system uses a graphic user interface on the ground in conjunction with an onboard, programmed system, to manage the control systems of the aircraft, providing autonomous flight.

I. Introduction

Worldwide there is an increasing interest in the capabilities of unmanned flight. According to an independent study from a defense and aerospace market analysis firm based in Fairfax, VA, the field of UAVs is and will be the most increasing division of the world aerospace industry. It is suggested in this study that UAV spending will triple over the next decade, all the while the United States is predicted to account for 73% of the worldwide spending on UAV technology.[1] With the increasing need for improvement in the areas of functionality and implementation of UAVs, it is important to research and develop innovative ideas that will overcome the future challenges in unmanned flight.

The ability for students to build and understand this new and prominent area of the aerospace industry is essential. The aim of this group is to create, test, and successfully fly an autonomous UAV for a specified mission. The future roles for UAVs in data collecting are limitless. The UAV's specific mission is to collect air samples in order to track pollen rising from a field during the course of a day. Post flight analysis of the samples will be conducted. Due to this specific mission the UAV has been affectionately named the Bumblebee.

Designing an affordable, yet durable UAV is a main priority for this project. The overall cost of the vehicle will be minimized by optimizing certain design parameters such as size. To increase the marketability of the Bumblebee, the design will have a compartment that can carry a fifteen-pound payload. This compartment can be used for a number of different purposes, one of which is holding a pollen measurement device to collect data for later analysis. Another design requirement is that the vehicle must be assembled and disassembled quickly and easily as to not delay the specified mission. Prioritizing design parameters is an important task, but optimizing the overall design will require definite tradeoffs. Understanding the optimization process is an invaluable lesson that students must learn to embrace before and during their careers as engineers. Projects like the Bumblebee provide students with the opportunity design their own trade studies prior to entering the work environment.

II. The Team

The team in charge of designing and building the Bumblebee consists of five senior aerospace engineering students. Although the core team only consists of five members the help of several additional people is needed in the design process. For example, the electrical system of the UAV would not be possible without the help of electrical engineers. This type of interdisciplinary interaction is important to the completion of any aerospace project. The processes of seeking advice from those that have expertise in a certain area is important in the design of the overall system. As with most aircraft, the Bumblebee is much more than just the sum of its parts because without the subsystems working together the UAV would never get off the ground. Systems engineers allow the Bumblebee to function at its highest potential by combining all the subsystems and making sure that they function in unison. Thus, the most challenging part of the design will be the systems-engineering part.

This design project is very instructional in the sense that the design team members must realize the interactions of multiple disciplines when creating a complete product. The team has incorporated many systems into the Bumblebee design including control systems, a blended wing-body, fuel systems, and an autopilot. The premise of systems engineering, then, is combining these different components effectively and efficiently. In turn, systems engineering highlights the division of labor within projects and the need for constant communication. Engineers must rely on each other to complete specific designs that will be incorporated into larger projects.

III. Educational Value

Capstone projects are a great way to educate students in the labor and practices of engineers before actually joining the industry. Projects like these are a valuable learning experience for each person involved. Presenting a project in an academic environment provides students with valuable criticism from peers and instructors or even from industry representatives. Comfort ability and speaking knowledgeably to an expert audience is essential to the development of young engineers. It also prepares the student on manners of professional communication and demonstration. During the course of a presentation, the presenter, the peers, and the industry representatives can all benefit from this exchange of information. The presenter receives feedback from the peers as well as the industry representatives; therefore, improving their projects based on the input of other well respected engineers. The peers benefit from this exchange with new ideas and techniques for their own presentations. The industry representatives ideally gain knowledge on the academic level and creativity of the present day student and in turn lend their wisdom to the young minds of the future workforce.

Nowadays most engineering projects are increasingly complex, as such, requiring a team effort. It is improbable that a single person can lead all areas of a project with absolute skill, especially in the aerospace industry. That is why teamwork is necessary. The benefits associated with teamwork are obvious, but human nature often makes high-quality teamwork hard to achieve. Communication issues of various reasons tend to delay projects as well as decrease the performance of the team as a whole. Therefore, communication and understanding between members of a team are pivotal. Several factors make communication more fluid between team members.

A well qualified team leader is paramount. Well qualified does not mean that the leader has to have more technical skills. Also, a team leader can emerge in a couple of different ways. Team leaders can either be appointed by the group, hired by a company into the position or develop naturally in the design process. The team leader must organize and speak for the team. The leader must be responsible for settling disputes within the team. Therefore, good communication between the leader and all members is important. This means that the leader must help to establish mutual respect amongst the group. Knowing that all members are knowledgeable and capable allows the group to portion the work equally between members while having confidence that each member is fully capable of completing an assigned task. Each member is responsible for their own calculations but peer reviews are held in order to prevent any errors. A thorough examination of the work completed is part of the design process and must be done to prevent small mistakes from having serious effects.

In the process of designing our UAV we had to manage the requirements of the mission given together with a good and feasible overall design. The Bumblebee UAV is meant to be built and manufactured by the team members, so the design must be easily manufactured. The experience of undergoing the appropriate iterative process has been very useful, and the knowledge gained in optimizing that process will be probably applied throughout our professional careers.

IV. Initial Design

A blended-wing-body (BWB) configuration was chosen for the UAV. This innovative configuration has several advantages mainly in fuel efficiency. In a BWB configuration, the fuselage generates lift in addition to the wings. It has an airfoil-like cross section although it is thicker than the actual wing, but it still yields lift in the same way that the wing does.

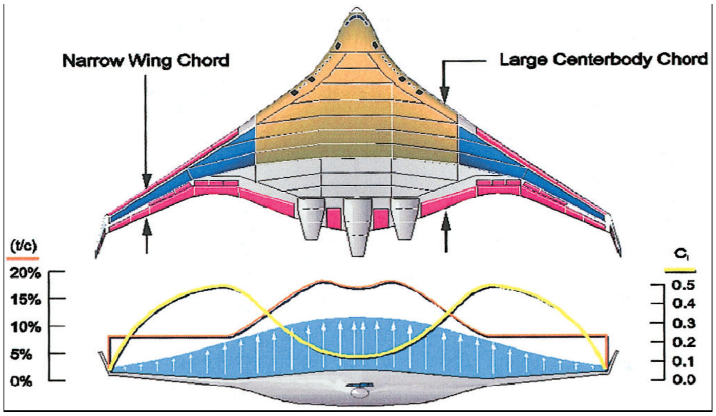

Figure 1: Section lift coefficient and thickness-to-chord ratio variation [2]

The first advantage of BWB, then, is that the aircraft requires less wing surface to generate the same amount of lift than the classical cylindrical fuselage with attached wings. This fact leads to a reduction in skin friction drag of the aircraft since less exposed surface is required.[3] The interference drag in the junction of body and wing is also reduced since it is blended and the change in cross section is smoother. The typical BWB aircraft has no tail, so skin friction drag is reduced but a trim drag penalty is associated with this configuration. The control of the aircraft is carried out by rudders in the winglets and elevons for pitch control. This configuration was not chosen in this project. The control and coupling of the control surfaces in a tailless aircraft is highly complex and it does not match with our requirement of simplicity of design for a general aviation UAV. A boom-mounted high tail was chosen together with a pusher propeller. The propeller location is not in the nose like in most of the UAVs today. The main reason for that is that almost all control devices and sensors of the airplane are located in the nose, and the propeller blades and its wake would disturb them. In the same way, the boom-mounted high tail was chosen so that the control surfaces are less affected by the wake of the propeller. On the other hand, the BWB configuration is less efficient as a pressure vessel since the cross section is not circular. This problem does not affect the Bumblebee because the fuselage is not pressurized. A three view drawing of the Bumblebee is attached to the report for reference purposes.

V. Drag Calculations

One of the basic pillars of the design calculations for the UAV was the drag build-up. Since the aircraft design is not yet frozen, an Excel spreadsheet was designed in order to change inputs easily. The spreadsheet was designed in such a way as to separate the calculations for each major component of the Bumblebee. The aircraft was divided into three sections: wing, fuselage and empennage. The empennage takes into account both the horizontal and vertical tail components as well as the tail booms.

Basic aircraft parameters such as the span, aspect ratio and other important aircraft characteristics were based on the initial design. A span efficiency was also estimated and used in the calculations for the induced drag.

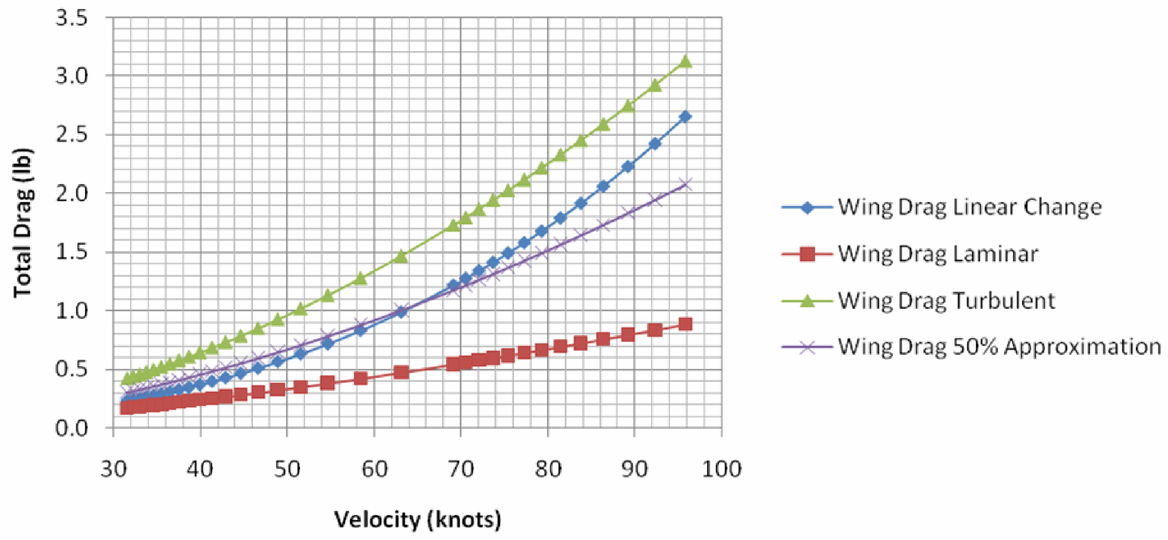

Figure 2: Drag for different boundary layer types

Skin friction drag was approximated using the method given in Shevell.[4] Based on a given Reynold's number, the skin friction coefficient was calculated. These calculations raised a few concerns. Flat plate boundary layer changes from laminar to turbulent between Reynold's numbers of 200,000 and 1,500,000. Those are roughly the Reynold's numbers at which the Bumblebee flies. In order to simulate that change, a linearized change of the total skin friction coefficient from laminar to turbulent flow was performed. This simulation was assumed for a low Reynold's number 200,000 up to 1,500,000. Past this point the skin friction coefficient was calculated assuming only a turbulent boundary layer. The skin friction drag for high velocities within the aircraft's range was extremely penalizing where as the drag was too benevolent for the slower velocities. In order to correct this problem an approximation needed to be made so the skin friction drag coefficient was calculated assuming that 50% of the boundary layer is turbulent and the other 50% was laminar. This approximation can be seen in Fig 2. With this approximation the results were much more realistic and the total drag based on the aircraft speed is shown in Fig. 3.

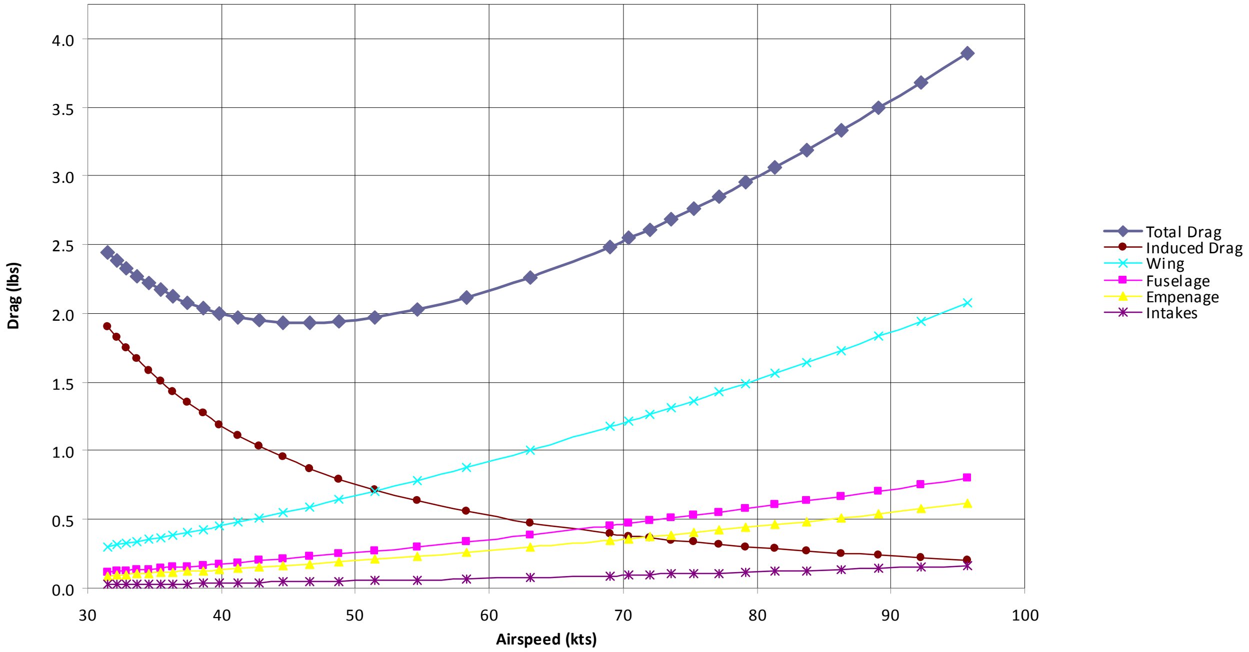

Figure 3: Drag Build Up

From the graph of results the best L/D was founded to be 20.35 at an airspeed of 46.5 kts and a C_L of 0.55 at sea level.

It should be said that these calculations are conservative. When selecting an airfoil that is specifically designed for low Reynold's numbers, the drag at cruise speed will be lower. Those approximations should be verified by wind tunnel tests of a model Bumblebee.

The payload stated in the requirements of the project is somewhat large compared to the total weight of the airplane. The payload weight is also a conservative estimate because the payload will only be pollen sensors. The hardware weight associated with pollen collection is most likely less than 15 lb. Although the Bumblebee is capable of carrying the maximum payload, a realistic weight for the payload will yield better performance.

VI. Tail Calculations

The tail dimensions were calculated using the method detailed in Raymer.[5] This method associates a fuselage length for a given gross weight with a type of aircraft. In the same fashion the method associates vertical and horizontal tail volume coefficients for each type of plane.

As an initial approach for the Bumblebee, the type of aircraft was restricted to a single type. Since the Bumblebee does not exactly match the ordinary aircraft assumptions, values were selected between the ones associated with powered sailplanes and single engine general aviation aircraft for the fuselage length and tail volumes. In doing so, the chosen fuselage length is 5 ft (including the 3 ft length of the tail booms) and the tail volume coefficients are $C_{VT}=0.04$ and $C_{HT}=0.6$. The tail can be seen in Fig. 4.

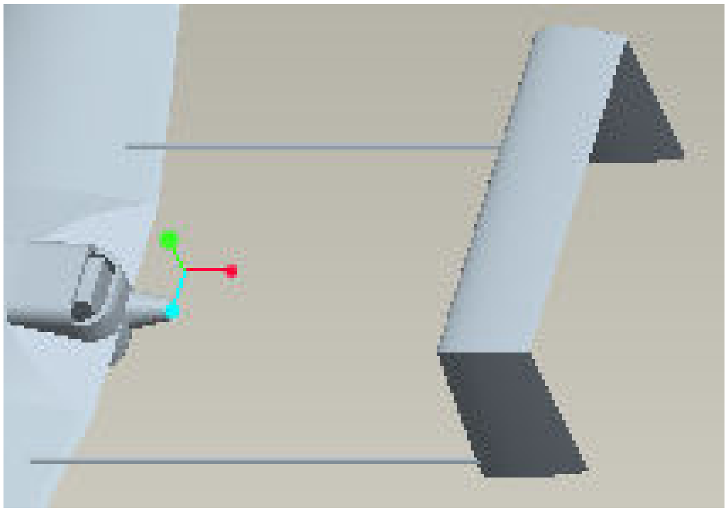

Figure 4: The tail boom and tail of the Bumblebee modeled to scale in Pro-E

VII. Constraint Analysis

The idea of a constraint analysis is to develop an initial design window for an aircraft. In addition to the initial weight constraints and preliminary wing design, several other considerations must be stated before the constraint analysis can be started. A propeller was estimated using data gathered from similar aircraft. A max lift coefficient at takeoff was estimated to be 1.2. A zero lift drag must also be estimated in order to start the analysis. Initial drag calculations were made using methods outlined in Shevell.[4] The actual calculations were done using excel. Each value of the lift coefficient gives a different value for the drag coefficient and these points were plotted. A trend line was added to the plot in order to estimate the drag coefficient at zero lift. This value was approximated to be 0.0056. These values as well as values corresponding to wing geometry were used to start the constraint analysis. There are four main factors that constrain this UAV: takeoff, landing, cruise at constant velocity and altitude, and a maximum horsepower.

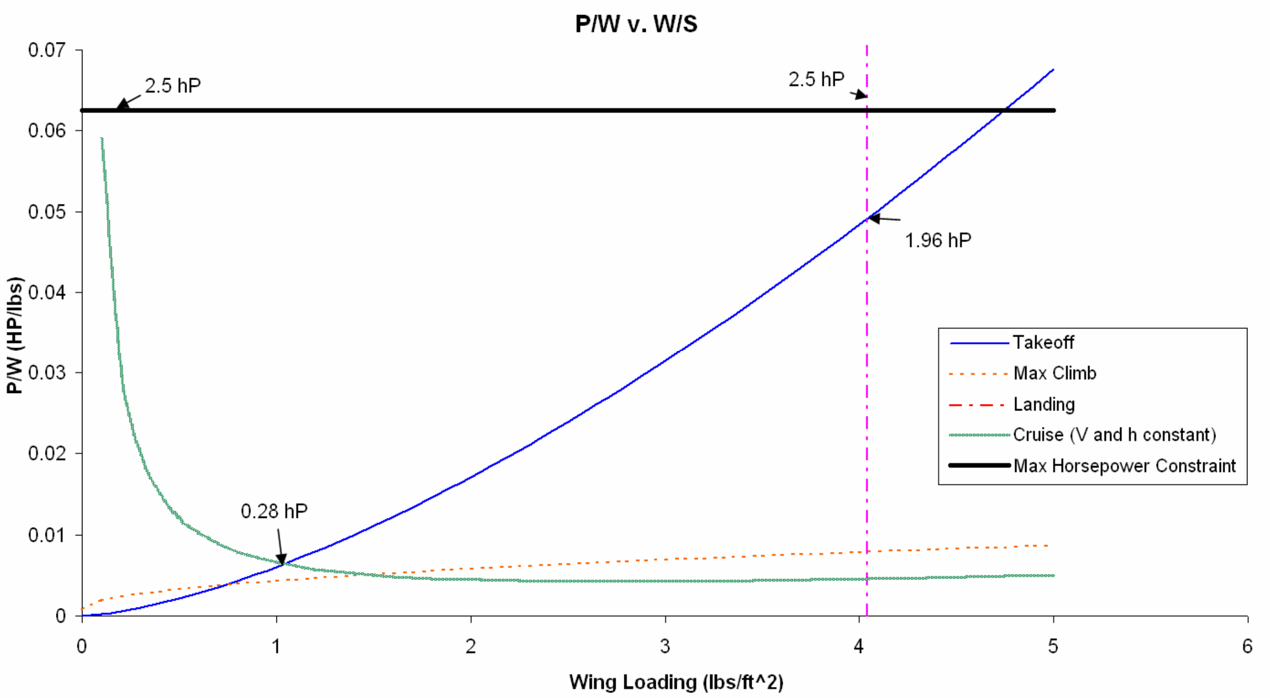

Figure 5: Constraint Analysis

The takeoff power to weight ratio can be expressed in terms of wing loading.[6] Varying the wing loading gives a minimum value for horsepower at several different values of wing loading. As seen in Fig. 5, the area above the take-off line approximation is considered within the design space because the initial calculations are minimums.

The constant altitude constant velocity approximation is a driving factor in the constraint analysis. The major requirement for the aircraft is to fly at a constant altitude over a field; thus, this approximation is important to estimate the design space with the least wing loading for the loiter condition of the aircraft. The drag calculations were used to estimate a lift coefficient for loiter and the wing loading was calculated in terms of the power to weight ratio.

The maximum horsepower of the engine was limited to 2.5 hP because of a few different factors. The main factor is weight. An engine with greater power would be more bulky and in turn have a greater weight. More weight for the engine limits the allowable weight for the payload. Another main concern with a higher power engine is that the cost would be out of our initial price range for the entire project. This limit is based on a similar UAV known as the Forest Fire UAV. Additional horsepower would offer no significant advantage to the specific mission of the aircraft.

The landing constraint is constant for all values of power. The constraint is calculated by dividing the maximum weight by the estimated wing area. Typically the UAV would not be landing at max gross weight, but in order to incorporate the worst case scenario of the aircraft returning for landing shortly after an initial takeoff the max gross weight is used providing the largest possible design window. This allows a user to takeoff and immediately land in the event that a sensor had not been turned on. This constraint can be seen in Fig. 5 and is depicted as the vertical line.

The constraint analysis is done in order to identify a design window for specific aircraft and mission requirements. The design can be changed and rearranged as long as the new design fits within the constraint analysis. This initial window allows designers to optimize certain aspects of the design while ensuring that the design is flight-worthy. The selection process will be based on the idea that the UAV must meet the original constraints defined by the initial constraint analysis.

VIII. Engine Selection

The initial engine selection is constricted by the maximum horsepower assumption of 2.5 hP. Several engines were considered that fit the requirements of the constraint analysis. The engine selection process was narrowed to these four engines: Evolution 26GX, Zenoah G-26, OSMG0575 and Y.S. 170DZ. The most obvious difference between engines is the different fuels that are needed to power them. The first two engines are powered by a gasoline and oil mixture where as the later two are powered by a fuel known as Nitro. The commonly known Nitro fuel is composed of methanol, nitro methane for burning and oil for lubrication. Each fuel has certain characteristics that would be advantageous to a ten hour flight. Nitro engines tend to be smaller. Nitro engines have relatively high power to weight ratios and require less cooling than gas engines. Thus are also less prone to radio interference than gas engines. Nitro fuel is also generally lighter than that of the oil gas mixture. Gas engines are more reliable. The fuel consumption for gas planes is much cheaper than that of their Nitro counterpart and gas engines have built in fuel pumps which helps performance at higher altitudes. Gas engines are also much cleaner in the shop because they do not create an oily environment like most Nitro planes.

All facts must be considered when choosing an engine. The first and probably most important fact is that the fuel consumptions in gas engines are much more economical. A further advantage of gas over Nitro is that the cost of Nitro is about three times the cost of gas. The disadvantage of a gas engine is that it is about one hundred dollars more expensive than the Nitro engine and about twice as heavy. After weighing all the options the best choice for the current mission is to choose the gas powered Zenoah G26.

The OSMG0575 and the Y.S. 170DZ are Nitro fueled engines weighing slightly less than the Zenoah G26. The Y.S. 170DZ is a fuel injected Nitro engine which would eliminate the concern that might arise from engine performance with a change in pressure. These two Nitro engines offer certain benefits but the mission requirement of a ten hour endurance suggests that an engine should be chosen based on its power and fuel consumption. This means that a gas engine must be chosen to eliminate high fuel costs and minimize the cost needed to refuel. With this assumption made the two gas engines are examined. The Evolution 26GX and the Zenoah G-26 are similar engines in the fact that they produce relatively similar powers and are almost the identical size. The next issue that arises in selecting an engine is cost. The Zenoah engine is nearly one hundred dollars cheaper than the Evolution while the Evolution does not offer any particular increase in performance. In order to provide the most economical and reliable design the Zenoah G26 was chosen as the engine to power the UAV.

IX. Airfoil Selection

Selecting the appropriate airfoil for this Unmanned Aerial Vehicle (UAV) is critical in order to optimize the performance of the aircraft, and many considerations were made. One important concern is the speed at which the aircraft will be flying during most of the flight. This UAV, like similar R/C planes, flies subsonic at very low Reynolds numbers. Another consideration is thickness to chord ratio. While thicker wings have more drag, thicker wings offer advantages in other areas.[5] The added volume gives space for fuel storage, structural load-bearing members, electronics, and control mechanisms.

After scouring books for airfoils, the S8036 airfoil was selected because of its gradual drag polar. According to Lyon, at Reynolds Number 400,000, the S8036's drag coefficient does not increase noticeably with the lift coefficient until a very extreme lift coefficient is achieved.[7] This relationship is ideal because the UAV operates over a range of velocities, and is, therefore, conducive to a slight, gradual change in drag with lift. From the same set of data, it can be found that the base drag coefficient (C_{do}) for the S8036 is low relative to other airfoils in the final options. With these criteria in mind, the S8036 is the airfoil of choice.

X. Autopilot

Though the mission could be accomplished through the use of radio control technology, fully autonomous operation expands the scope of Bumblebee. The program of choice for the autopilot of the UAV is an open source project called Paparazzi. This autopilot software has been in development on a multi-national level for over three years with much success. The source code is available through the Paparazzi home page with additional links discussing recommended hardware that is compatible with the code.[8] Using the bundled hardware and software package, only small alterations to the code are required for a particular aircraft, such as aircraft dimensions, terrain information, and flight plan. This on-board system in conjunction with the ground control station provides streaming data about aircraft position and basic control.

The bundled package selected for the Bumblebee is the Twog V1 released in June 2008.[9] The Twog allows for a flexible airframe installation, instead of the GPS antennae being on the control board itself, it can be connected via a cable from somewhere else on the airframe. This helps to delete any possible electronic interference with the GPS system. The Twog system uses 6 orthogonal infrared sensors for orientation control: one single-axis IR sensor on the z- axis, and the other a dual-axis IR sensor on both the x and y-axis. The single axis sensor detects differences in heat above and below the aircraft as shown in Fig. 6. The actual sensor can be seen in Fig. 7. The multi-axis sensor detects differences in heat laterally and longitudinally. The sensors are wired to each other, and when they are even and the aircraft is level, the readout from the sensor is zero. Likewise the sensors have a maximum readout of 90^o when the aircraft is completely sideways. This information is simultaneously broadcasted to the Ground Control Station (GCS) and used for stability and control of the aircraft. The IR-sensors in collaboration with the 3-D GPS programming imbedded within the Paparazzi software, helps to calculate altitude of the aircraft during flight. Due to the problems of GPS altitude resolution becoming inaccurate near the ground a more precise manner to estimate the altitude of the aircraft near the ground during flight.

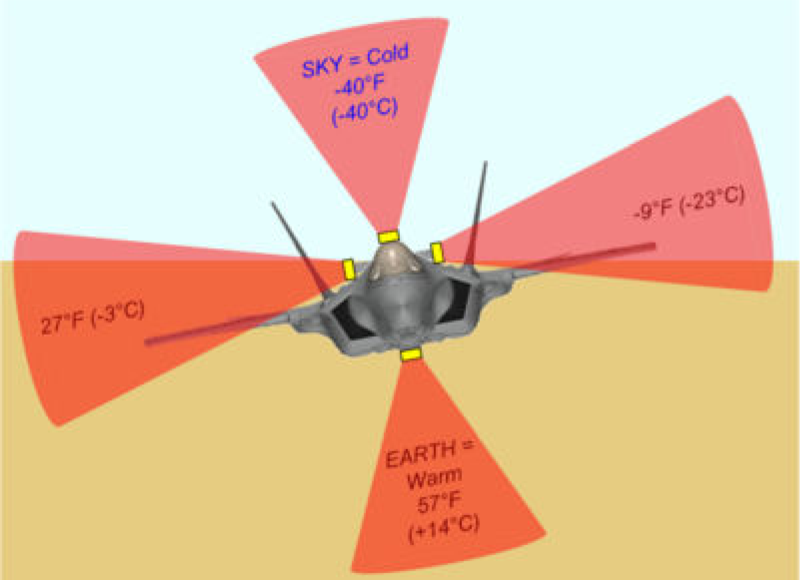

Figure 6: IR sensor collaboration [9]

The GPS system integrated into the Paparazzi system is the LEA-4P, built by U-Blox. This GPS system works at a 4Hz position update rate. Using this GPS technology combined with the live feed from the GCS, the aircraft is able to fly along a programmed route. An advantage of the Paparazzi Project is that this route can be pre-programmed or altered mid-flight, allowing for flexible mission profiles. Also with a connection to a standard patched RC receiver it is possible to manually control the aircraft in flight. This is good a good safety measure as well as a good manner to tune the Bumblebee to the Paparazzi system. All together the autopilot hardware amounts to a mere 25g, offering no significant change to the gross weight of the aircraft.

The software is written primarily in C with some user inputs stored in .xml files, thus only light programming knowledge is required. It should be noted, however, that the instructions on the Paparazzi Project's web page [5] describe in great detail the workings of the program. The program is designed to operate through the Linux OS, specifically through the Debian-based distributions. Also included in the downloadable software is the Graphical User Interface for the GCS. Communication between the aircraft and the ground control station is carried out via a modem and transceiver relationship. A variety of modem/transceiver options are available, however the XBee 2.4GHz modem and transceiver are used in the Bumblebee.[9] Recalling some information about modern wireless communication, it is discovered that this band would get interference from any BlueTooth ® devices or Wi-Fi transmitters nearby. This consideration is mollified as the aircraft will be flying in lightly populated areas, like open fields or remote stretches of power lines. The biggest advantage of using the 2.4GHz frequency is the higher data rate transmitted between the modem and the receiver. Obviously a higher data rate means less lag time and room for more robust communications.

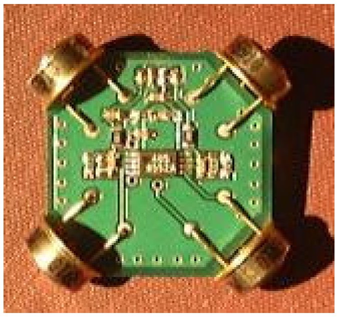

Figure 7: Lateral and Longitudinal IR sensor [9]

XI. Bumblebee Performance

The performance characteristics of an aircraft depend on its weight, the aerodynamic characteristics of its airframe, and the thrust or power developed by the propulsion unit. The main performance parameters are power, endurance and range. The power required and available curves of the Bumblebee are shown in Fig. 8.

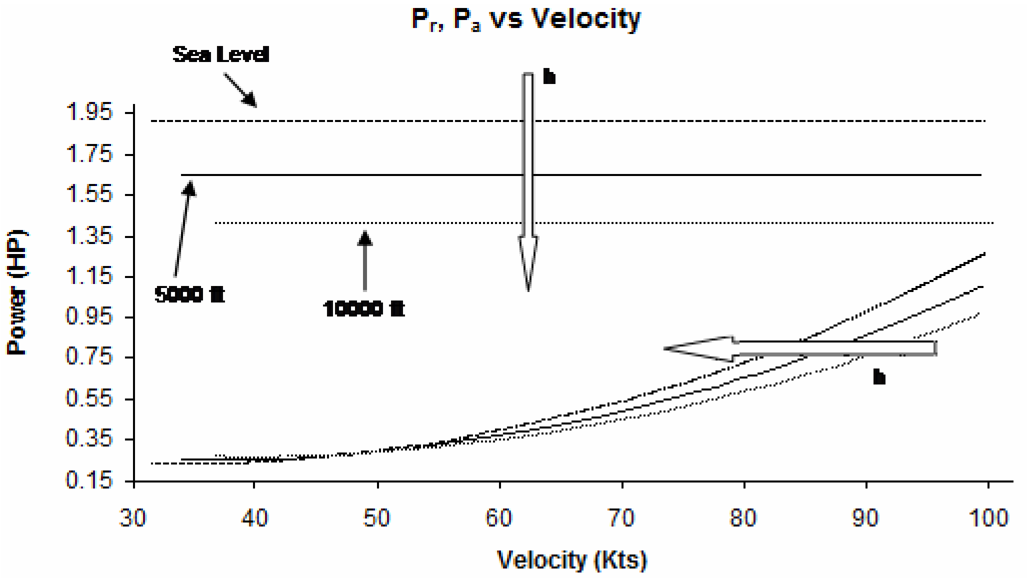

Figure 8: It represents power required & power available versus velocity for three different altitudes

Considering level flight, the minimum power required at sea level is 0.235 Hp, and a minimum of 0.271 Hp at 10,000 ft. Maximum endurance was calculated at both altitudes to be 16.3 hours at sea level and 14 hours at 10,000ft. Observing this outcome, for altitude of 10,000 ft the endurance requirement is accomplished. Although the Bumblebee is not meant to fly in altitudes above 6000 ft, the requirements are still met for higher altitudes which in turn accomplish a minor goal of designing a multi-role UAV. The endurance of the Bumblebee can be seen at a couple of different altitudes in Fig. 9.

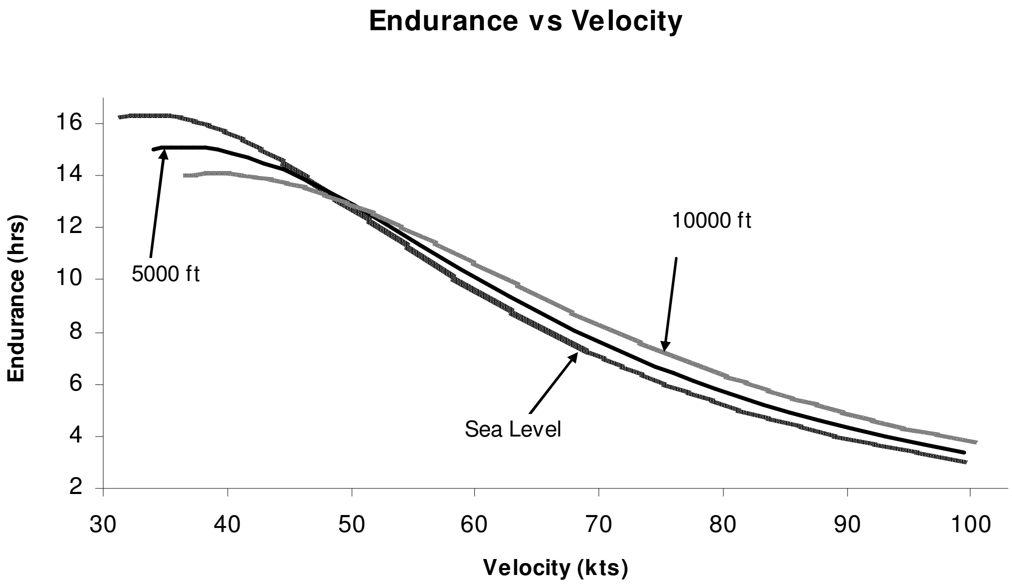

Figure 9: It represents the endurance versus velocity for three different altitudes

The power available reduces as the altitude increases, since power available often is proportional to the density of the air. The power available for a propeller engine depends on the propeller efficiency and the break-horse power. The break-horse power of the engine selected is 2.4 Hp and the estimated propeller efficiency is 0.8. This is important to note because this value affects not only the power available, but also the endurance and range, since both characteristics are dependent on the propeller efficiency. The propeller efficiency affects these values in such way that an increase on the propeller efficiency would increase the range and the endurance. It is also important to note that the propeller efficiency considered does not change with altitude. This is not true in reality, but it is a good approximation as an early approach.

There are some other performance characteristics that are important for a conventional aircraft such as the range, rate of climb, best climb angle, absolute ceiling, service ceiling and time to climb. For the bumblebee mission these performance features are not as important due to the low altitude requirement, 10 ft above the ground. The main performance requirement of the Bumblebee is to have an endurance of 10 hours. These aforementioned performance characteristics were calculated for the Bumblebee, in order to have a grip on other possible missions.

XII. Conclusion

The Bumblebee is a versatile vehicle with a main goal of collecting pollen for ten hours above an agricultural field. The Bumblebee's intricate design allows the aircraft to outperform the initial requirements but at the same time remain fully adaptable to several different missions. In order to prove that the Bumblebee is capable of performing its primary mission many different calculations were needed. Drag calculations were done that incorporated a transition from laminar to turbulent flow. The drag calculations provide initial values such as the drag and lift coefficients at different airspeeds. The drag calculations were then used to establish the performance characteristics of the Bumblebee. The performance characteristics then verified that the UAV met all the performance requirements. Another requirement for this aircraft was that it must be able to fly autonomously. This problem was resolved by using the Paparazzi Autopilot software. The use of an open sourced autopilot as well as an efficient gas engine allows for optimized fuel consumption and in turn lowers operating costs. The Bumblebee's mission is not unique, but this project offers distinct design points. The blended-wing-body is a relatively new feature in the world of aviation, while the autopilot is in continuous development on a worldwide scale. Aircraft characteristics like these make this project an effective investigation in the design process of aerial vehicles.

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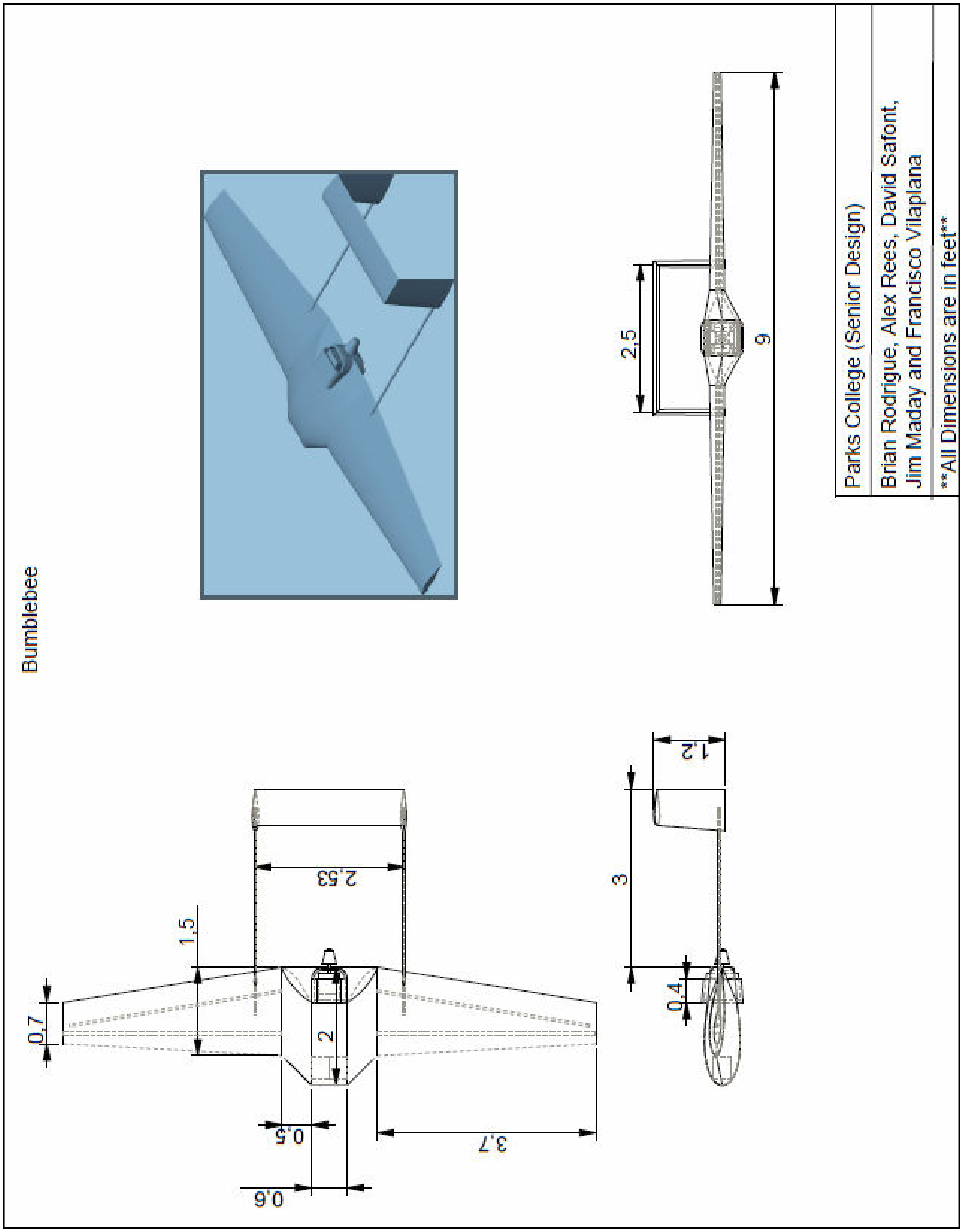

Figure 10: Three view drawing of the Bumblebee