Scaled Electromechanical Modeling of the F-35A Joint Strike Fighter

by

Leonardo F. Marmorato

Submitted to the Department of Mechanical Engineering in Partial
Fulfillment of the Requirements for the Degree of

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ABSTRACT

During the early 1990s, The U.S. Department of Defense embarked on a search for an affordable, next generation fighter aircraft that could fit the common needs of the Navy, Air Force, and Marines, as well as several allied nations. Lockheed Martin Corporation provided the answer with a cutting-edge fighter jet design that fulfilled all of the DoD's needs; the F-35 Joint Strike Fighter. The JSF was produced in three different variants, the first and simplest being the F-35A CTOL (Conventional Take-off, Landing), designed especially for the Air Force. In order to explore the underlying principles of the JSF's design as well as its aerodynamic characteristics, a scaled electromechanical model of the JSF F-35A variant was constructed using limited information about the aircraft's unclassified dimensions and features.

The design process involved at first a CAD solid model of the entire structure. Once the computer-based model was completed, parts were manufactured with high precision out of 1/16" polycarbonate with the aid of a waterjet. The scaled model also had several electrical components such as an R/C transmitter and receiver, servos for controlling the aerodynamic surfaces; high speed ducted fan motor for providing the necessary thrust, and LEDs to mimic the aircraft's external lighting system.

Despite some minor differences in detail, the F-35A 25:1 scaled model closely resembled most of the physical features contained in the Joint Strike Fighter conventional takeoff/ landing variant. It should be made clear that the decision for making the airframe out of polycarbonate was greatly influenced by time limitations and budget constraints experienced throughout the term. Our original intention was to make the airframe completely out of balsa wood, a material with a stiffness (E) similar to that of polycarbonate, yet up to eight times lighter. Nevertheless, the fact that balsa stock comes in relatively small sizes meant more time would be spent loading and unloading pieces on the waterjet. In general, having limited resources had a lot of leverage on our design approach, especially so when the cost for operating the waterjet at the LMP facilities was tagged at $100 per hour. It is then proposed as a side project to build the same model out of balsa for flying purposes in the near future.

Thesis Supervisor: Ernesto E. Blanco
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1. Introduction

1.1 Brief overview of the Joint Strike Fighter

The Joint Strike Fighter (JSF) Program, formerly known as the Joint Advanced Strike Technology (JAST) Program, was until recently the Department of Defense's focal point for defining affordable, next generation strike aircraft weapon systems for the U.S. Navy, Air Force, and Marines, as well as several allied nations. The main focus of the program was affordability -- reducing the overall cost for development, production, and ownership of the JSF family of aircraft. Prior to the start of the System Design and Development (SDD) phase in the fall of 2001, the program facilitated the Services' development of fully validated, affordable operational requirements, and it also lowered risk by investing in and demonstrating key leveraging technologies and operational concepts. Once the SDD contract was awarded to Lockheed Martin Corporation on 26 October 2001, the program embarked on the full development of three affordable and effective JSF variants. The first and simplest is the F-35A CTOL (Conventional Take-off, Landing) variant (Figure 1), designed for the U.S. Air Force as a substitution to its weary fleet of F-16s and A-10s. The F-35B STVOL (Short Takeoff, Vertical Landing) variant was designed for the Marines to replace their old and troublesome Sea Harriers. Finally, the Navy had the final variant, the F-35C, made specifically for aircraft carrier operations. A more detailed explanation of these variants as well as a thorough background of the JSF Program can be found in **Appendix. A**.

1.2 Goals and Expectations

In order to explore the underlying principles of the JSF's design as well as its aerodynamic characteristics, a scaled model of the JSF F-35A variant is to be constructed using limited information about the aircraft's unclassified dimensions and features. The design process will involve at first a CAD solid model of the airframe, which would become conceptualized once the manufacturing method and proper materials have been selected. The scaled model will also have electrical components such as servos for aileron/ elevator controls; a high speed motor for thrust, and colored LEDs (both flashing and static) for the aircraft's navigation lights system. Once the scaled model has been completed, it will undergo tests for weight and balance prior to initial flying runs as an R/C aircraft. This last section is prone to significant testing and is therefore beyond the scope of the thesis statement. As of this moment, there are no scaled models of the JSF available on the market capable of powered flight.

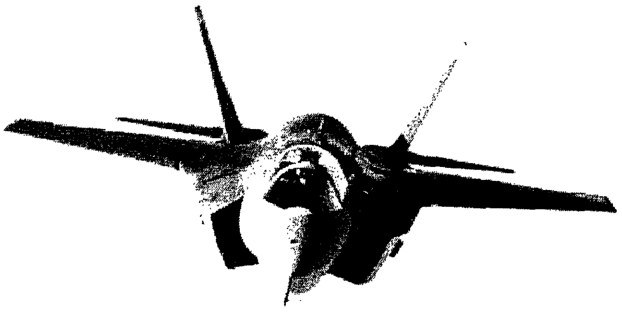

***Figure 1**: JSF F-35A variant designed primarily for the U.S. Air Force.*

2. Structural Design Criterions

2.1 Selection of Scale

Although not necessarily a time-consuming step in the development of a scaled design, determining the overall size of the aircraft is definitely a crucial decision that should be based on good engineering judgment and reasoning. For this case in particular, the limiting factors reside on the usable space within the airframe as well as on the aircraft's overall weight. Proportionally speaking, as the aircraft becomes larger, its weight will too, requiring larger amounts of thrust to keep itself aloft. Since we want to remain conservative on the amount of power necessary for flight, we will choose a scale small enough to maintain the overall weight relatively light in the order of 1 to 2 pounds, yet large enough to accommodate all the necessary mechanisms and electrical components for operation and control of the aircraft. Most military R/C models available in the market are between two and three feet in length (nose to tail). Thus, it has been decided that the F-35A model should have a length around 24-26 inches. With the full-scale F-35A having a length of 50.5 feet, the proposed size translates into a scaled version of approximately 25:1.

2.2 Design for Manufacturing

Although different forms of manufacturing can be suggested for this design, very few were actually plausible from the available facilities in the Department of Mechanical Engineering. For instance, producing a hollow foam core body, a favorite for R/C airplanes, was not an option for this endeavor. Similarly, neither injection molding nor thermoforming were useful methods due to the fact that mold sizes for these two forms of manufacturing were relatively small (about 4"x4"). Finally, the waterjet was considered as a useful alternative, despite its expensive cost to operate. The benefit of this approach was based on the idea of having cross-sections of the airframe cut from stock material with high precision in a relatively short amount of time, and then assembled together to form the overall body of the airplane. This method closely resembles the real-world approach of airplane construction, based on layered cross-sectional members, lightweight enough so as to permit flight, yet strong enough to hold the whole structure together. **Figure 2** shows an internal preview of the F-35A, clearly illustrating the intersecting members of the airframe.

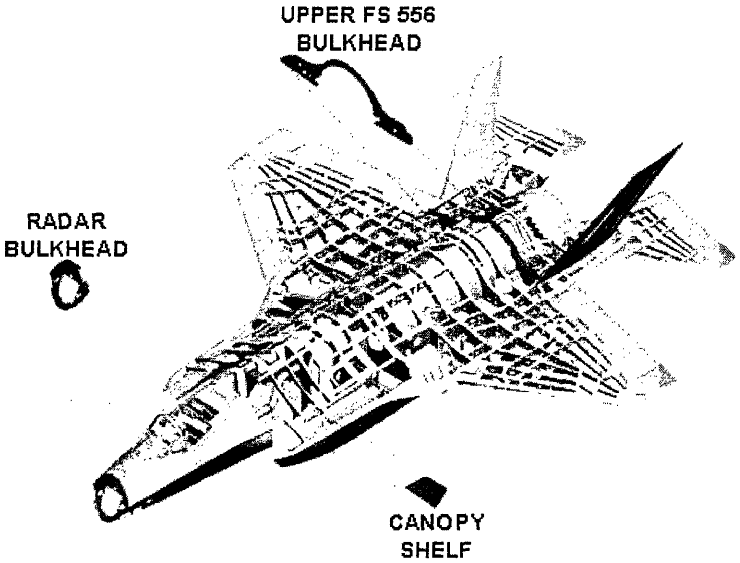

***Figure** 2: Internal view of the F-35A's airframe*

2.3 Material Selection

Model airplanes are no different than any other type of flying machine, large or small. The lighter it is built, the better its flight performance will be. With that in mind, it is easy to understand why balsa wood has been the standard material for model airplane construction since it first became readily available in the U.S. in the late 1920s. Its outstanding strength-to-weight ratio allows for the construction of durable models that are capable of maintaining controlled flight. Balsa's lightness is attributed to the fact that its cells are considerably large and thin walled, resulting in an small ratio of solid matter to open space (see **Figure 3**). On average, about 40% of the volume of a piece of balsa is solid substance. In addition, balsa is known to absorb shock and vibration relatively well and can be easily cut, shaped, and adhered with the aid of simple hand tools[1].

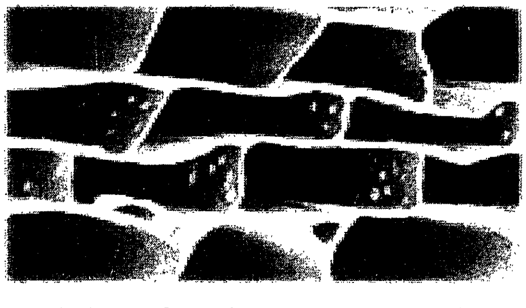

***Figure** 3: View of balsa cells under a microscope. Their large thin walls give this wood type advantageous low density for construction of airborne crafts.*

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[1] Excerpt from online article, "Interesting Facts About Balsa Wood" http://www.mat.uc.pt/~pedro/ncientificos/artigos/techbal.html

Despite the wonderful properties of balsa, the stock size commonly available on the market is quite limited. Regardless of thickness, sheets of balsa, although long (up to 3 feet), have a constrained width of only a few inches (6 at most). This fact hinders the manufacturing process, since only a few cross-sectional components could be cut from one sheet of balsa at a time. This would lead to prolonged loading/ unloading times on the waterjet, making the overall process considerably less cost effective.

Since time is crucial for the completion of this project, it has been decided to construct at first a prototype consisting of a material other than balsa. Of the several materials considered, polycarbonate was chosen as the alternative based on the excellent properties of the material. Polycarbonate (PC) is a clear, colorless polymer used extensively for engineering and optical applications and is available commercially in sheet form at rather inexpensive costs. Commonly known for its impact strength and scratch resistance, it is also vastly popular for its ease to machine. In general, PC's stiffness and cost is comparable to that of balsa wood. The main disadvantage of PC lies in its density, which is at least 4 to 5 times higher than balsa. That is why the PC prototype would only serve as a tangible representation of the three dimensional model.

2.4 Acquisition of Dimensions for Airframe Design

Having already decided on the scaled size of our JSF fighter model (25:1), a detailed online search for the F-35A dimensions was conducted. Fortunately, Lockheed Martin Aeronautics Company provided on its official website three-view drawings of its new line of fighter jets, among other useful unclassified data. Thumbnails of these views are shown in **Figure 4**.

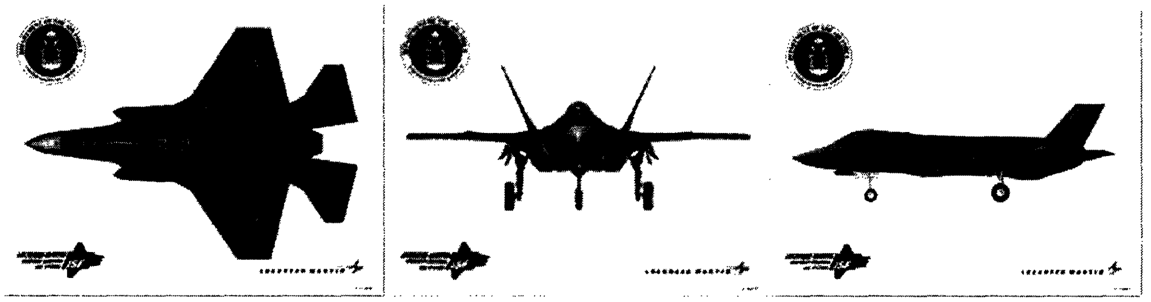


***Figure 4**: Top, front, and side views of the JSF F-35A variant as provided by Lockheed Martin Aeronautics Company website.*

To ensure geometric compatibility, all three views were imported as images into SolidWorks™ (computer solid-modeling program), from where they were fitted to meet the specified scale of 25:1. Once this task was accomplished, we proceeded to measure the aircraft's horizontal and vertical dimensions in steps of ½", starting from the nose of the plane and moving backwards. These two dimensional measurements later served to construct the cross-sectional members of the airframe. **Figure 5** shows a magnified view of the dimensioning procedure performed near the cockpit of the aircraft.

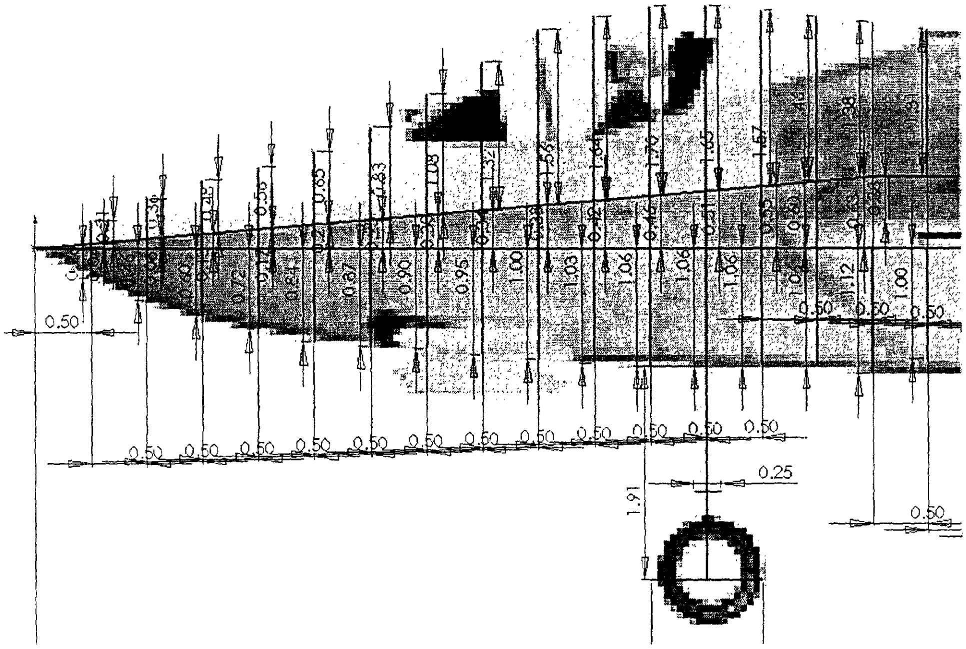


Figure 5: Close-up of the vertical dimensions measured near the cockpit.

It should be noted that although the three views were essential for the construction of the scaled CAD solid model, no relevant drawings were readily available for dimensioning the area underneath the aircraft. In order to approximate the aerodynamic contours of the F-35A's bottom surface, pictures of the actual experimental fighter, such as the those shown in **Figure 6**, were used to give us a general idea of its streamlined form. **Figure 7** depicts the original three views with the relevant dimensions that where used to construct the three-dimensional model. Areas void of lines denote typical dimensions, and where thus not drawn for clarity of the images.

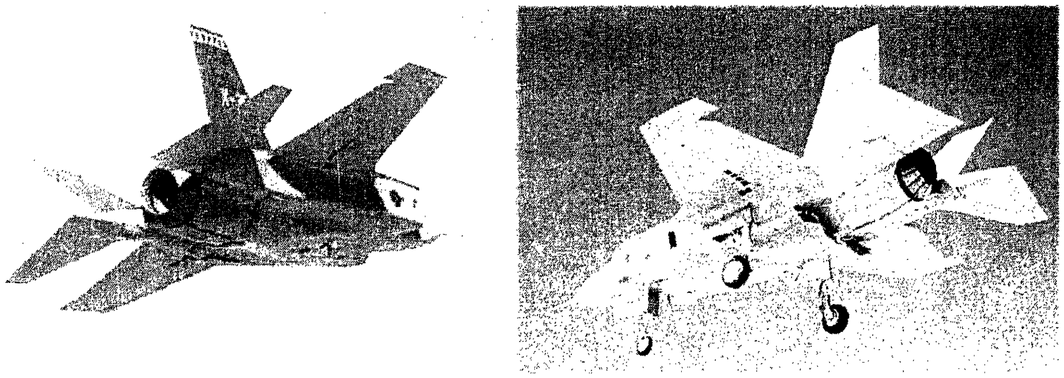


Figure 6: View of the F-35A's bottom surface used for dimensioning purposes.

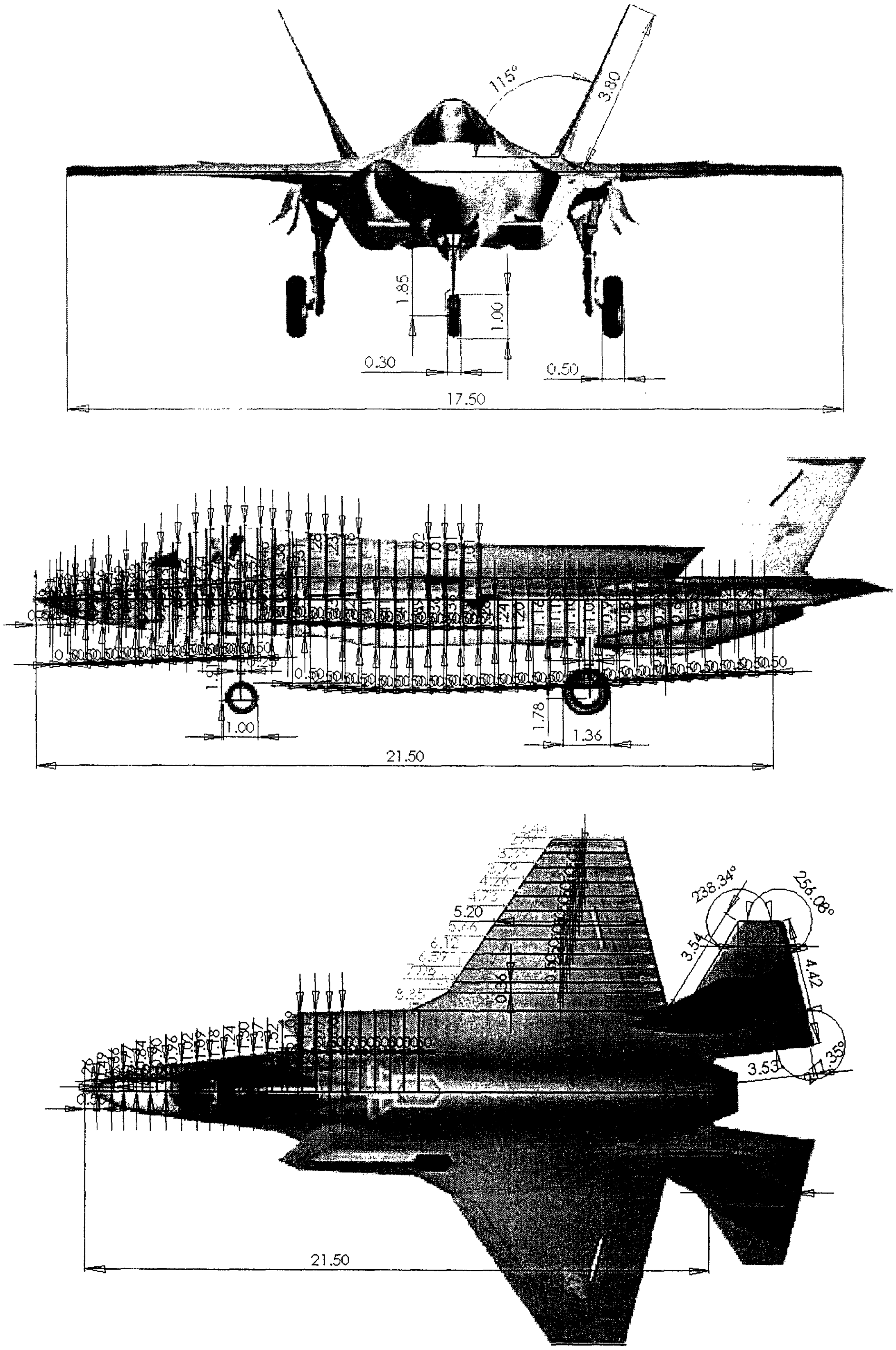


***Figure 7**: Dimensioned front, side, and top views of the F-35A scaled model.*

3 Computer-aided Design

Because of its simple, user-friendly interface and gratuitous availability from the Department of Mechanical Engineering, SolidWorks™ was used to generate all the necessary parts of the model and later to conglomerate them into one complete assembly. This section explains how the solid modeling for each main component of the aircraft was conducted, as well as the criterions required for their design.

3.1 Fuselage

Using the dimensions (in ½” steps) specified in the previous section, airframe components were solid-modeled having a thickness equal to the PC sheet from which they will be cut on the waterjet (1/16”). In order to couple the parts of the fuselage, a ¼” polycarbonate rod was used as a supporting axis. Since reducing weight is a priority, the interior portions of the cross-sectional components were made hollow, leaving the outlined borders of 0.1” in thickness. These borders were made to have relatively smooth and round transitions so as to minimize stress concentrations. **Figure 8** contains an example part from the fuselage that portrays the characteristics just mentioned.

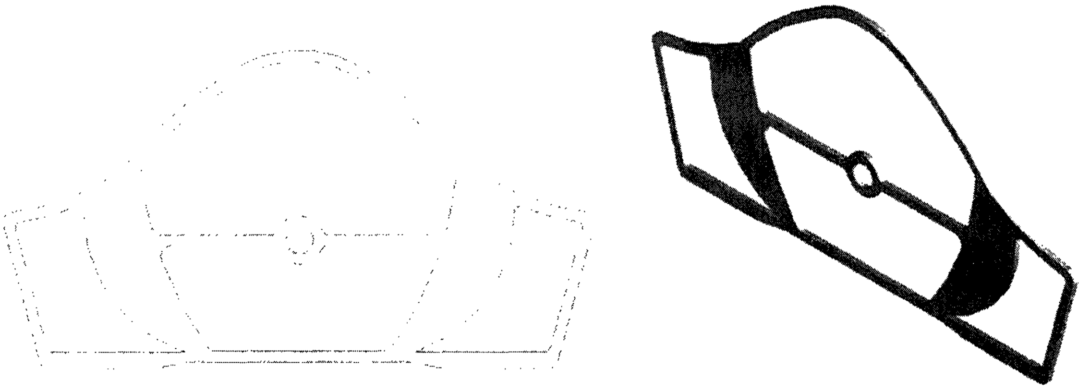


***Figure 8**: Cross-sectional component of the fuselage in front and isometric views. Hollow spaces for weight reduction, fillets for minimizing stress concentrations and circular cavity for rod insertion are clearly shown.*

Additional consideration was given to the fuselage assembly in order to make it compatible with the overall airframe. Among the issues addressed were such things as integration with the wing structures, motor housing with the necessary air duct along the fuselage up until the fan intake, support for the tail section, servo fixtures for controlling moving surfaces, and proper spacing for the axles of the landing gear. These issues are discussed in detail in the following sections. **Figure 9** shows the fuselage portion of the F-35A model prior to assembling other crucial components.

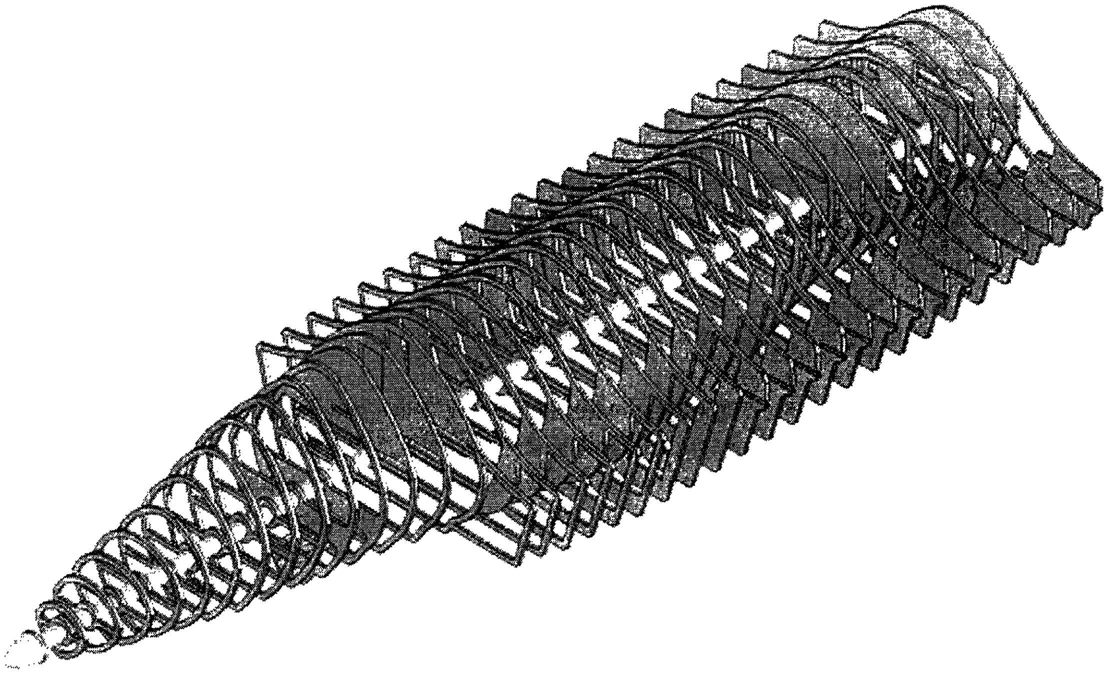
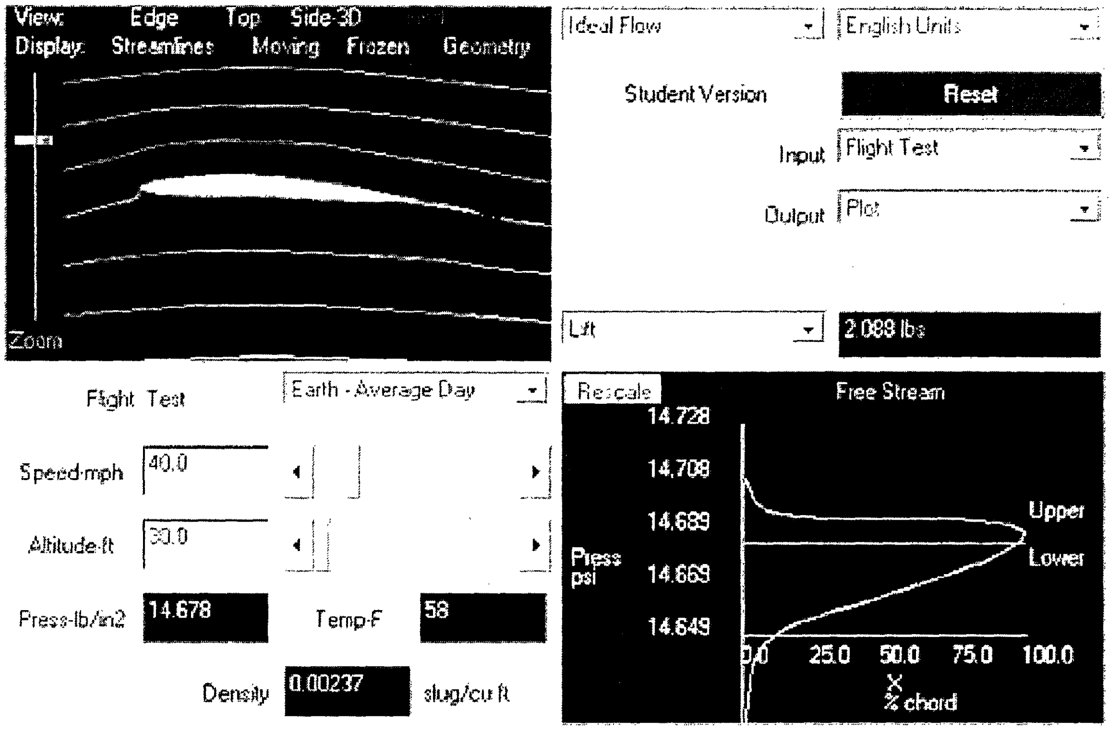


***Figure 9**: Fuselage construction of the F-35A model composed of parallel 1/16" cross-sectional members supported by a ¼" rod through its center. Notice the air intake passage from the front to the rear end of the fuselage where the motor-driven fan will be located.*

3.2 Wing Structures

In order to retain the exact shape of the actual F-35A, a 1/16" thick base plate was created from the provided dimensional data. Airfoils would then be attached to the top surface of this plate to create the aerodynamic shape of the wing. The specific forms of the airfoils are dependent on the desired characteristics of the aircraft. Although expensive programs for airfoil analysis and construction are commonly sold, NASA conveniently provides a very basic version free of charge on its website named FoilSim II (1.5a beta) as shown in **Figure 10**. With the aid of this program, we were able to calculate the resulting lift force exerted on the wings. In order to attain this result, many parameters about the wings geometry, aircraft's speed and altitude, as well as atmospheric pressure and temperature, had to be provided. **Table 1** summarizes all the necessary parameters required by the foil simulation program to give an estimated value of the resulting lift force.



Ideal Flow

English Units

Input: Flight Test

Output: Plot

Lift: 2.088 lbs

Flight Test: Earth - Average Day

Speed-mph: 40.0

Altitude-ft: 30.0

Press-lb/in2: 14.678

Temp-F: 58

Density: 0.00237 slug/cu ft

***Figure 10**: View of NASA's FoilSim II java-based program used for the wing's airfoil design.*

***Table 1**: Summary of values required for lift calculation.*

PARAMETER	***VALUE***	***UNITS***
Pressure	14.7	*lb/in*^{2}
Temperature	58	*F*
Air Density	0.00237	*slug/ft*^{3}
Airspeed	40	*mph*
Altitute	30	*ft*
Chord	0.433	*ft*
Rel. Wingspan	1.1	*ft*
Surface Area	0.476	*ft*^{2}
Angle	3	*deg*
Camber	4	*% chord*
Thickness	5	*% chord*

For the given configuration described in **Table 1**, the resulting lifting force by the foil simulation program was 2.088 lbs for straight and level flight. This value satisfied our requirements since the F-35A model's weight should be in the range between 1 and 2 pounds.

Since the wings of the JSF have a trapezoidal form that narrows down from the support to the tip, airfoils were constructed at ½" intervals having a vertical thickness of 5% of the respective chord line (distance between the wing's leading edge to the trailing edge). The ailerons (moving surfaces that control roll movement) were modeled precisely as the actual F-35A. An actuator was used to couple the aileron to the wing surface. These actuators served to convert horizontal displacement provided by a servo (talked in detailed further ahead) to vertical displacement of the aileron. Finally, passages were made through the airfoils for the navigation lights as well as for the pushrod cable connecting the servo motor to the aileron actuator. **Figure 11** shows the solid-modeled left wing of the aircraft. Perpendicular cross-sections were not shown for clarity of the image. Also note 0.4" overhang from the inside edge of the wing, which serves to couple the wing structure to the fuselage via grooves with a dihedral angle of 4 degrees.

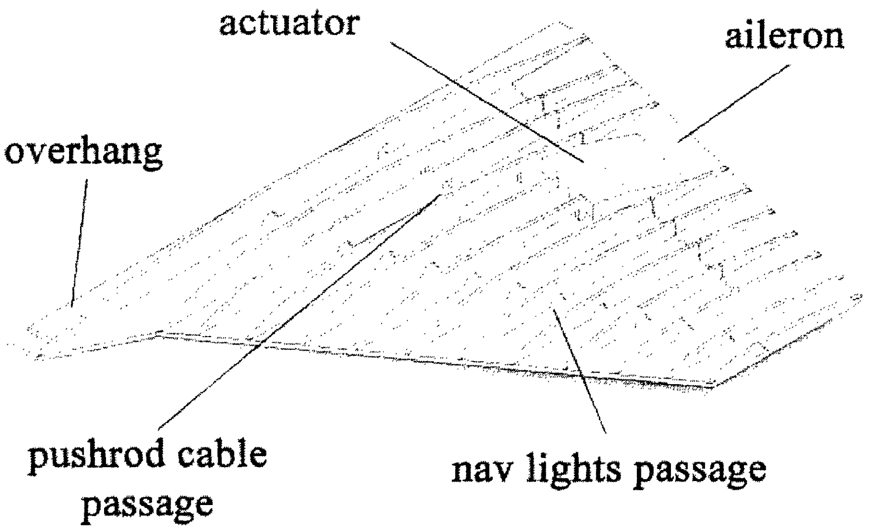


***Figure 11**: Left wing structure consisting of a main base plate, parallel airfoils of similar aerodynamic shape, aileron, coupling actuator, as well as the required clearances for the pushrod cable and navigation lights.*

3.3 Ducted Fan Housing

In order to resemble the jet engine of the actual F-35A, our scaled model used a ducted fan electric motor for providing thrust, as shown in **Figure 12**. This system consisted of a 2.95" long hollow carbon fiber cylinder of outer diameter of 2.60" with a high-speed motor-driven impeller (carbon fiber is known for its strength and lightness). The electric motor was capable of reaching speeds around 20,000 rpm, causing incoming air to accelerate enough so as to provide the necessary thrust for maintaining flight.

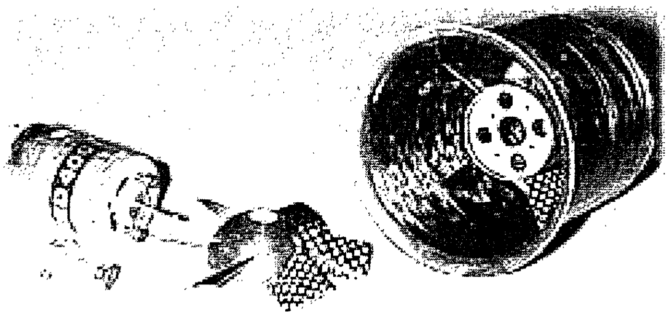


Figure 12: Ducted fan assembly consisting of a high-speed motor coupled to spinning blades within the carbon fiber cylinder, resulting in the considerable acceleration of air particles.

In order to fix the ducted fan to the whole structural design, cross sections were made so as to tightly fit around the outer diameter of the carbon fiber cylinder. This cross sectional parts would then be attached to the rest of the airframe by the wings through the grooves cut on the sides of the cross-sectional members, where the wing's overhang can be press-fitted. **Figure 13** shows an example cross-sectional member as well as the portion of the airframe containing the ducted fan.

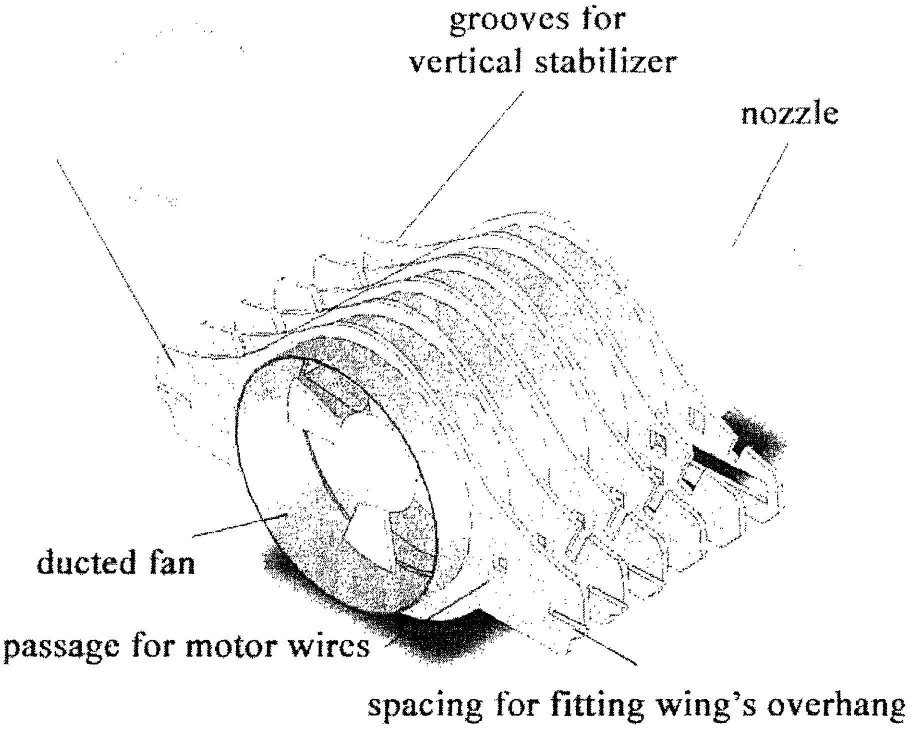


Figure 13: Assembly of ducted fan housing.

A thermoformed nozzle was attached to the rear section of the ducted fan so as to increase the velocity of exiting air even further. Since the power connections of the motor are on its back side, a passage had to be cut between the cross-sectional members so that wires can reach the center of the airframe were the electric components will be located. In addition, groves were cut on both sides of the cross sections to fit the twin vertical stabilizers of the F-35A. The design of the aircraft's tail section can be found in the following section.

3.4 Tail Section Components

Using the dimensions provided in **Figure 7**, the twin set of vertical stabilizers was designed with a thickness equivalent to two sheets of PC (1/8"). Similar to the wing's overhang design, the vertical stabilizers of the tail section were dimensionally constrained by fitting themselves onto a set of grooves on the sides of the rear cross-sectional members of the airframe. Also, for precision alignment purposes, one groove was made on each of the vertical stabilizers so that it could be fit onto a specific non-grooved cross section. For simplicity, these vertical stabilizers have been made rigid without rudders, which are the moving surfaces located on the stabilizer's trailing edge, and have the purpose of controlling yaw (rotational displacement about the airplane's vertical axis).

For the case of the elevators (horizontal surfaces of the tail that control the airplane's vertical pitch), these too were made with a thickness of 1/8" from two separate PC pieces. Conveniently, the lower piece was made with a cavity in the shape of the actuator so that it could be press-fitted together. Since the F-35A's elevators are located aft of the ducted fan, joining cross-sectional members were constructed and supported by a beam to the main portion of the airframe. The last two cross sections had cavities so as to press fit the controlling side of the actuator to the structure. **Figure 14** portrays comprehensive view of the tail section of the aircraft.

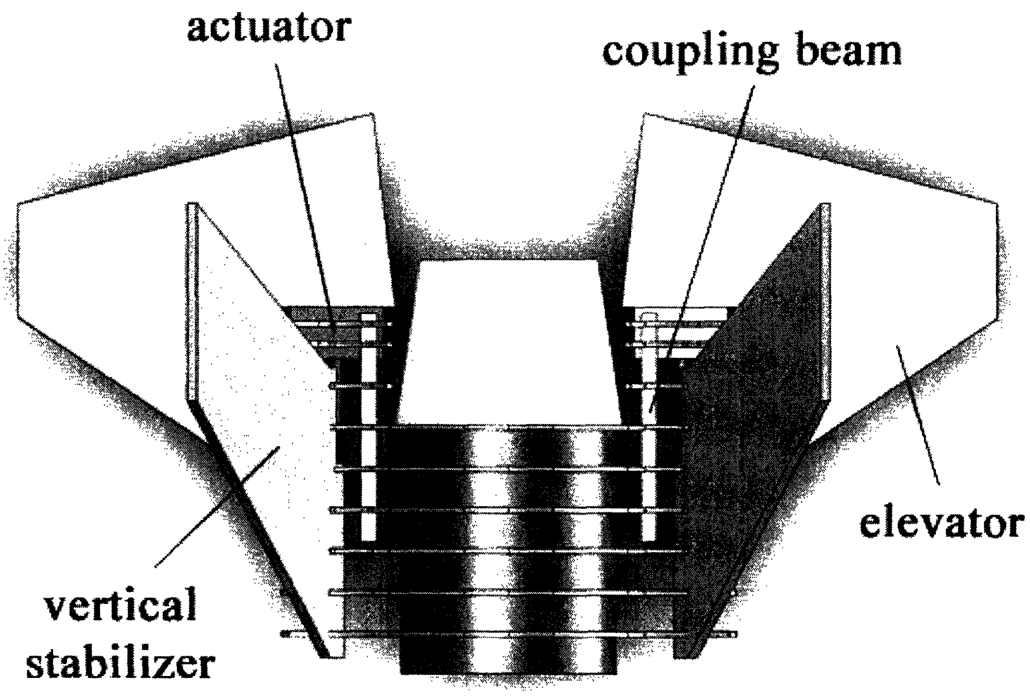


Figure 14: Top view of the tail section of the F-35A model.

3.5 Landing Gear

Like most modern aircraft, the F-35A's tricycle-based landing gear consisted of two main wheels on the rear portion of the structure which support the vast majority of the weight, and one at the front for the purpose of steering the airplane while taxiing to and from the runway. Once the aircraft becomes airborne, landing gear is retracted to reduce drag and thus improve the aerodynamic efficiency of the airplane. For simplicity, our JSF scaled model will have fixed (non-retracting) landing gear that will serve to support the aircraft at a safe distance from the surface. The design criterions for both the nose and main wheels are described below.

Since the landing gear main wheels have to sustain the impact with the surface at touchdown, a shock-absorbing design was deemed necessary. First, we modeled the axle connecting the wheel to the assembly from the same ¼" polycarbonate rod used to sustain the airframe together. To couple the axle to the main structure, two 1/8" PC bearings were added. These bearings were positioned ½" apart from each other. In between this distance, a tightly fit washer was attached to the axle. On top of this washer went a compressed spring which served the purpose of pushing the axle down, until the washer was against the lower bearing. Hypothetically speaking, when the airplane lands, the axle will want to rise but the spring would then compress and ultimately bring the rod back to its starting position once the impulse force has dissipated. Therefore, this spring-based system serves as a very simple solution for our shock-absorbing needs. Finally, the axle was faced cut 0.1" deep from the bottom for a length of 0.8" and connected to a 1-3/8" wheel through a pin. **Figure 15** shows the assembly that characterizes the two main wheels of the landing gear.

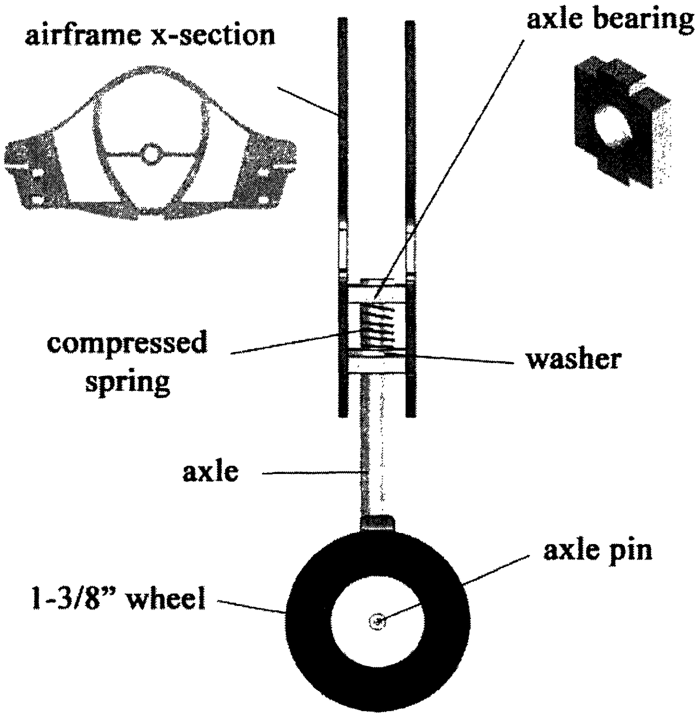


***Figure 15**: Main landing gear assembly with basic shock-absorbing design.*

For the case of the nose wheel, we wanted it to be able to steer while on the ground. To accomplish this objective, we used a similar design to that of the main landing gear wheels but without the sock-absorbing spring. Between the two bearings, the axle was attached a small horizontal rod which would be connected via cables to a servo motor, thus controlling the steering angle. Although the actual F-35A has only one nose wheel at its front, the scaled model was designed with two for balancing and esthetics purposes. Please note that the required servo motor to swivel the nose wheel axle was fixed to the structure by press-fitting it to several cross-sectional members of the airframe containing cavities that match the dimensions of the servo. Components of the nose wheel portion of the landing gear can be seen in **Figure 16**.

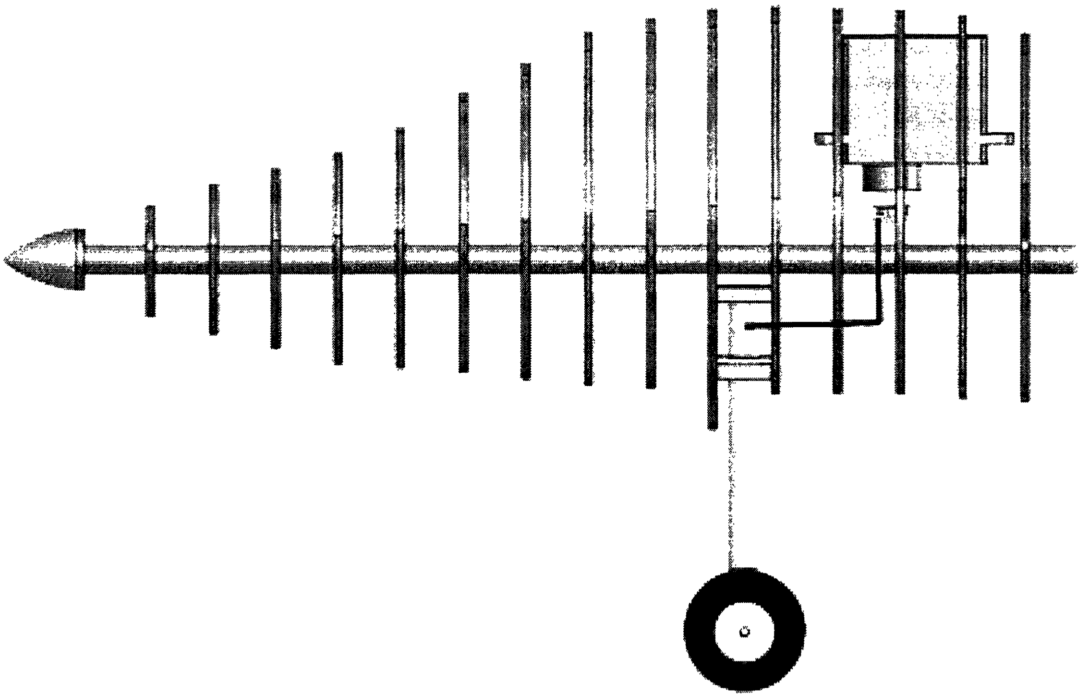


***Figure 16**: View of nose landing gear assembly consisting mainly of a swiveling axle supported by two bearings and controlled by a servo motor. Two 1" wheels were used to give the aircraft better balance as well as a symmetrical, esthetically pleasant look.*

So far, we have discussed the main components of the F-35A scaled model consisting of the fuselage, wings, ducted fan motor, tail structure, and landing gear system. Although there were some minor design elements in addition to those previously mentioned, we have decided not to include them in this document so as to conserve the clarity, directness, and length of the reading. **Figure 17** shows the principal views of the finalized F-35A solid model assembly constructed with SolidWorks™.

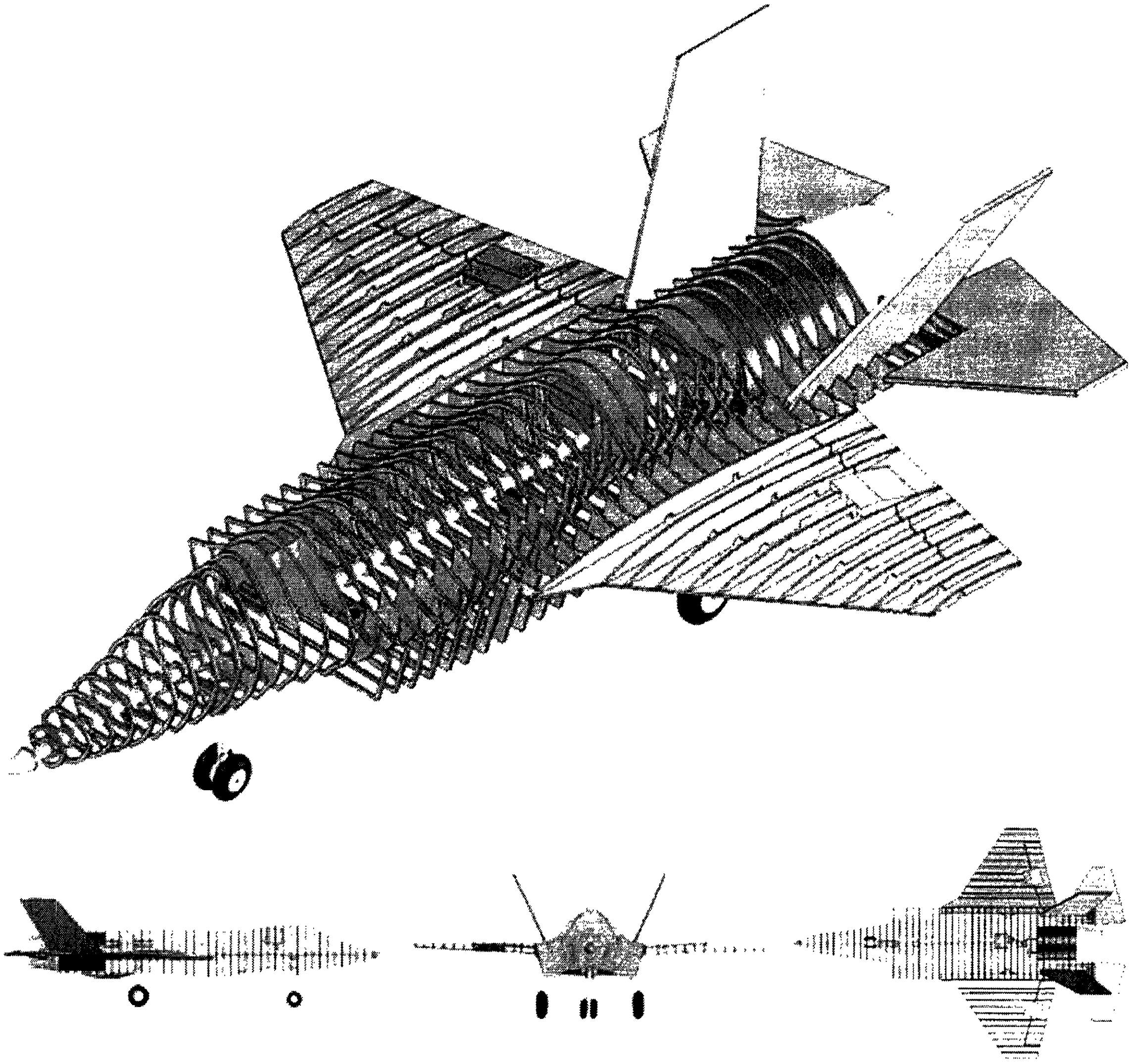


***Figure 17**: Isometric, side, front, and top views of the F-35A solid model assembly.*

4 Aircraft Control Inputs

For an airplane to maintain stable flight, a set of input combinations must be present, which can easily and accurately control the aircraft's attitude for all its degrees of freedom. In order to accomplish this, fixed-wing airplanes have ailerons, elevators, and rudders so as to be able to control roll, pitch, and yaw movements as intended by the pilot in command. The R/C transmitter and receiver package acquired for the F-35A scaled model provides only four separate radio channels, which translates into four independent control inputs that can be set concurrently by the user. Since yaw control for model airplanes is not a priority for maintaining coordinated flight, the four inputs selected for our F-35A fighter jet were set to control the motor's power setting, aileron surfaces, elevator surfaces, and the nose wheel.

First and foremost, the throttle setting is responsible for controlling the thrust output of the ducted fan motor, which in turns turn provides the acceleration necessary to reach airspeeds required for flight. As shown in **Figure 18**, throttle output can be modified by applying vertical displacement on the left control lever of the transmitter. Full down position of the lever cuts all current from passing to the motor (idle state), while the full upward position gives the highest power output possible by the motor. A detailed explanation of how the electrical components work will be provided in the next section.

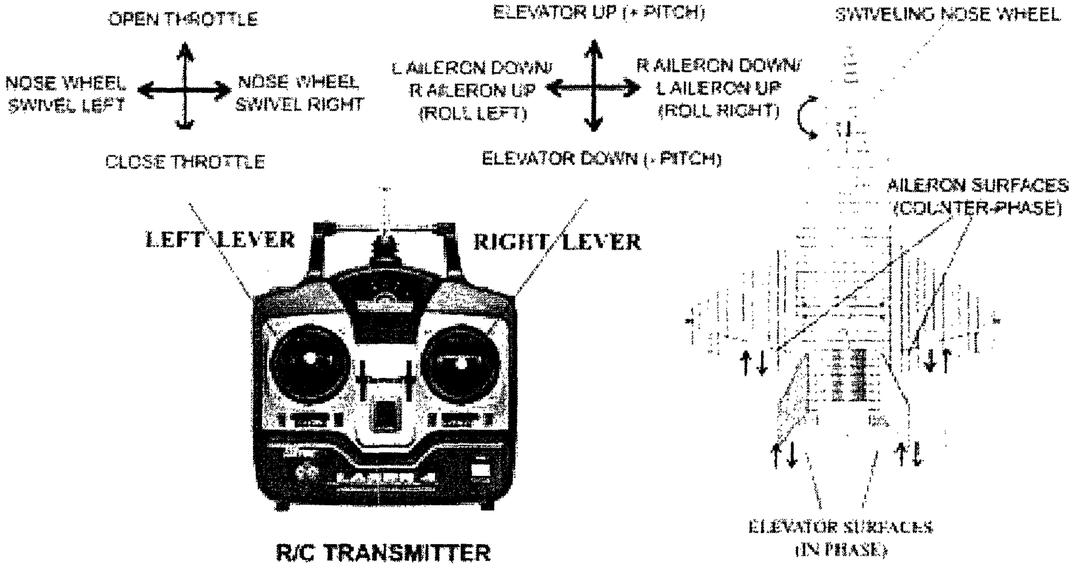


Figure 18: Overview of aircraft's 4 main control inputs.

For the case of the nose wheel, the horizontal displacement of the same left lever regulates the swiveling action of the wheel, making taxiing possible while on the ground. The farther the lever is pushed to either side, the greater the swiveling angle will become, thus making the turn narrower. Once the aircraft becomes airborne, our emphasis will reside on small input corrections of the ailerons and elevator surfaces.

Ailerons, as mentioned earlier, are the necessary aerodynamic surfaces that permit control of the airplane's roll, directly responsible for making airplanes turn in flight. Turning is accomplished by having ailerons from each wing move in opposite directions. The wing in the aileron-down position provides higher lift than the other (just like flap surfaces), making the aircraft rotate about its longitudinal axis, and thus turn to the side the lower wing is facing. In the case of our JSF F-35A model, this is made possible by having opposite-moving actuators coupled to the same servo, which is controlled by horizontal displacement of the right-hand-side lever of the R/C transmitter. Thus, moving the lever to the left causes the left aileron to lower and the right one to rise, making the aircraft turn to the left and vice versa.

Finally, the elevator surfaces which control the pitch of the aircraft are symmetrically controlled by a single servo coupled to a pair of actuators that hold these surfaces to the fuselage. On the R/C transmitter, pitch can be modified by using the lever on the right side in the vertical direction. Keep in mind that lowering the stick provides a positive pitch attitude necessary for climb and conversely a negative pitch for settings were the lever is vertically raised. **Section 7** provides images of all control surfaces once the scaled model was constructed.

5 Electrical Components

For simplicity, our scaled model was designed to be completely electrically powered in order to avoid having issues with gasoline leakage and corrosion, common for models dealing with fuel-powered engines, which are also quite heavy in general. In addition, having rechargeable batteries is significantly more convenient than dealing with the issue of loading gas on the plane. **Figure 19** depicts a schematic diagram of the electrical components and their respective interconnections for transmission of signals required to maintain proper control of the aircraft.

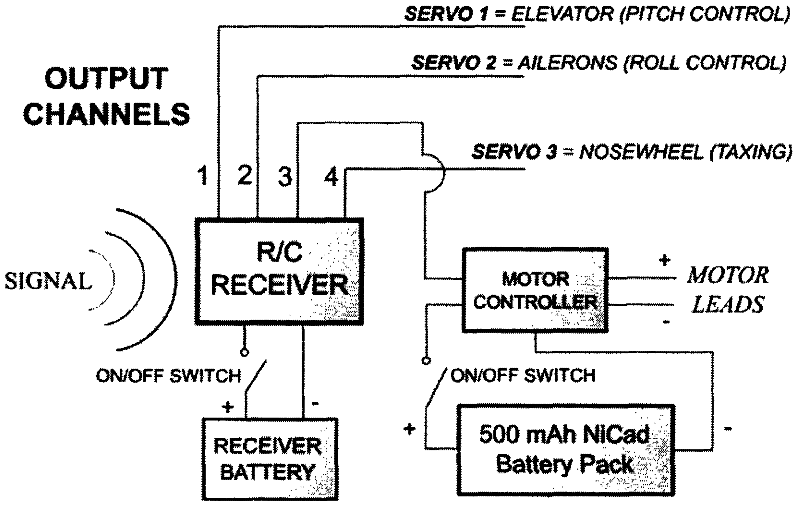


***Figure 19**: Schematic representation of electrical system*

In essence, radio signals sent by the R/C transmitter (shown previously in **Figure 18**) are captured by a radio receiver located inside the airframe. The operating frequency used for this one-way communication was 72.77 MHz. The receiver, in turn, sends signals through wire simultaneously to four different operating channels. Channel #1 controls the servo coupled to the elevator surfaces, and thus is in charge of controlling the aircraft's pitch attitude. Similarly, channel #2 controls the servo coupled to both aileron surfaces necessary for making the airplane turn. On the other hand, channel #4 is coupled to the nose wheel and therefore responsible for modifying the swivel angle for taxiing. Finally, channel #3 was used to control the power setting of the ducted fan motor. In order to do so, the signal had to go through a microchip controller before reaching the motors. This controller was capable of setting the current flow passing to the motors, relative to the input given by the transmitter. In addition, it also served as a current limiting device so as to avoid damaging the motor with an overcharge and also had a warning system for when the batteries where running low. Since the motor requires a lot of power to provide the necessary thrust, a separate NiCad rechargeable battery was connected to the controller solely for the purpose of providing high current flow to the motor. The receiver also had a smaller, less powerful NiCad battery to power the servo motors. Notice that both batteries have on/off switches to prevent unnecessary drain in states of idleness. The motor battery was rated to be 500mAh, good enough to last approximately 20 minutes at moderate power settings.

In addition to the main electrical system, a separate circuit was made for powering the external lights of the aircraft. The circuit consisted of 6 different sets of LEDs, grouped in parallel configuration with one kilo-ohm resistors in series (see **Figure 20**). These were all powered by a single A-23 12-volt battery, chosen for its relatively small size and weight. The first two lights were high-intensity white LEDs that served as landing lights, located underneath the nose area of the airplane. One red and another green LEDs simulated the navigational lights, located at the opposite ends of the wings. One blinking red LED was used as the beacon underneath the airframe. Finally a blue LED was placed inside the airframe near the motor so as to give the impression of hot engine exhaust at night. Views of constructed lighting system can be found in **Section 7.**

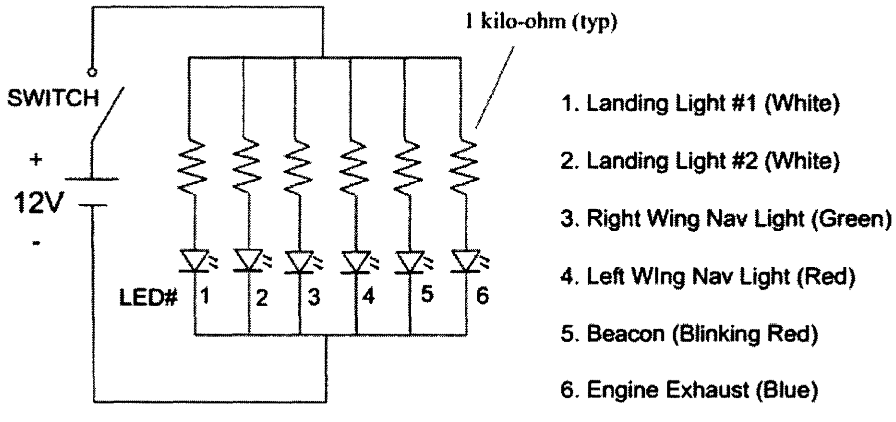


***Figure 20**: LED-based lighting system circuit schematics.*

6 Design for Manufacturing

Having already completed in full the scaled solid model of the F-35A, we proceeded to prepare the individual CAD parts for manufacturing. Using SolidWorks™," several drawing files were created so as to compile all components of the assembly. Grouped parts were enclosed by 12"x12" margins, representing the square-foot polycarbonate sheets (1/16" thick) to be cut with the waterjet machine. After verifying that all parts had been transferred successfully into drawings files, these were converted to DXF (Drawing Exchange Format) for the creation of their waterjet tool paths. The OMAX Layout computer program was utilized for this purpose, as shown in **Figure 21**. To ensure the smoothness of contours contained in these drawing files, a quality setting of '5' was given to all parts to be cut. This setting provided the best possible finish without adding a significant amount time for completion of the abrasive cutting procedure. Additionally, all parts were made with gaps in between the lead ins/outs on their outermost boundary so as to ensure that each remained attached to the polycarbonate sheet, thus eliminating the possibility of loosing pieces during the cutting process. Once all the tool paths for the different drawings had been completed and saved as ORD files, they were loaded via floppy to the OMAX waterjet computer for automated production of parts. In total, ten 12"x12" polycarbonate sheets were used to create 129 individual parts, each sheet taking approximately six to eight minutes to complete. Views of individual drawings can be found in **Appendix B**. For a complete view of all manufactured parts, see **Figure 22**.

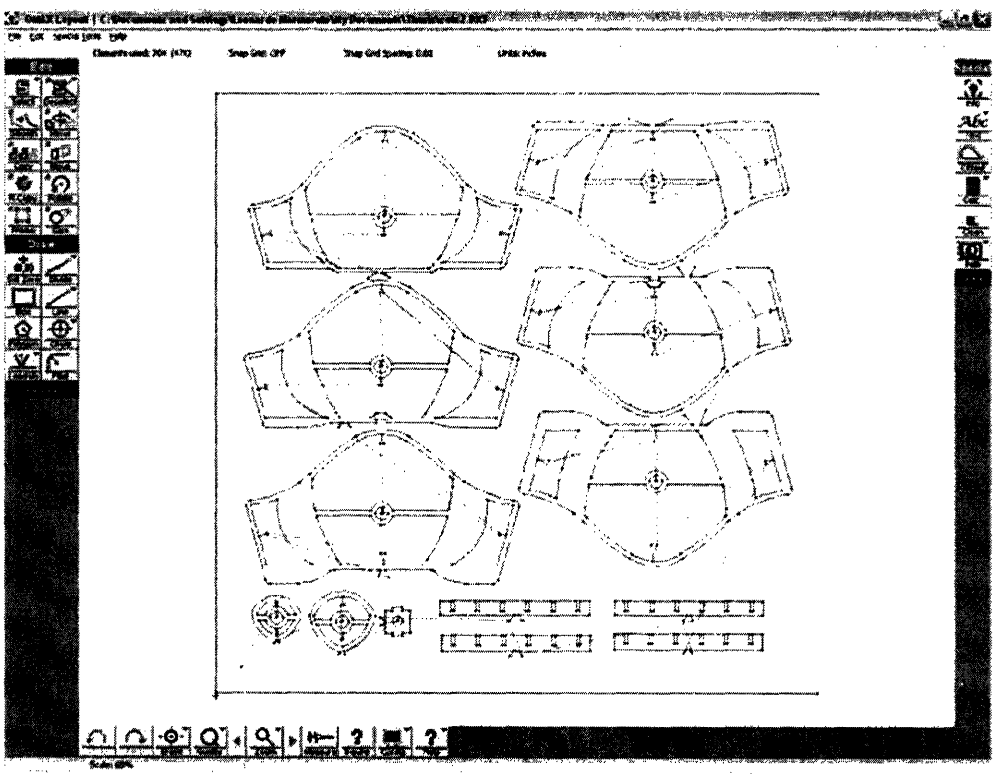


***Figure 21**: View of the OMAX Layout program used to create the waterjet tool path profile necessary for the manufacturing of individual parts contained in the F-35A scaled model.*

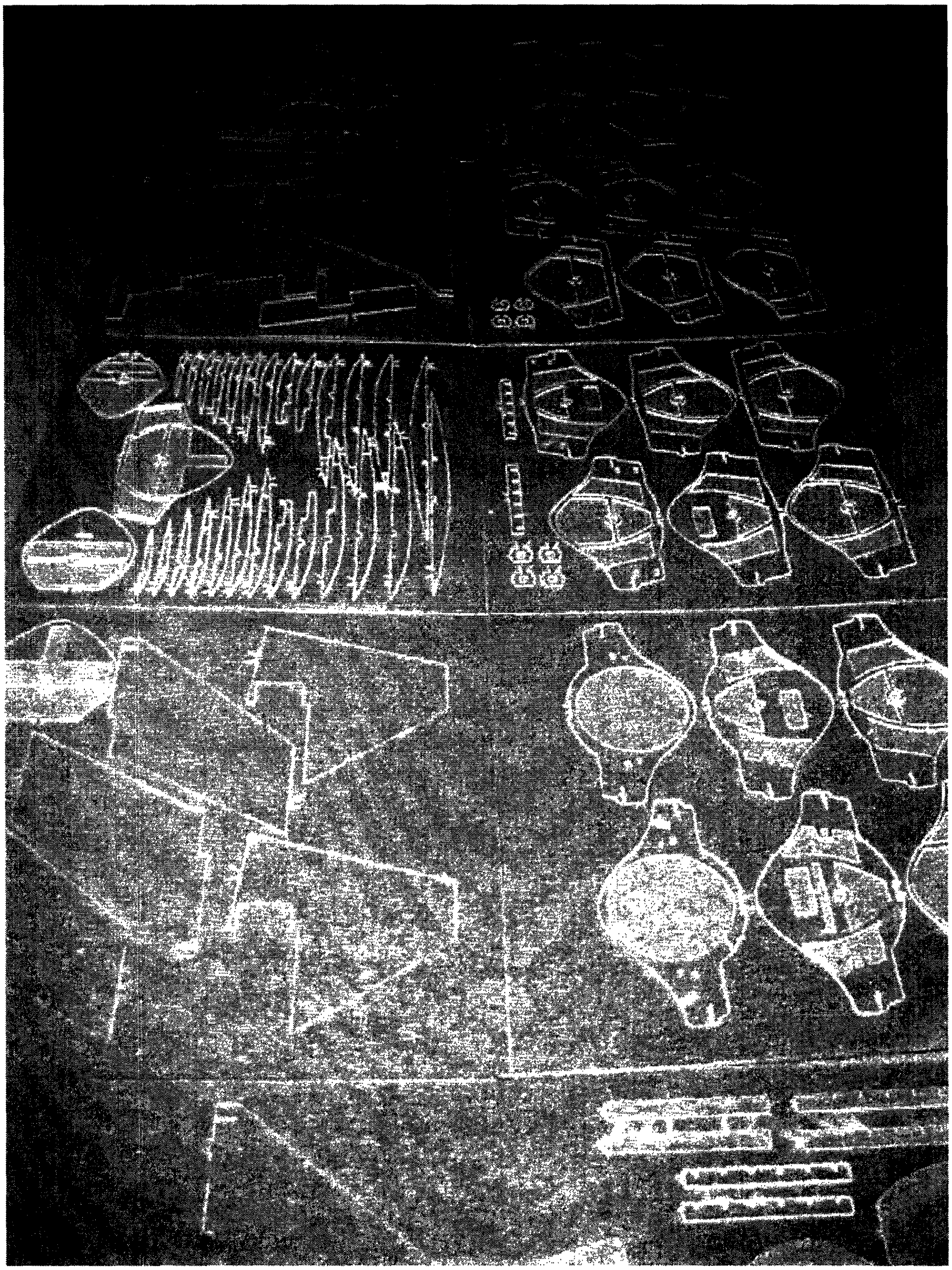


***Figure 22**: Assembly parts cut out of 12”x12” polycarbonate sheets (1/16” thick) by the waterjet.*

7 Assembly of Prototype Model

Having already designed, manufactured, and or purchased all the required components of the scaled model assembly, we proceeded to build the polycarbonate-based prototype. Starting off with the fuselage, we assembled cross-sections one by one with the aid of the transverse ¼" PC rod. For alignment purposes, waterjet-made spacers were used to constrain the cross-sectional members at a preset distance of 0.4375" (1/2" gap taken from the dimensions minus the 1/16" of the PC thickness). Once parts were considered to be perfectly aligned, they were fixed to the remaining structure with all-purpose adhesive, which worked remarkably well in bonding plastic surfaces together in a very short amount of time. Once the main portion of the fuselage was completed, we proceeded to construct the wing structures by assembling the airfoils onto the already shaped polycarbonate base. Both ailerons where then connected to their respective wings through actuators, which in turn were coupled to the servo via a pushrod cable so as to permit movement of the control surfaces. Finally, after completion of the wing assembly, these wings were fitted into the fuselage's grove via a 0.4" overhang. Afterwards, the ducted fan portion of the airframe was attached to the main structure, followed by the members of the airplane's tail section. Landing gear system was also integrated soon thereafter. As a final step, all the electronics were inserted through the gaps between airframe cross-sectional members and were shifted around until CG (center of gravity) specifications were met (discussed more profoundly in the next section). The next set of figures present some of the main components of the assembly in full visual detail.

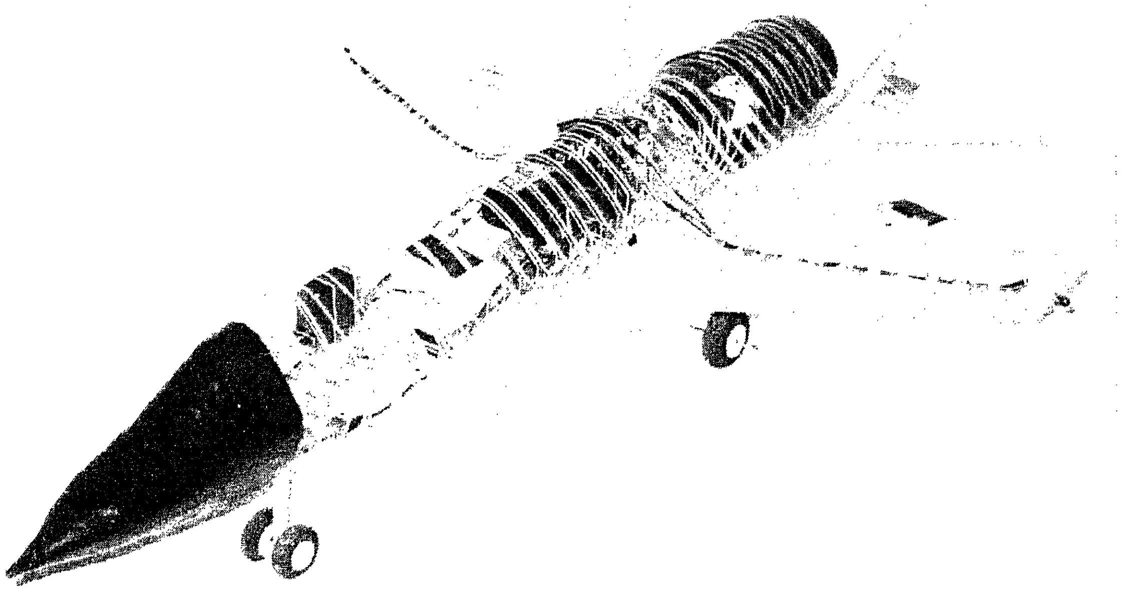


***Figure** 23: View of the completed assembly of the polycarbonate prototype model.*

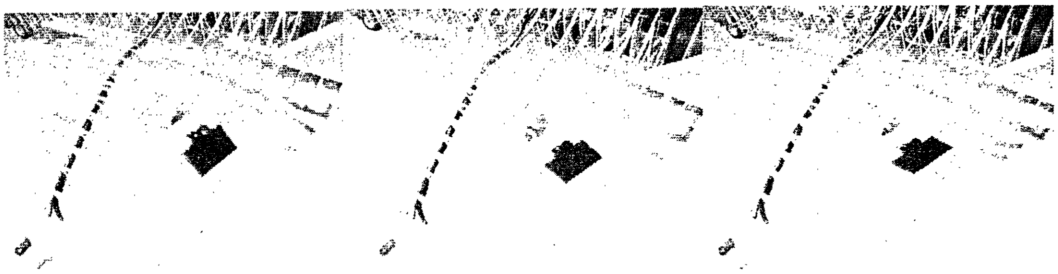


Figure 24: *Views of aileron's up, neutral, and up positions.*

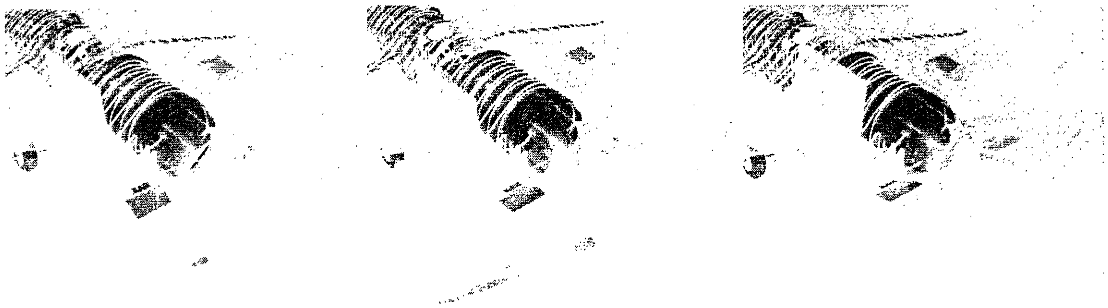


Figure 25: *Views of elevators' up, neutral, and up positions.*

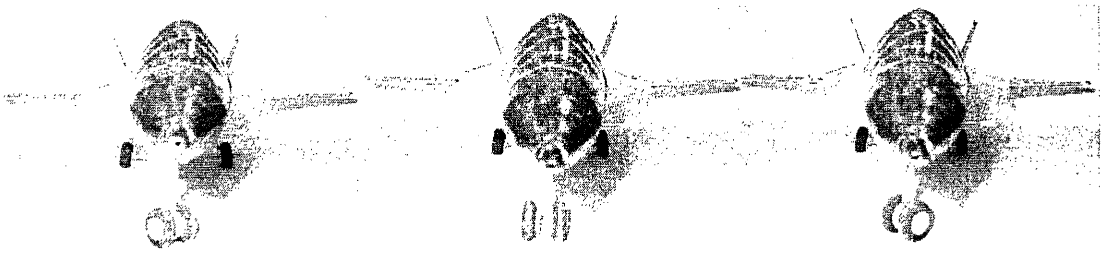


Figure 26: *Views of nose wheel's left, neutral, and right positions.*

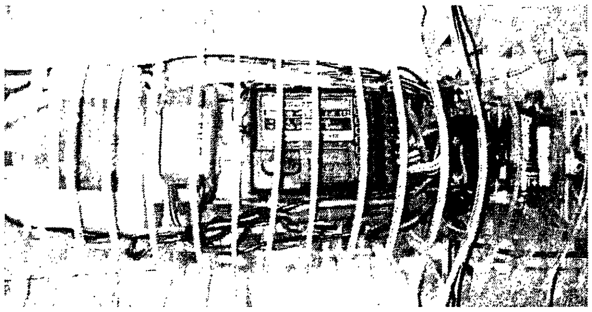
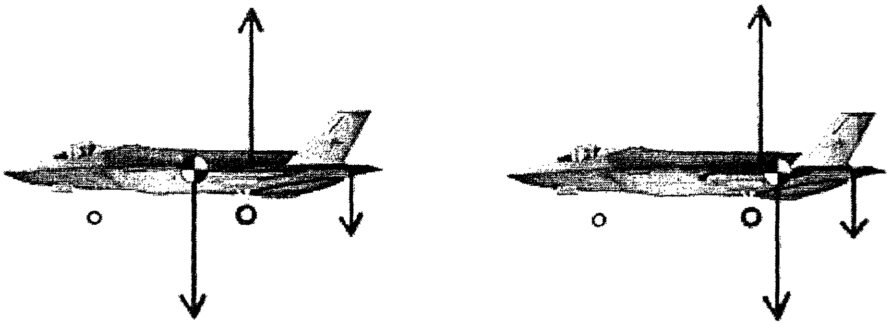


Figure 27: *View of electrical components: (from left to right) reciver battery, motor microcontroller, R/C receiver w/ connections, and A-23 Energizer battery for powering LEDs.*

8 Weight and CG Calculations

In aviation, there are two main ways in which pilots can greatly alter the flight characteristics of their airplane. Although not commonly realized, both the CG (center of gravity) and the gross (total) weight of the airplane play an important role in determining how well the aircraft will respond to input variations, and also how well can it recover to unstable attitude configurations. For instance, we know that lift on the wings is produced by rushing air, resulting in what is known as the venturi effect. The pressure differential that pushes the wings up is proportional as well as limited to the airspeed of the aircraft. Because of this, airplanes must not be loaded to a point were its weight far exceeds the possible lift created by the wings. On the other hand, CG calculation is inherently valuable as it is an indication of the airplane's overall stability. In order for the aircraft to be considered stable, moments acting on the its lateral axis must be able to balance without much effort on the elevator (pitch) controls. Since the elevators are known to cause a moment at the far end of the aircraft, the ideal situation for stability will be when the center of gravity is considerably distant from the center of lift located at the wings. The closer the two force vectors get, the more unstable the aircraft will become, as shown in **Figure X**. An eminent danger from bad CG positioning is that positive pitch attitudes might never be returned to level due to the backwards rotation tendency, resulting in a stall (loss of lift) when a critical angle of attack is reached.



STABLE

Has natural tendency to return to the neutral horizontal state

UNSTABLE

Has the tendency to pitch up, possibly leading to an unrecoverable stall

***Figure 28**: Comparison of airplane stability dependent on CG location.*

In order to find the airplane's gross weight, we started off by calculating the density of our polycarbonate stock. This task was performed by weighting a PC sheet on a scale and then dividing it by its volume (12"x12"x1/16"), yielding an estimated density of 0.694 oz/in3. Fortunately, SolidWorks™ provides a utility that permits the calculation of the weight of an object by its geometry once the density is specified. For the rest of the non-polycarbonate components, their respective weights were in most cases provided by the manufacturer, making our calculations even easier. **Appendix D** provides additional weight data by individual components used for gross weight calculation.

It should be noted that the weight of things such as adhesive, pushrod cables, electrical wiring, etc. were considered for this calculation by adding a 5% margin of error to the total weight. Finally the resulting gross weight came out to be 2.05 lbs, very close to our 2.09 lbf calculated by the shape of the wing's airfoils. This result shouldn't alarm us, since this polycarbonate model is only a working prototype and is not intended exactly for flying practices. Regarding the center of gravity, all electrical components that were fitted inside the airframe gave the sufficient amount of weight leverage necessary to place the CG specifically where we wanted. We chose the CG to be approximately 1" aft of the inner leading edges of the wings for good control and overall stability of the aircraft.

9 Conclusion and Recommendations

As we have seen throughout the project development of the 25:1 scaled F-35A electromechanical model, making a fully working aircraft requires considerable amounts of time in designing as well as testing and troubleshooting. Despite some minor differences in detail, such as the two-wheeled front landing gear and the oversized nozzle, we can conclude that our model closely resembled the vast majority of the physical features contained in the Joint Strike Fighter conventional takeoff/ landing variant.

It should be made clear that the decision for making the airframe out of polycarbonate was greatly influenced by time limitations and budget constraints experienced throughout the term. Our original intention was to make the airframe completely out of balsa wood, a material with stiffness similar to that of polycarbonate, yet up to eight times lighter. The mayor disadvantage of balsa lies in the fact that it comes in small width sizes, being 6" the largest. This obviously is a something to consider since having smaller stock sizes to cut from in the waterjet implies longer periods spent loading and unloading the material to and from the machine, as well as other setup nuisances included in the process. In general, having limited resources had a lot of leverage on our design approach, especially so when the cost for operating the waterjet at the LMP facilities was tagged at $100 per hour. It is then recommended that once the 2.007 design and manufacturing course (which has complete priority over Pappalardo Lab during the spring term) comes to an end, their waterjet facilities be used for cutting the assembly parts out of balsa for no extra cost, and then be built throughout the second half of the month of may.

From the experience in building the polycarbonate prototype, it is possible to make further recommendations for the proposed model to be made out of balsa. One example lies in reinforcing the front section of the plane so as to correct minor bending effects noticed across the fuselage. In addition, a more powerful battery in the range of 1700mAh is suggested so as to provide prolonged flight time of at least 30 to 45 minutes. Finally, in order to reduce induced drag and weight on the model aircraft, the balsa version can be constructed with detachable landing gear, so as to improve aerodynamic effects in general.

Appendix A: History of the JSF[2]

The Joint Strike Fighter (JSF) originated in the early 1990s through the restructure and integration of several DoD tactical aircraft and technology initiatives already underway. The DoD's goal was to use the latest technology in a common family of aircraft to meet the future strike requirements of the Services and US Allies.

In 1993, the Defense Advanced Research Projects Agency executed a program to develop a supersonic Short Take-Off and Vertical Landing (STOVL) aircraft as a replacement for the AV-8B Harrier. At about the same time, the Department of Defense (DoD) considered canceling the Navy's Advanced Attack/Fighter (A/F-X) that was being studied to fill the void left after the cancellation of the General Dynamics/McDonnell Douglas A-12 Avenger II aircraft being designed for the U.S. Navy.

Senior leadership at the Pentagon suggested a Joint Attack Fighter (JAF) to replace the Navy's A/F-X program. Not only would the JAF be much cheaper than the A/F-X, it would also be designed with a common airframe suitable to the three services. It was believed that such an aircraft would herald significant manufacturing and operational cost savings. Much of the philosophy surrounding the JAF would later be incorporated into JAST, such as its single-engine design and its unprecedented level of commonality.

The Joint Advanced Strike Technology (JAST) Program was initiated in late 1993 as a result of the DoD Bottom-Up-Review (BUR). The major tactical aviation results of the BUR were to continue the ongoing F-22 and F/A-18E/F programs, cancel the Multi-Role Fighter (MRF) and the A/F-X programs, curtail F-16 and F/A-18C/D procurement and initiate the JAST Program.

The JAST program office was established on 27 January 1994. Its mission was to define and develop aircraft, weapon, and sensor technology that would support the future development of tactical aircraft. The program subsequently moved from a broad, all-encompassing program to one that would develop a common family of aircraft to replace several aging US and UK aircraft.

By the end of 1994, the JAST program had absorbed the DARPA Common Affordable Lightweight Fighter (CALF) program. CALF, then renamed ALF, became the primary focus of JAST. However, JAST was also considering modifying the CTOL versions of the aircraft to perform in a STOVL role. Congress subsequently mandated the merger of JAST with the DARPA Advanced Short Take-Off / Vertical Landing program. As JAST was already considering STOVL variants, this merger was accommodated with comparatively little disruption. The JAST Program initially explored a wide range of potential strike warfare concepts using six-month, Concept Exploration (CE) study contracts awarded in May 1994. The findings of the CE studies showed that a "tri-service family" of aircraft was the most affordable solution to the collective joint-service needs. The tri-service family would entail a single basic airframe design with three distinct variants: Conventional Take-Off and Landing (CTOL) for the U.S. Air Force to complement the F-22 Raptor and replace the aging F-16 Fighting Falcon and the A-10 Thunderbolt; Short Take-Off/Vertical Landing (STOVL) for

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[2] Excerpt from the Joint Strike Fighter official Website, http://www.jsf.mil

the U.S. Marine Corps to replace both the AV-8B Harrier and the F/A-18 C/D Hornet; and a Carrier (CV) variant for the U.S. Navy to complement the F/A-18 E/F Super Hornet.

Following numerous trade studies, two critical decisions were made: the JAST family of aircraft would be single-crew and single-engine. Navy attack/fighter aircraft have been preferred to have two engines in case one is lost during flight. The choice of a single-crew aircraft was accepted - subject to continued studies and appropriate technology maturation - on the projection that a single crewmember could perform all of the intended missions.

Boeing, Lockheed Martin, McDonnell Douglas, and Northrop Grumman were each awarded fifteen-month Concept Definition and Design Research (CDDR) contracts in December 1994. Northrop Grumman and McDonnell Douglas/British Aerospace teamed shortly after the CDDR contracts were awarded. The contractors refined their Preferred Weapons System Concept (PWSC) designs and performed a number of risk reduction activities (e.g., wind tunnel tests, powered-model STOVL tests, and engineering analyses).

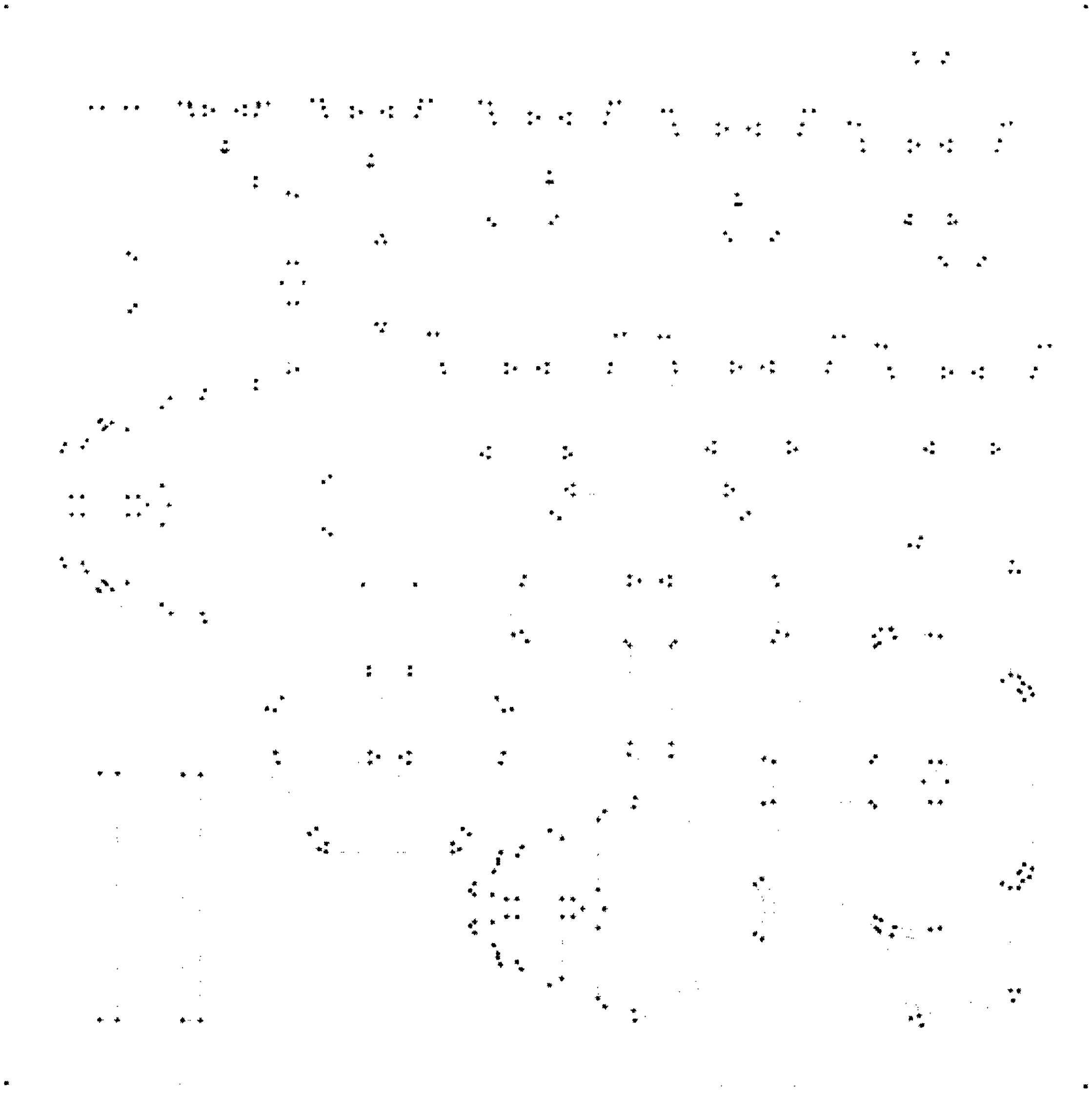
In the spring of 1995, all three of the contractor teams selected derivatives of the Pratt & Whitney (P&W) F119 engine to power their aircraft. Accordingly, in November 1995, P&W was awarded a contract for preliminary design of each of the primary JSF engine concepts. Concurrently, General Electric was awarded a contract to investigate whether the GE F110 or YF120 could be developed into an alternate engine for one or more of the JSF variants. In 1996, the YF120 was identified as the "best fit" for a tri-service solution and GE initiated preliminary design efforts.

Several Defense Acquisition Board (DAB)-level program reviews were conducted in late 1995. The final Requests for Proposal (RFP) were issued to the contractors in March 1996. By that time the JAST program name had changed to Joint Strike Fighter (JSF).

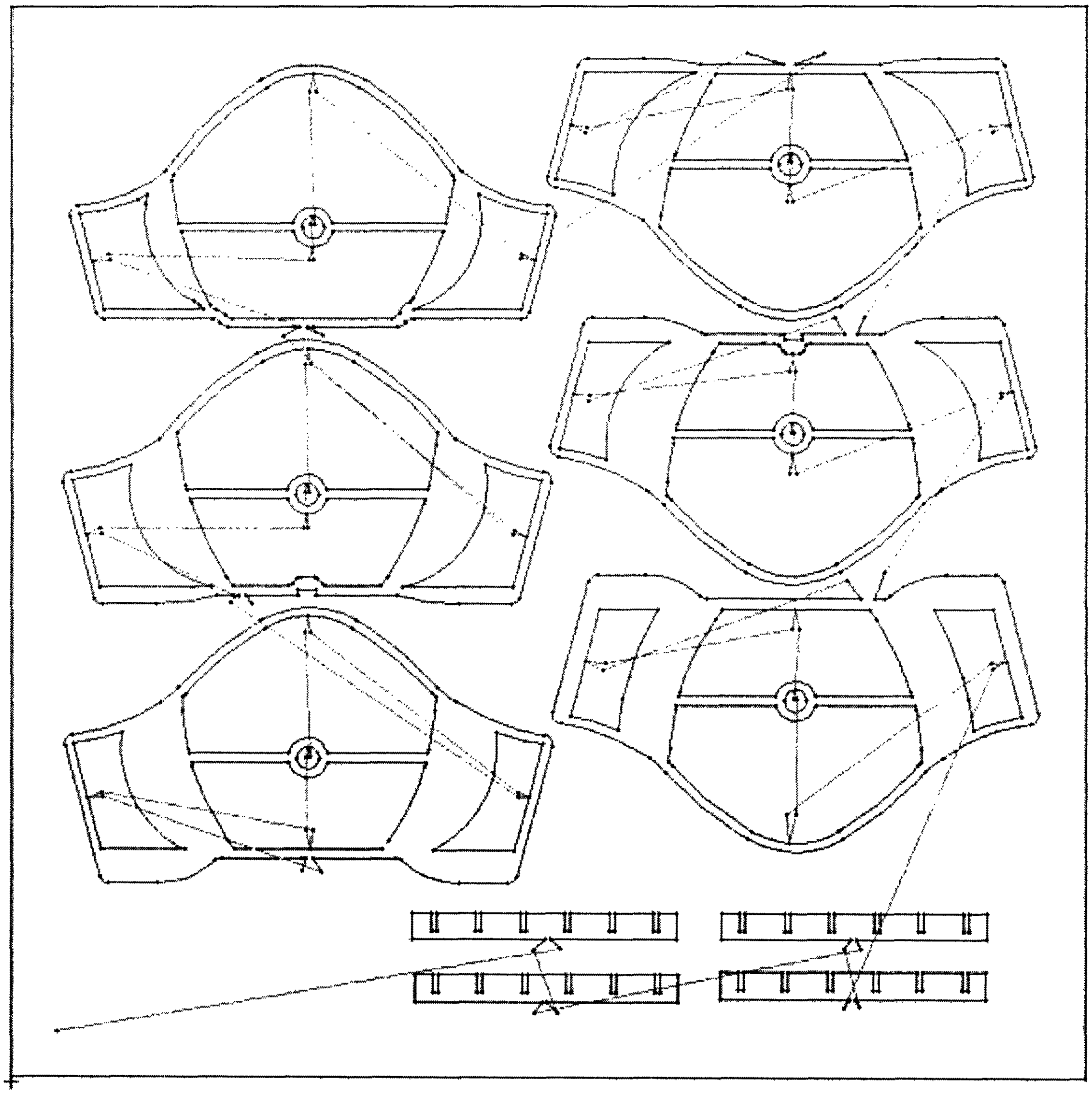
In May 1996, JSF was designated an Acquisition Category I, DoD acquisition program. In June, the weapon system prime contractors submitted their Concept Demonstration Phase (CDP) proposals. A formal Milestone I Acquisition Decision Memorandum was signed by the Under Secretary of Defense (Acquisition & Technology) on 15 November 1996, clearing the way for the award of CDP prime contracts to Boeing and Lockheed Martin on 16 November 1996.

In the end, Lockheed Martin was awarded the Engineering & Manufacturing Development (EMD) contract to begin developing and producing the Joint Strike Fighter for the U.S. and its allies. The U.S. Air Force will be the largest JSF customer, purchasing 1763 CTOL aircraft. The U.S. Marine Corps is expected to purchase 609 STOVL aircraft, and the U.S. Navy about 480 CV aircraft. The U.K. Royal Air Force and Royal Navy will purchase 150 of the STOVL variant.

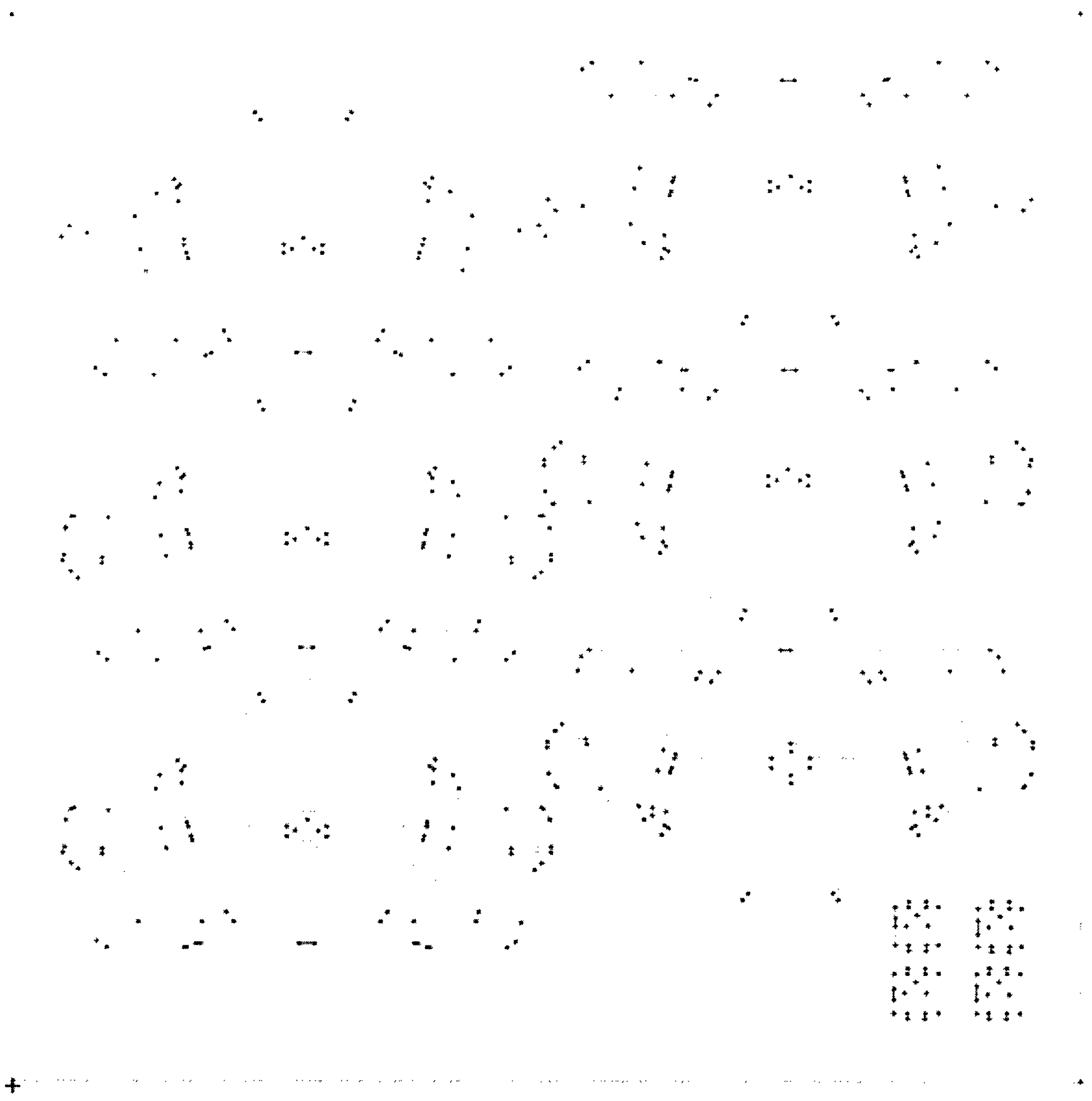
Appendix B: Model Parts for Waterjet Manufacturing



Sheet #1 prior to waterjet tool path design (17 individual pieces)



Sheet #2 waterjet tool path design (10 individual pieces)



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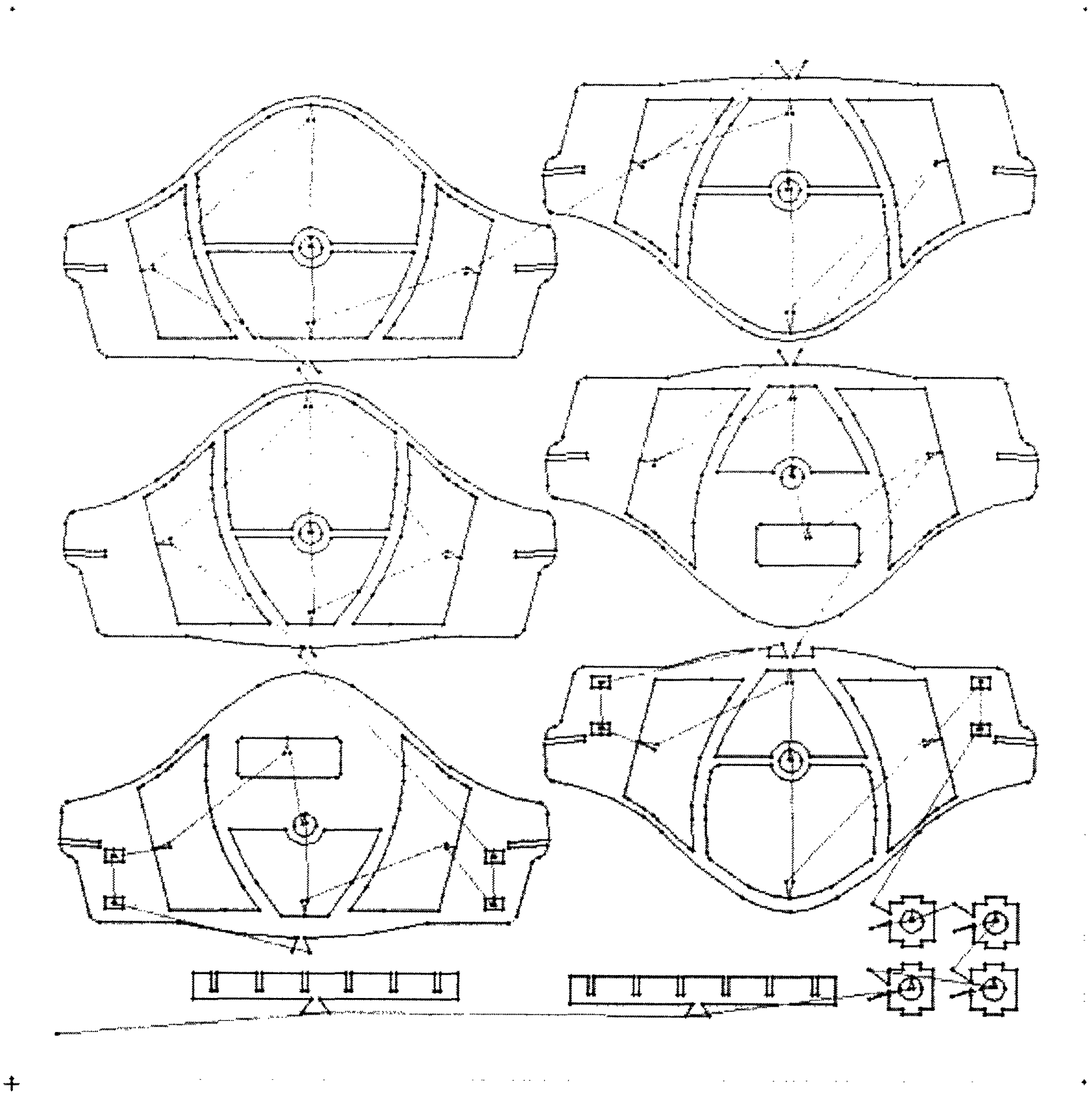
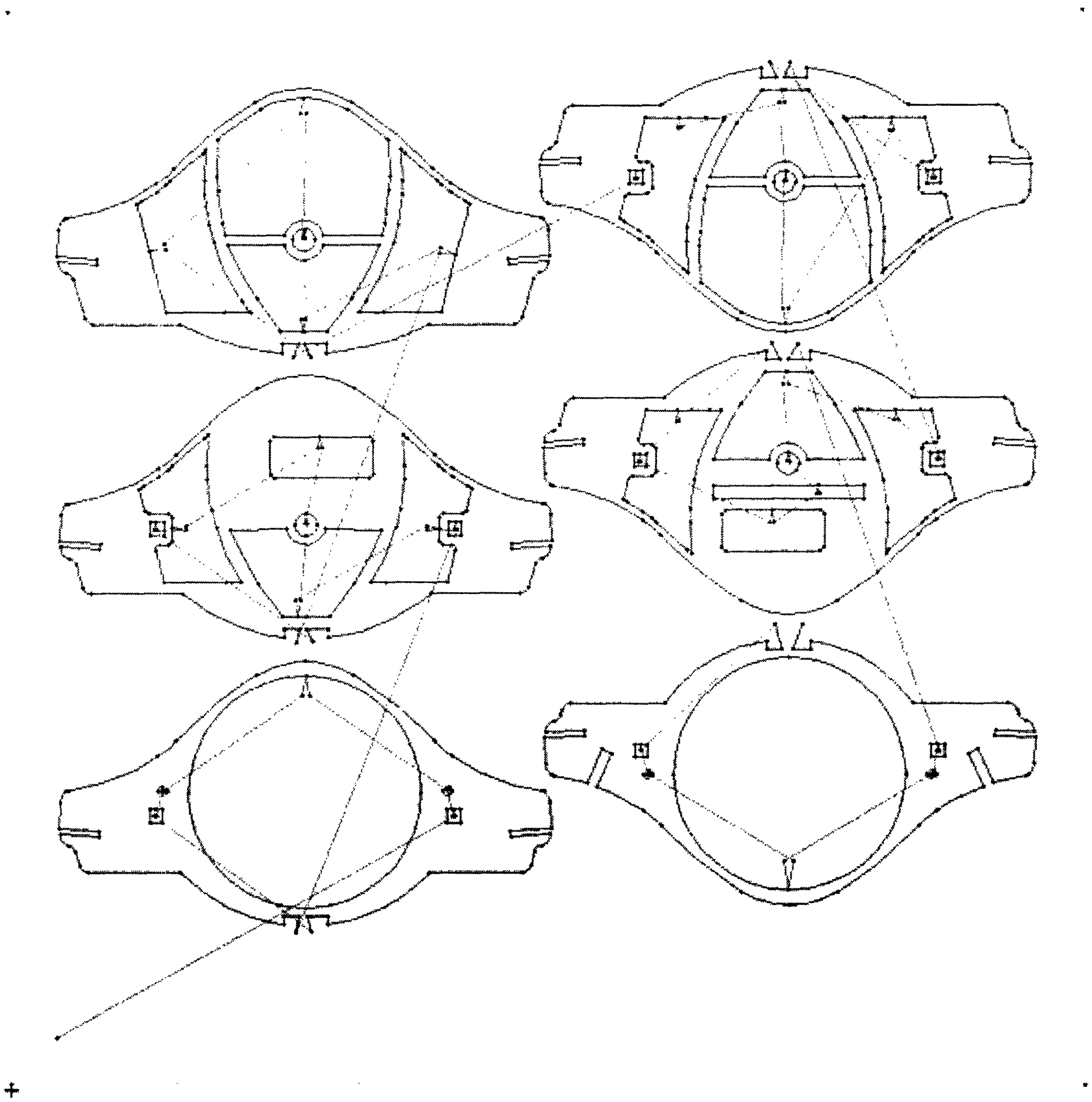
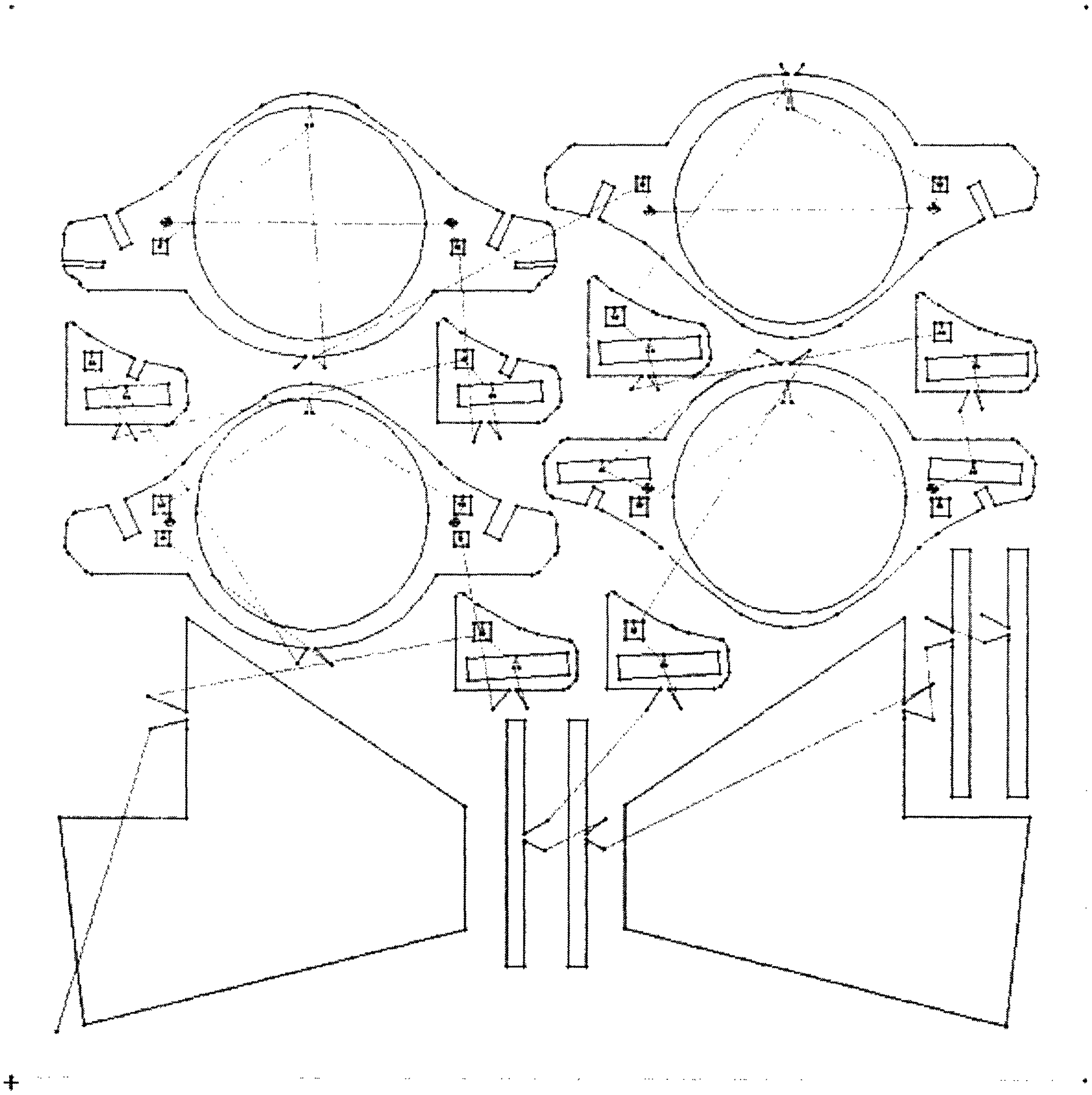


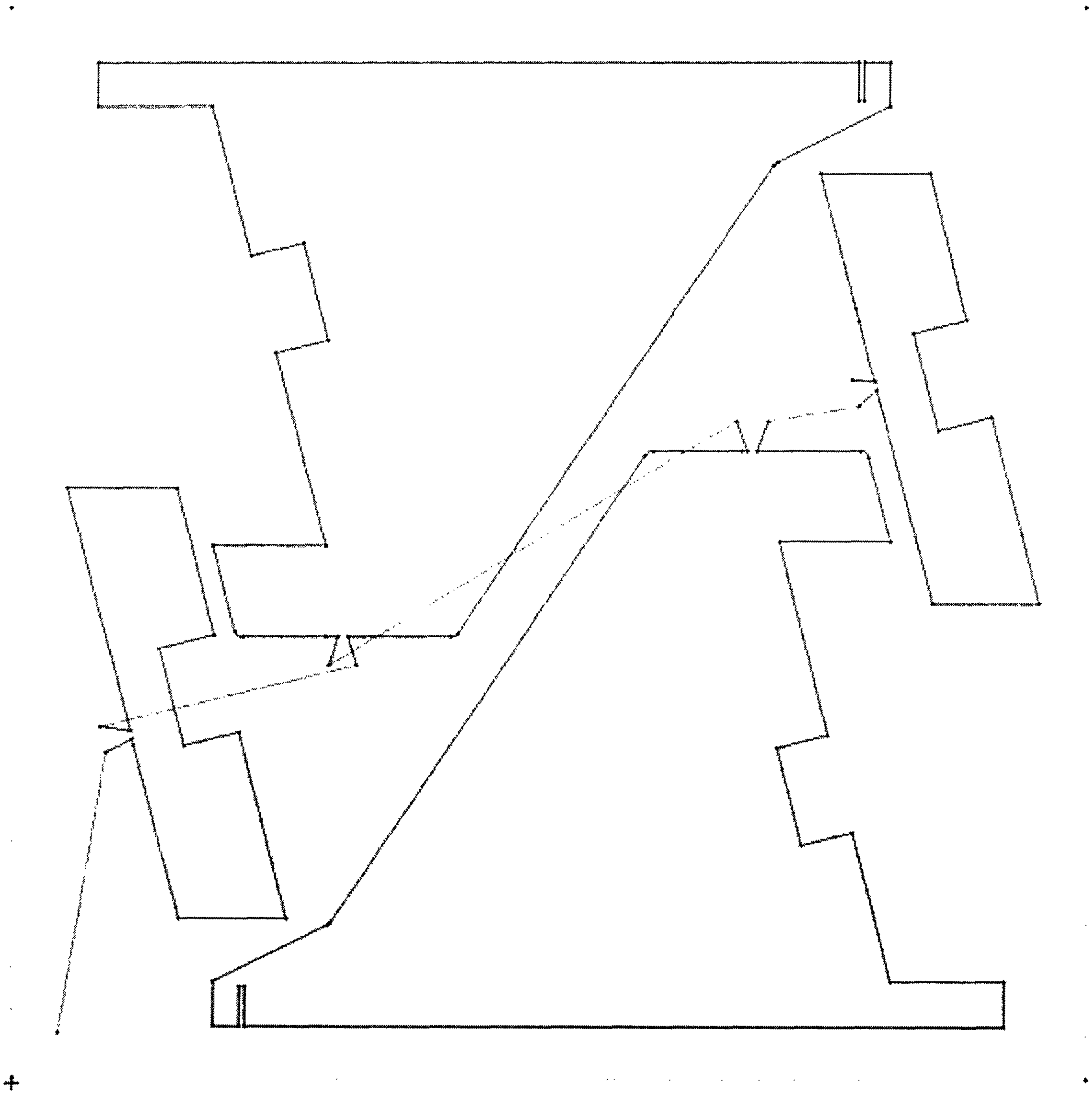
Sheet #4 waterjet tool path design (12 individual pieces)



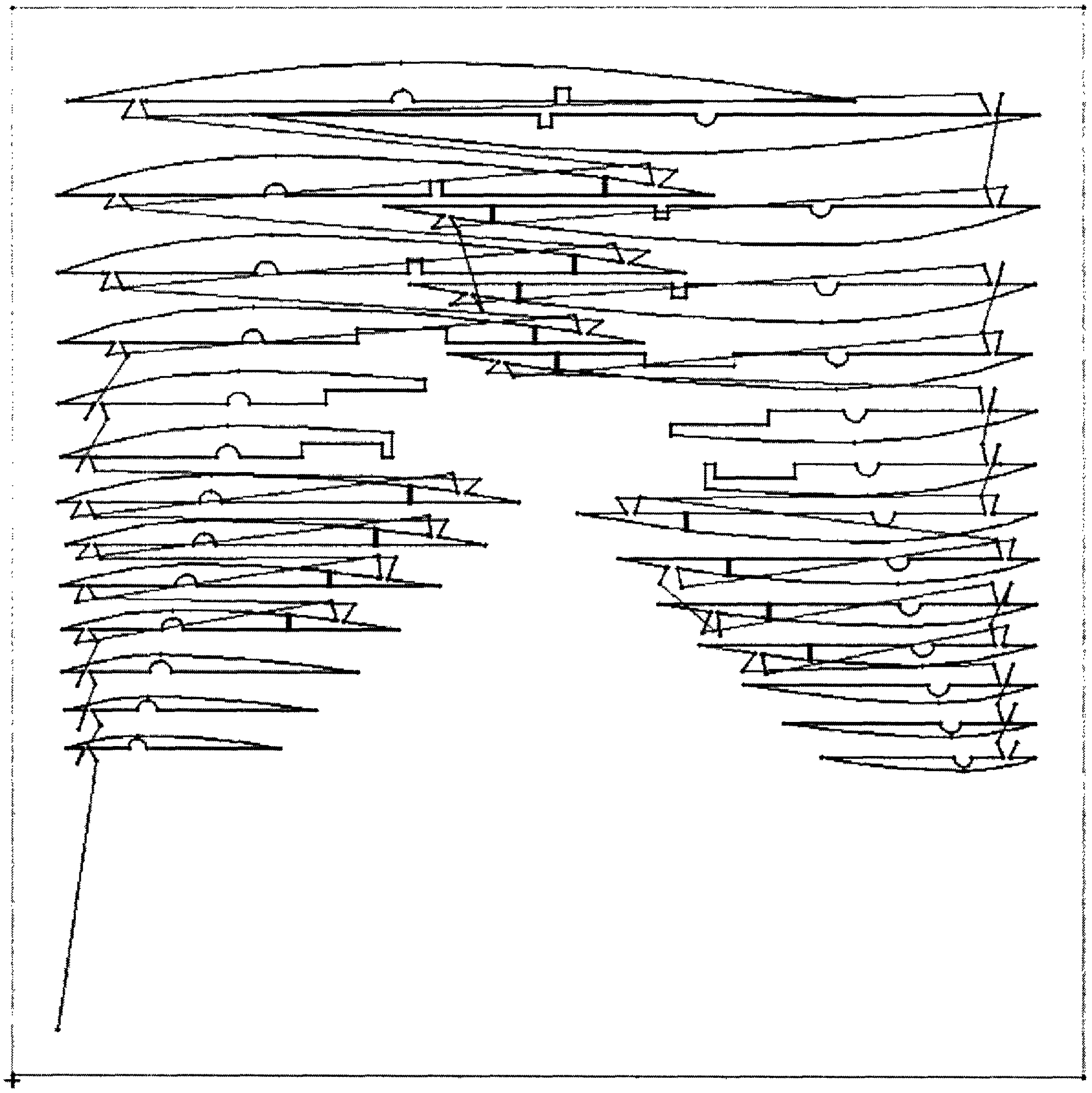
Sheet #5 waterjet tool path design (6 individual pieces)



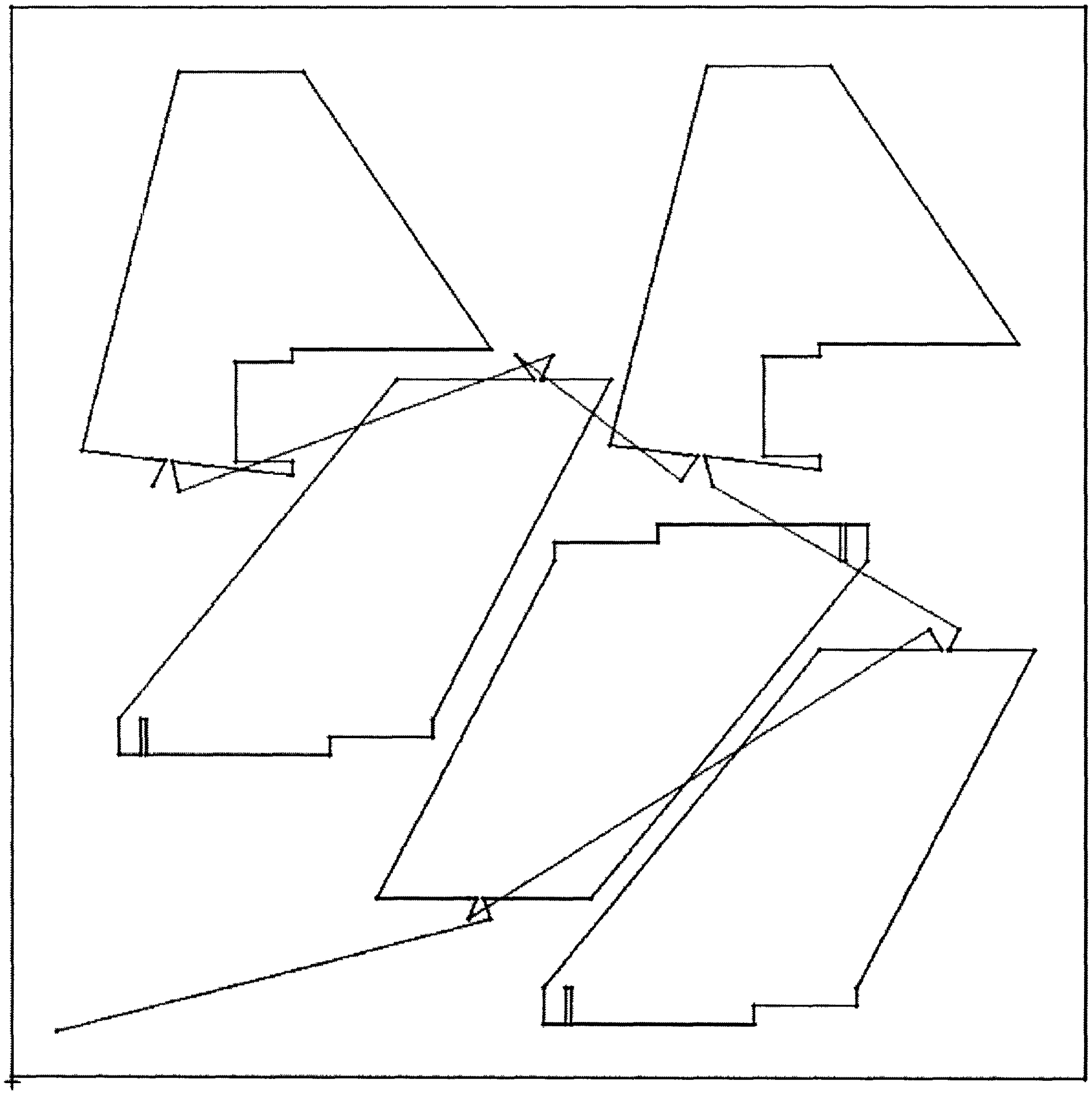
Sheet #6 waterjet tool path design (16 individual pieces)



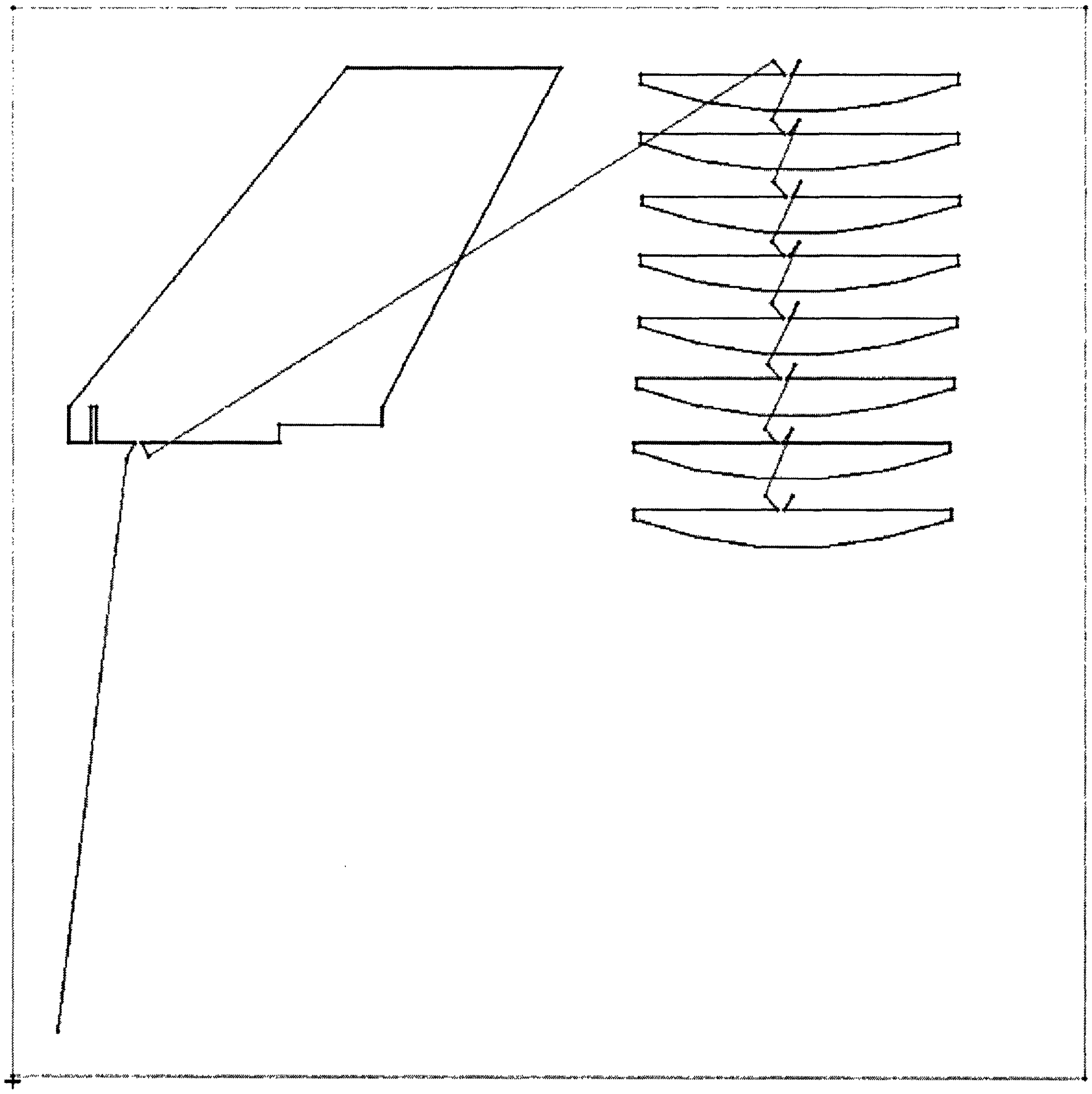
Sheet #7 waterjet tool path design (4 individual pieces)



Sheet #8 waterjet tool path design (40 individual pieces)

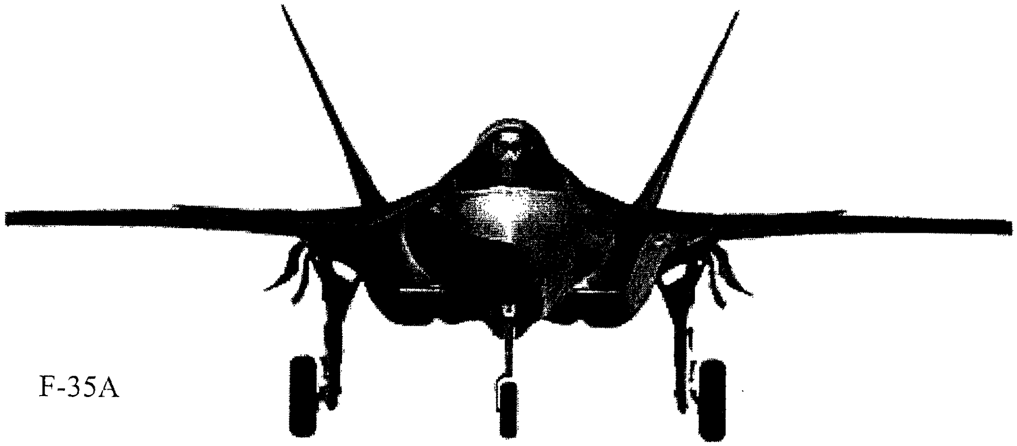


Sheet #9 waterjet tool path design (5 individual pieces)

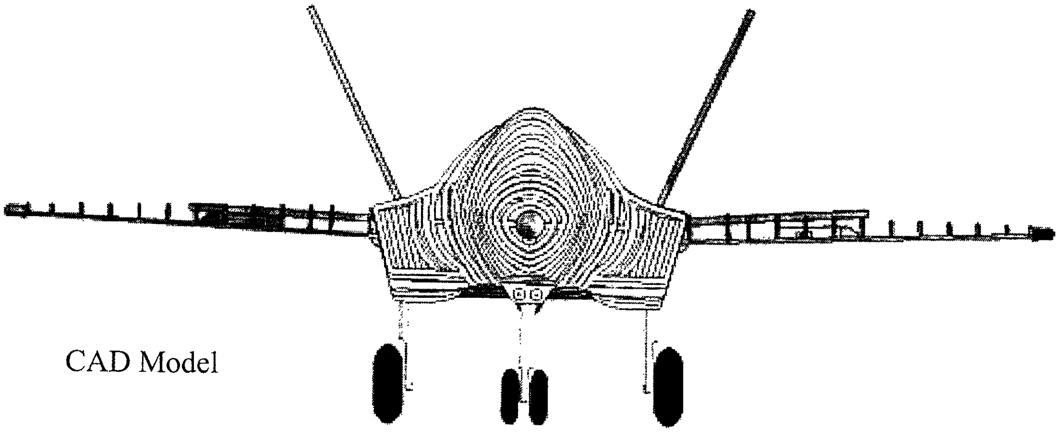


Sheet #10 waterjet tool path design (9 individual pieces)

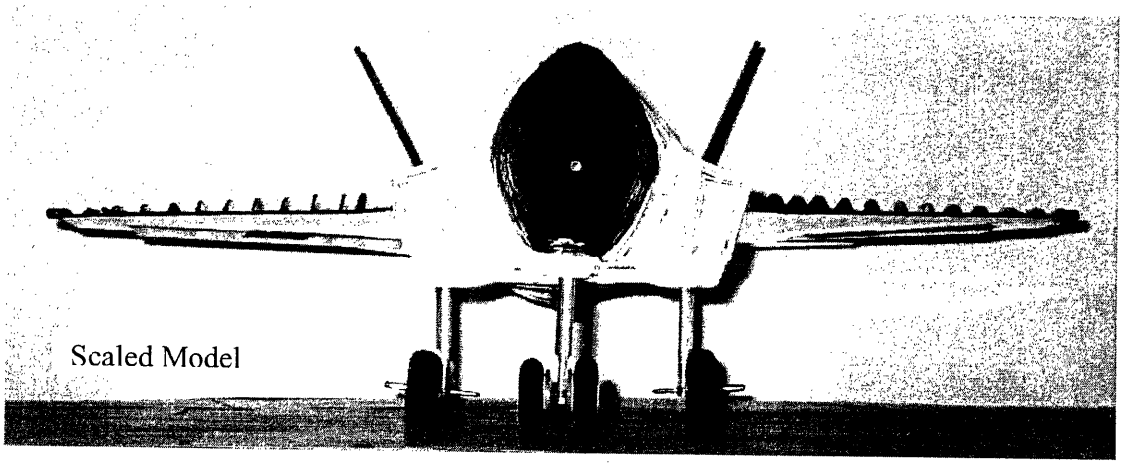
Appendix C: Three-view Comparison of the F-35A



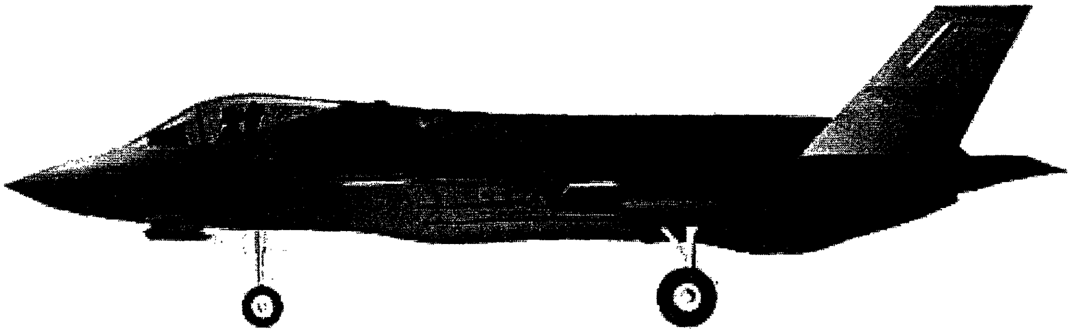
F-35A

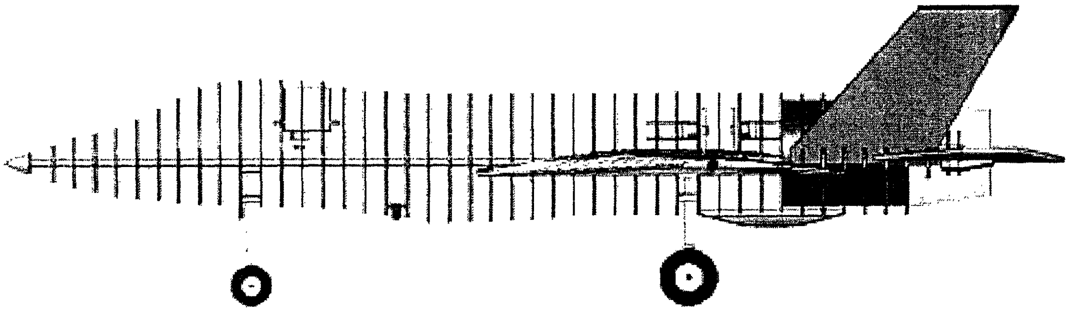


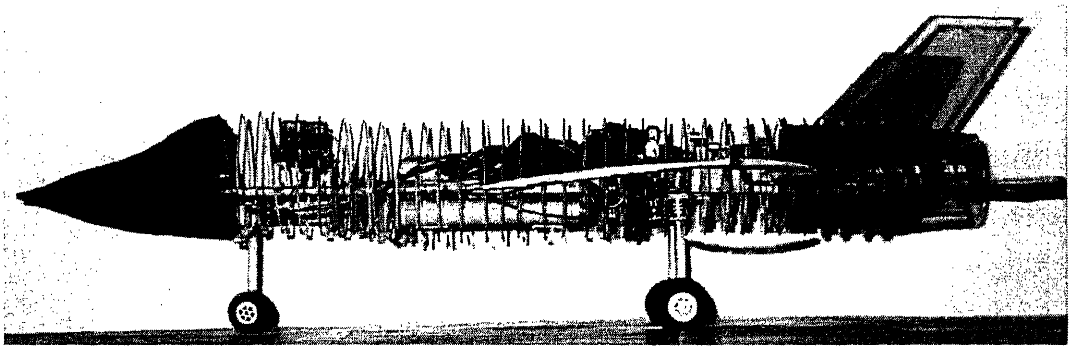
CAD Model

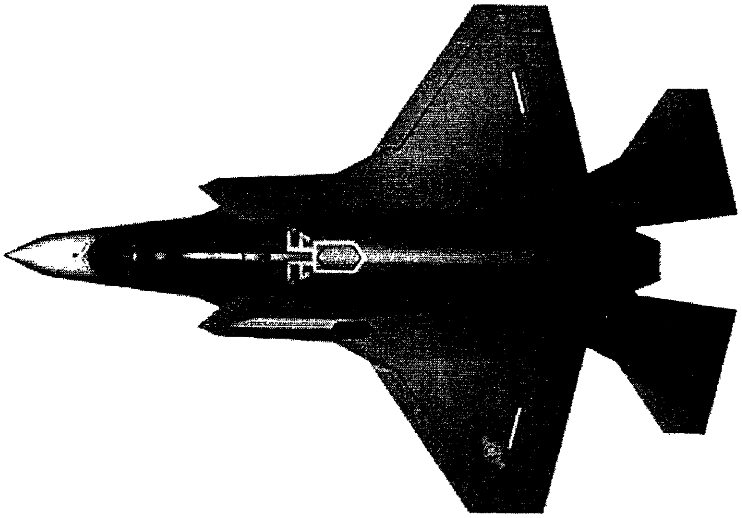


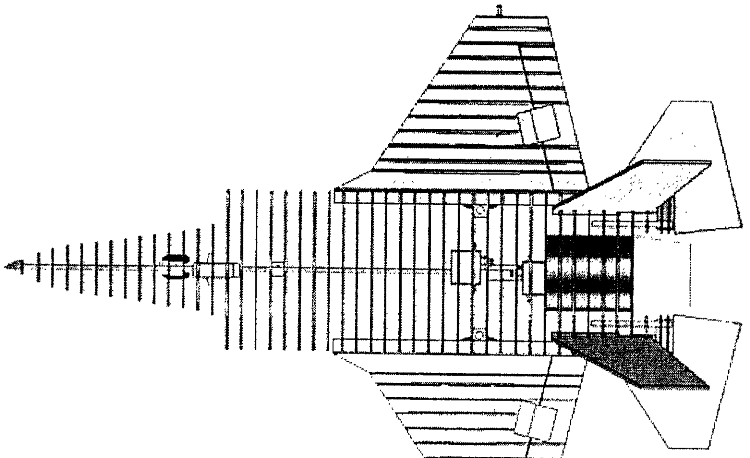
Scaled Model

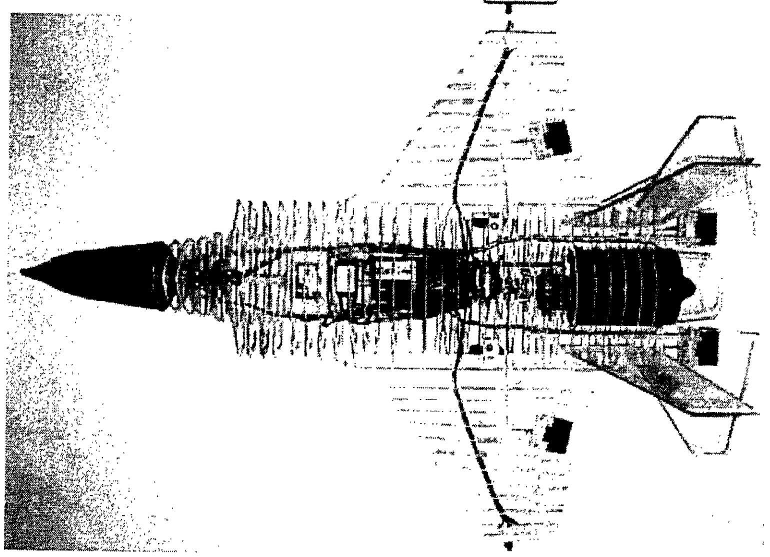












Appendix D: Product Information & Expenses Datasheet

[illegible]	[illegible]	Product	Dimensions (in)	Weight (oz)	Unit Price	Quantity	Cost
Motor	GR3321	Speed 400 6v	1-3/32 dia x 1.5	2.6	$ 9.50	1	$ 9.50
Ducted Fan	VAS400	fan for 400 motor	2.60 OD x 2.95	1.3	$ 69.90	1	$ 69.90
Controller	JE110AW	Jeti 110 Motor Microprocessor	1.03 x 0.75 x 0.24	0.6	$ 35.90	1	$ 35.90
Radio System	HTR971C	4-Channel Radio TX/RX w/ 2 HS-81 servos	1.16 x .47 x 1.02	1.2	$ 139.90	1	$ 139.90
Nosewheel Servo	HS-81	Additional Servo for Nosewheel	1.16 x .47 x 1.02	0.58	$ 18.50	1	$ 18.50
Batteries	FK5503	8 Cell 500AR NiCad with Speed 400 Conn	4-5/8 x 1-3/8 x 11/16	5.6	$ 46.90	1	$ 46.90
Battery Charger	ARK340	Mobile Battery Charger for NiCad Batteries	n/a	n/a	$ 45.90	1	$ 45.90
Actuator Pair	HLBB001	Concealed Actuators for control surfaces	1-1/4L 1-1/8W 1/4T	?	$ 11.50	2	$ 23.00
Flexible Cable	HLH805	20 Feet Flex Cable Pushrod	n/a	?	$ 6.30	1	$ 6.30
Servo Connectors	HLH502	Pushrod Connectors	n/a	?	$ 1.50	1	$ 1.50
Nosewheel	LYT26	1" Wheels pair	1 dia	0.05	$ 2.80	1	$ 2.80
Mainwheels	LYT35	1-3/8" Wheels pair	1-3/8 dia	0.16	$ 3.90	1	$ 3.90
Fuselage skin	HLC608	USAF Aluminum Superkote	72x26	?	$ 8.50	2	$ 17.00
		Shipping & Handling					$ 7.99
						Subtotal	**$ 428.99**
Structural X-Sections	8574K24	Polycarbonate Sheets	12 x 12 x 1/16 T	?	$ 2.88	10	$ 28.80
Frame Supporting Rod	8571K12	Polycarbonate Rod	1/4 dia x 8 feet	?	$ 0.69	8	$ 5.52
		Shipping & Handling					$ 24.00
						Subtotal	**$ 58.32**
White Nav/ Landing Lights	15552	Mega bright white LED	n/a	?	$ 3.50	3	$ 10.50
Beacon Light	1364	Blinking red LED	n/a	?	$ 1.00	1	$ 1.00
Right Wing Nav Light	1299	Standard green LED	n/a	?	$ 0.45	1	$ 0.45
Left Wing Nav Light	1298	Standard red LED	n/a	?	$ 0.45	1	$ 0.45
		Shipping & Handling					$ 2.83
						Subtotal	**$ 15.23**
2 hrs. Waterjet	n/a	Waterjet Cutting time for producing parts	n/a	n/a	$100	2	$ 200.00
						TOTAL	**$ 702.54**

Appendix E: JSF F-35A Solid Model Comparison Wallpaper