45th AIAA Aerospace Sciences Meeting and Exhibit
8 - 11 January 2007, Reno, Nevada

AIAA 2007-244

Mars Intelligent Reconnaissance Aerial and Ground Explorer (MIRAGE)

John Aguirre*, Vanesa Casado† and Norella Chamie‡
University of Miami, Coral Gables, FL, 33124

GeCheng Zha Ph.D§
University of Miami, Coral Gables, FL, 33124

[Abstract] The MIRAGE is a vehicle designed to explore the Martian atmosphere and surface by synergizing the advantages of satellites and ground explorers. Its mission includes scouting sites of scientific interest for future manned exploration. While cruising at an average altitude of 1000 meters above Martian sea level at Mach 0.45, its instrumentation collects atmospheric samples and obtains high resolution measurements and images. MIRAGE will employ the Co-Flow Jet (CFJ) Airfoil, which can achieve extraordinarily high lift, low drag, and high stall margin to deal with the low density and Laminar regime of the Martian atmosphere. Thrust is generated by a propeller which is in turn powered by Hydrogen fuel cells. With a landing gear with wheels derived from the Mars Exploration Rovers, the MIRAGE has the ability to roam on the ground and collect soil samples with a robotic arm equipped with a rock abrasion tool. These samples are further examined by a state-of-the-art instrumentation, including a novel microbe detector that can help establish whether life exists or has existed on Mars. The mission also aims at scouting the Martian surface for sites of interest for future manned exploration.

Nomenclature

S	=	wing surface area
b	=	wingspan
AR	=	aspect ratio
t/c_{max}	=	maximum thickness to chord ratio
S_W	=	whetted wing surface area
Λ_{LE}	=	average leading-edge sweep angle
c_t	=	chord at wing-tip
c_r	=	chord at wing root
mac	=	mean aerodynamic chord
Re	=	Reynolds Number
$C_{L,\alpha}$	=	slope of lift vs. angle of attack curve
$C_{L,0}$	=	coefficient of lift at 0 degrees angle of attack
$C_{L,trim}$	=	coefficient of lift required for trim flight
L/D	=	lift over drag ratio, aerodynamic efficiency
cg	=	center of gravity
ψ	=	turnover angle
M	=	cruise Mach number

* Graduate Student, Department of Aerospace and Mechanical Engineering, AIAA Student Member.
† Undergraduate Student, Department of Aerospace and Mechanical Engineering.
‡ Undergraduate Student, Department of Aerospace and Mechanical Engineering.
§ Associate Professor, Department of Aerospace and Mechanical Engineering, AIAA Member.

I. Introduction

SENDING a manned mission to Mars no longer seems far-fetched as scientific genius strives to obtain sufficient information to guarantee the safety of the crew and the efficient use of financial and technological resources. In order to further the knowledge about our neighboring planet however, it is necessary to improve upon existing aerospace technology. The next step in unmanned Mars exploration calls for a vehicle that synergizes the advantages of both satellites and landers. The MIRAGE is such a vehicle. Designed to take off, land and roam on the Martian surface, the robot cruises at Mach 0.45 on the lower atmosphere to closely examine and capture a vast area. In doing so, it is able to scout for possible landing sites and areas of interest for a future manned expedition, in support of NASA's new Vision for Space Exploration. In order to perform the two critical functions of flying and roaming, the MIRAGE has Vertical Take-off and Landing capability, among other distinctive features. It utilizes a unique propulsion system along with a novel enhanced-lift device in order to optimize aerodynamic performance in the hostile Martian atmosphere. In short, the MIRAGE has the potential to provide a wider range of data and better understanding of the Martian atmosphere and geology than other proposed vehicles.

Flying in the Martian atmosphere is an immense challenge in itself. The atmosphere is composed of over 95.5% Carbon dioxide at a density of 1.5% of the Earth's, which greatly increases the difficulty of sustaining flight. In addition, surface winds in Mars can cause buildup of sand particles on exposed components, leading to mechanical failure. Moreover, the average surface temperature ranges from -30° C at daytime to -130° C at night, which may hinder the performance of some components. On the other hand, the low gravitational acceleration, merely one-third of that of the Earth, is favorable for flight.

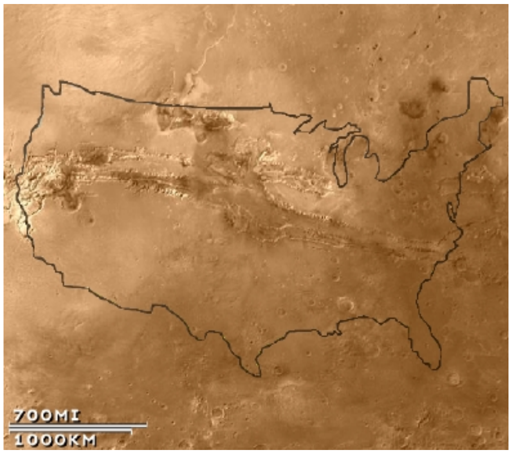

Figure 1. The length of Valles Marineris relative to the U.S.

The MIRAGE is a versatile vehicle that can be configured to perform a variety of missions. It carries enough fuel on board to cruise more than the full width of Valles Marineris, the largest system of canyons in the Solar System, in order to characterize the layered beds that are suspected to have formed due to the existence of large bodies of water. It can carry out three flights lasting 2 hours each. While on land, it will collect soil and atmospheric samples, render images of its surroundings, and perform similar functions to those of the Mars Exploration Rovers.

The features that enable the MIRAGE to efficiently accomplish a variety of missions are now further discussed.

II. Design Features

A. Airframe

Unlike the conventional airframe configuration where the fuselage and the wings are separate structures, the MIRAGE has an airframe where both of these components are incorporated into a single, blended body, as shown in Figure 2. This is referred to as a flying wing configuration. Because the fuselage has the same airfoil cross section as the wings, it acts as an extension to them and produces additional lift. Given that the density of the Martian atmosphere is so low that it becomes difficult to produce enough lift to fly the aircraft, this increase in lift is a highly desirable feature. The MIRAGE's flying wing therefore maximizes lift per unit of surface area due to this added lift generated by the fuselage. As a result, this configuration allows for a reduction in wingspan relative to a conventional airframe configuration. The flying wing is ideal for this application because the aircraft must

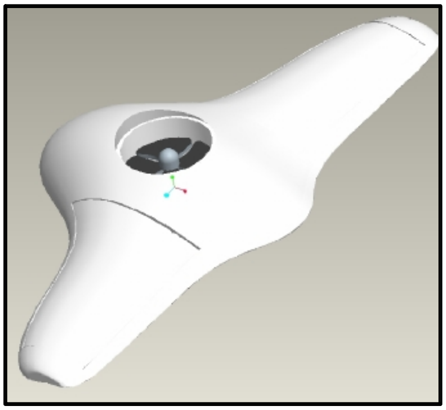
Figure 2. The MIRAGE's flying wing configuration in landing/take-off mode.

be able to fit neatly within an aeroshell of specified dimensions with as few folds as possible.

This flying wing allows the aircraft to fit within a 5 meter diameter aeroshell without the need of multiple folds. This aeroshell is sized to fit within the Delta IV Medium+ rocket payload bay. Most aerial vehicle designs proposed thus far for implementation in Mars, such as the ARES or the AME, require two or more folds in order to fit within an aeroshell, which leads to a higher probability of failure during initial deployment into the atmosphere[1 2].

Another advantage of the flying wing design is that it increases the storage space of the aircraft, especially if a thick airfoil is incorporated as in the case of the MIRAGE. Because of the blending of the wings with the fuselage, volume is added to the wings which can be used to store additional instrumentation and fuel. Consequently, the aircraft's range is also increased by using this configuration due to the increased fuel capacity. The aeroshell being used for this mission is a derivative of that used for the Viking and other similar operations. It has an inner diameter of 5 meters and a total height of 3 m, as can be seen in Figure 3. The MIRAGE has a wing span of 4.8 m in order to fit neatly into this aeroshell. With this wingspan and a root chord of 2.32m, the aircraft reaches a surface area of about 6m^2. These and other design specifications are summarized in Table 1.

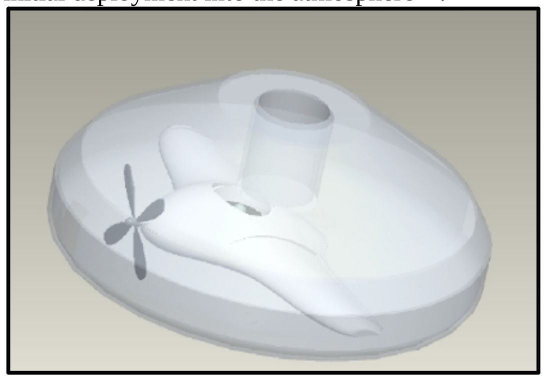

Figure 3. Aeroshell that houses the MIRAGE within the launcher.

S	6	m^2
b	4.8	m
AR	3.84	
t/c_{max}	0.25	
S_W	12.64	m^2
$\overline{\Lambda}_{LE}$	32.6	deg
c_t	0.3	m
c_r	2.32	m
mac	0.4877	m
Re	162,274	Laminar
M	0.45	
Range	1778	km
Endurance	5	hr
L / D	11.56	

Table 1. Selected aircraft parameters.

In order to maintain level flight at a cruise Mach number of 0.45 with the design weight and geometry, a lift coefficient of 0.384 is required. This and the other specifications presented were calculated using mainly the spreadsheets developed by Corke[3].

The airfoil selected for the MIRAGE is the CFJ 11425-065-196, designed by Zha et al.[4] This particular airfoil was selected for its high coefficient of lift, low coefficient of drag, and 25% thickness. Due to its relatively large thickness, this airfoil produces greater lift than an airfoil with a lower t/c ratio, and increases the storage space within the airframe. However, such a thick airfoil also increases the probability of flow separation, leading to stall at high angles of attack, particularly because of the laminar flow regime. This significant challenge, however, is overcome by the introduction of the Co-Flow Jet feature.

The flying wing design of the MIRAGE eliminates the need of a conventional tail structure, which would need to be folded within the aeroshell. Instead, winglets would be located at the wingtips for lateral stability and control. These winglets make use of a symmetric airfoil cross-section. The use of a conventional tail was avoided in order to reduce instabilities introduced during planetary entry. Horizontal stability and control will be provided by elevons with split rudders at the edges, as used in the B-2 aircraft.

When the conceptual design for the wing-body is completed, it is necessary to perform a loading analysis. In order to do so, a distinction was made between the "fuselage" and "wing" sections. The point chosen for this separation was the beginning of the CFJ structure. Everything inwards from this point is considered fuselage for the purposes of the loading analysis. For the wing, the loads acting on the structure consist mainly of the lift distributed along the wing, the drag, the structural weight of the wings itself, as well as fuel stored in it and attachments such as engines. In our case, fuel is stored within the fuselage section and the engine is a propeller at the nose of the aircraft, so these last two sources of loads can be ignored. The main source of loading on the wing will be the lift. Because the wing has a finite aspect ratio, this lift distribution varies along the wingspan. In order to find the lift distribution along the wing, it was assumed that its shape is an average of an elliptical and a trapezoidal wing. This assumption closely follows the true design shape of our wing section. Also, the addition of lift during deflection of the elevons was included in the analysis; it was assumed that they would add 30% to the lift. The wing was then divided into 21 different sections along the wingspan, and the loads on each element were calculated separately. The shear and bending moments are defined by integrals, but because the wing was separated into finite elements, these integrals can be approximated by finite sums. Once all the loads were added for each element, the shear and moment distributions are as follows:

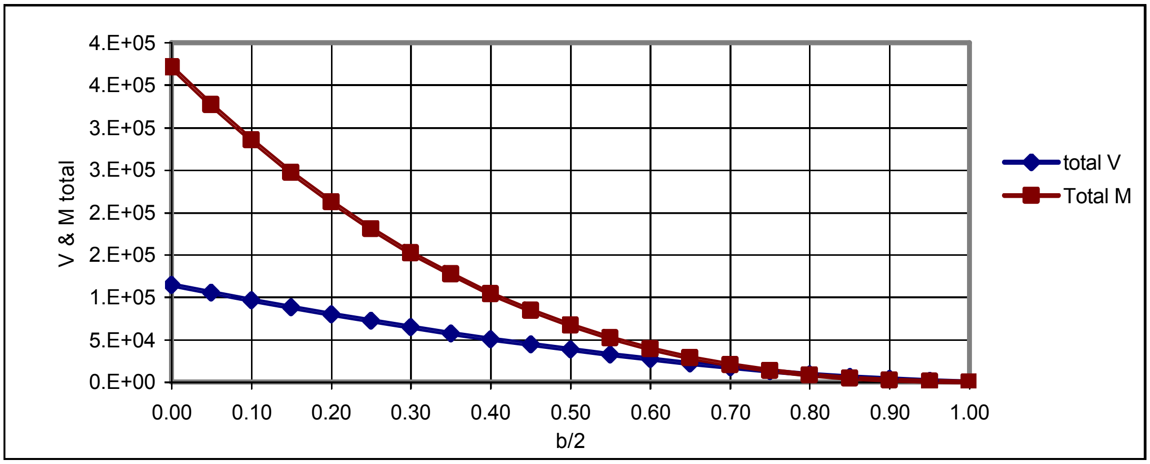

Figure 4: Shear and bending moment distribution along the wing as a function of wingspan

A similar analysis was also performed on the fuselage. The loads contributed by the fuselage structure, the engine (including the fuel cell), wing structure, the fuel and oxidizer and the instrumentation were taken into account. The resulting shear and bending moment diagram is shown in Figure 5.

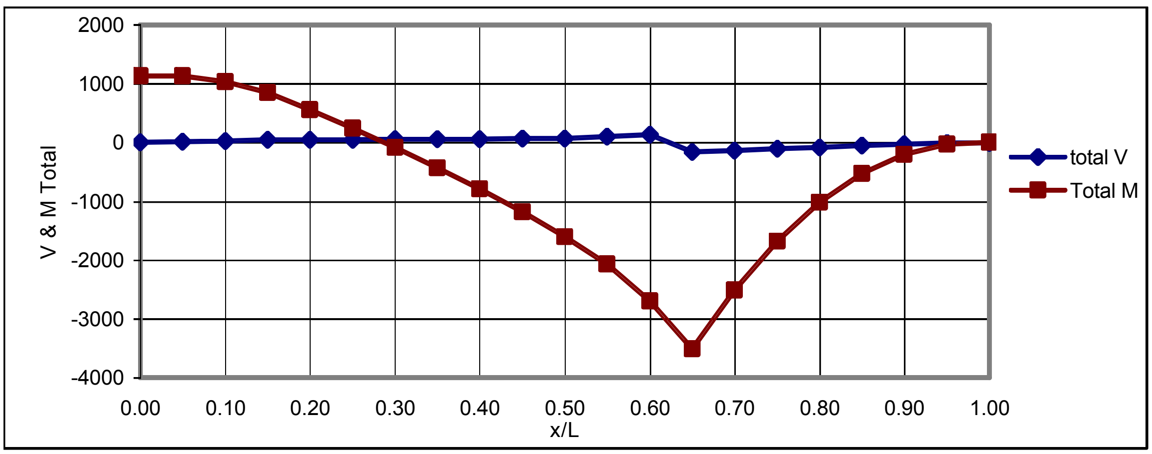

Figure 5: Shear and bending moments acting on the fuselage as function of fractional length.

The reason that the magnitude of the moment at x/L = 0 is not zero, as is usual for conventional aircraft, is because the propeller is placed at the front of the aircraft and contributes a significant amount of moment.

B. Co-Flow Jet (CFJ) Airfoil

Another unique feature of the MIRAGE is the Co-Flow Jet (CFJ) Airfoil, which is integrated into the flying wing design. Computational Fluid Dynamics (CFD) analysis and wind tunnel testing conducted by Zha et al. has proven that the CFJ airfoil can considerably increase stall margin and lift per surface area relative to a baseline airfoil, consequently reducing drag and the overall weight of the vehicle. The CFJ airfoil improves aerodynamic performance by introducing a continuous jet of air tangential to the suction surface. An injection slot is placed at the leading edge of the wing, from where air flow is introduced via a pump located within the wing structure. Wind tunnel testing also indicates that from two airfoils with different size injection slots, the airfoil with smaller injection slot size has better performance[5]. Additionally, a suction slot is made at the trailing edge of the wing to draw in the same amount of flow, thus achieving zero-net-mass-flux flow control. The suction at the trailing edge also reduces flow separation, as shown in Figure 6. The same amount of mass flow that is injected is also sucked in near the trailing edge. The turbulent shear layer between the main flow and the jet causes strong turbulent diffusion and mixing. Due to this mixing, the lateral transport of energy from the jet to the main flow is enhanced, which allows the main flow to overcome severe adverse pressure gradients and maintain attached flow.

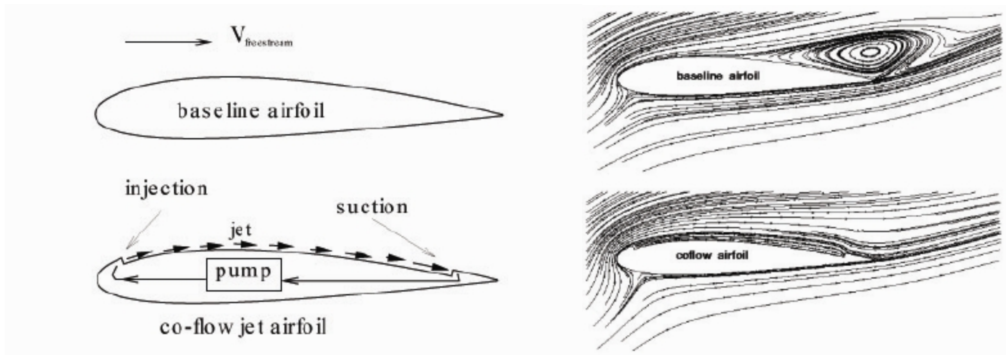

Figure 6: CFJ compared to baseline airfoil with streamlines at high angle of attack.

The resulting flow attachment is highly desirable due to the low Reynolds number experienced during flight in the Martian atmosphere, which induces easier flow separation. Not only does the CFJ airfoil dramatically increase lift, but, as new research shows, it also produces a limited amount of thrust. With powerful enough jets, the CFJ alone might be able to provide enough thrust to propel the vehicle, therefore eliminating the need for a propeller. In a sense, the CFJ could allow for "engineless" propulsion[6]. Our design, however, makes use of a more conservative version of the CFJ system, using it primarily for enhanced lift.

With the capabilities of the CFJ airfoil the overall gross weight of the aircraft at take off can be reduced. Consequently, the amount of fuel needed is decreased. This also provides the opportunity to carry a higher payload.

C. Propulsion

1. Lift Fan

Due to the uneven and rocky terrain of the Martian surface and the absence of an established infrastructure, a lift fan was chosen to achieve vertical take-off and landing (VTOL). The use of a lift fan provides a reliable solution to this gravity for maximum stability during take-off and landing. The lift fan operates only during take-off and landing, while a propeller enables horizontal flight.

A lift fan generates lift by sucking air into the center and forcing it out at the edges when the assembly is rotated at high speed. Lift fans operate efficiently in environments where the backpressure is high. They generally accelerate larger volumes of air for a given rotation speed than a propeller with the same speed and power input. The lift fan is rotated by an electric motor which is, in turn, powered by fuel cells.

The lift fan for the MIRAGE was sized based on the state-of-the-art lift fan designed for the Joint Strike Fighter (JSF)[7]. Based on the parameters available from references, a constant for geometrically similar operation was determined using conventional fan laws. Based on a dimensional analysis, it was then possible to determine the appropriate diameter, power consumption and rotational speed of the

Parameter	JSF	MIRAGE	Units
Density	1.1	0.013	kg/m^3
Mass flowrate	150	36.45	kg/s
Rotational Velocity	13,000	50,000	rpm
Power required	21,630	39.64	kW
Thrust	80	1.7	kN
V_{exit}	533.79	47.0	m/s
Diameter	1.73	0.9	m

Table 2: JSH and MIRAGE Lift fan parameters.

MIRAGE lift fan. Table 2 summarizes the data available for the JSF lift fan and the corresponding specifications for the MIRAGE lift fan.

The greatest challenge posed by a VTOL design is the transition from vertical to horizontal flight. This transition must be seamless and take place at the optimum altitude and velocity. The MIRAGE can achieve such an autonomous level of operation through a fly-by-wire control system such as that developed by Guidestar Technologies for the NASA Mars Flyer Demonstrator[8]. During the transition from horizontal to vertical flight, and vice versa, the total power required does not exceed the power requirements of the lift fan, which allows the entire configuration to operate with a fuel cell stack that generates 45 kW of power.

2. Propeller

The thrust required to overcome the drag and propel the vehicle forward is generated by a four-bladed propeller, located on the nose of the MIRAGE. The propeller is driven by an electric motor, which, in turn, is powered by fuel cells. The drag is small by Earth standards due to the low atmospheric density of the Martian atmosphere. However, this low density of 0.013 kg/m^3 at a cruise altitude of 1000m represents a design challenge because the propeller blades need to be longer than they would be on Earth in order to generate enough thrust to accelerate the vehicle forward.

A propeller generates thrust by accelerating the flow across the disk formed by the rotating propeller blades. The propeller diameter, thrust generated, power required, propulsive efficiency and other propeller specifications were determined using JavaProp, a software code based on blade element theory and the theory of the optimum propeller developed by the aerodynamicists Betz, Prandtl and Glauert[9]. JavaProp allows for both on-design and off-design analysis. Initially, different performance indicators were evaluated at off-design conditions in order to determine the optimum design point. After some iteration, the optimum diameter of 1.40m was established based on performance and geometric constraints posed by the landing gear.

The airfoil selected was the Clark Y airfoil, illustrated Figure 9 for its high aerodynamic performance. Its relatively low thickness of 11.7% of the chord is desirable in order to delay flow separation due to the laminar flow regime experienced during Martian flight.

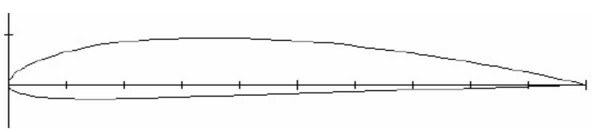

Figure 7: 11.7% Thickness Clark Y airfoil

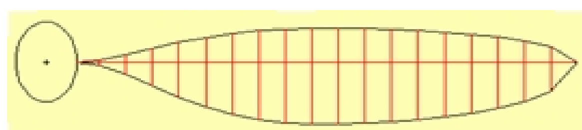

Figure 8: Propeller blade planform view

The blades are twisted from an 8° angle of attack at the root to 5° at the blade tip in order to account for the increasing resultant velocity from root to tip and thus maintain a constant loading on the blades.

The propeller blades are made of graphite-epoxy, a strong but lightweight polymer-carbon fiber composite which has been developed for aerospace applications. With a density of 1600 kg/m^3, the combined mass of the propeller blades is 15.55 kg. The hub and shaft are made of 8090 T3 Aluminum alloy.

Propeller performance was characterized from the propeller efficiency, the thrust generated and the power required. The efficiency was found to be 66.77%, the generated thrust was 112.77 N and the power required was 29.41 kW. For comparison, the total drag on the aircraft was found to be approximately 83.7 N. Efficiency was hindered by reducing the propeller diameter. For instance, for a two-meter-diameter propeller, the efficiency can be as high as 75%. However, having longer blades implies having to fold them in order to be able to fit in the aeroshell. This, in turn, increases the probability of mechanical failure. The thrust generated is enough to overcome drag and accelerate the vehicle to a cruise velocity of 109.75m/s or Mach 0.45. The power required is close to 20 kW, which is attainable through the use of fuel cells.

D. Landing Gear

One of the features that make MIRAGE a unique flying robot is its additional capability to roam on the Martian surface. In general, the landing gear is one of the more fundamental and essential components of the overall aircraft design. The design and integration must take into consideration factors such as structures, weights, and ground conditions. The weight of the landing gear is typically within the three to six percent range of the maximum aircraft take-off weight. To integrate the MIRAGE landing gear, special consideration is placed on the mobility and wheel material selection in order to overcome the obstacles posed by the rocky Martian terrain.

MIRAGE incorporates a wheel design derived from the Mars Exploration Rovers[10] (MER). Since the aircraft will be able to take off and land vertically, the wheels function to support the maximum aircraft take-off load and minimal dynamic loading while a particular nearby site of interest is scoped. One of the features shared with the MER, is the spiral flecture pattern in the caps, which connect with the spoke inside the wheel. The spiral flecture pattern absorbs the shocks imposed on the wheels by the rough, rocky terrain and prevents the shocks from transferring to the rest of the aircraft. Meanwhile, inside is an open-cell foam filling, known as solimide, which blocks any rock or debris from damaging the structure inside the wheel. The filling is ideal for Mars applications because it can sustain its form under extremely low temperatures. The wheels are also equipped with stainless steel cleats in order to tract through the soft sand and climb over small rocks and are anodized for surface protection.

Figure 9. MER Wheel design

Another important characteristic of the wheel design is determining the necessary wheel size. The primary consideration for the sizing of the wheels is the supporting load capacity. Thus, in order to obtain the appropriate wheel sizing, the static loading case was first analyzed with the formulations from Landing Gear Integration in Aircraft Conceptual Design by Chai and Mason[11]. By setting the main gear to support 90% of the total aircraft weight, and once the center of gravity (cg) of the airplane is defined, the nose and main landing gear positions relative to the center of gravity were calculated. The results are a nose gear distance of 70 cm in front of the cg and a main gear distance 7.78 cm aft of the cg.

The wheel sizing is first performed statistically by using the empirical formulations found in Design of Aircraft by Corke[1]. Afterwards, the size is rechecked with a Sport Aviation landing gear spreadsheet for light aircraft design and integration[12]. The spreadsheet is based on methods presented in Design of Light Aircraft by Hiscocks[13], The Landing Gear by Rawdon[14] and Analysis and Design of Flight Vehicle Structures by Bruhn[15]. The best result for the wheel diameter is 15.24cm, which is approximately equal to one-fourth of the fuselage height. The total main gear span is equal to 101.6cm.

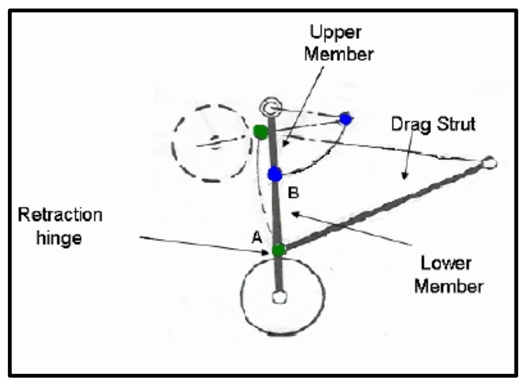

Figure 10: Kinematics of retraction.

Moreover, the spreadsheet considers the energy that must be absorbed by the landing gear system in order to support the aircraft take-off mass of 433.02 kg. In the spreadsheet results for the wheel sizing exceeds the requirements for a combined margin of safety of at least 0.5 for the energy conditions. The maximum vertical landing speed for the limit energy and reserve energy are 2.13 m/s and 2.44 m/s respectively.

Ultimately, the best landing gear material selection is Aluminum 8090 T3, which has a tensile strength and elastic modulus equal to 480 MPa and 77 GPa respectively. From the material density, which is 2.55 g/cm^3, and by calculating the volume of each landing gear part the total landing gear weight result is 12.2 kg.

The positioning of the wheels is determined by considering the requirements of the aircraft geometry, weight, and mission requirements. The vertical take-off and landing capability of the MIRAGE allows for flexibility when choosing the number of wheels. Other considerations such as stability, geometry and weight ultimately lead to the nose-wheel tricycle configuration, which is preferred for its improved stability during the airplane take off and taxiing phases.

Following the positioning of the wheels and given the weight and center of gravity, rolling stability considerations during taxiing, liftoff, and touchdown can be calculated. The roll angle is the angle at which the tip of the wings will touch the ground and the result is a maximum angle of 8.78 degrees from the ground. In order to prevent the unpredictable Martian winds from turning over the aircraft, the turnover

Figure 11: Landing Gear CAD Model

angle (ψ) has to be as small as possible. The maximum allowable overturn angle is 63 degrees for land-based aircraft. With the given total gear span of 101.6 cm, the turnover angle for the MIRAGE undercarriage is equal to 60.36 degrees.

The landing gear is stored by means of an actuated retraction mechanism equipped with the common oleo-pneumatic strut shock absorber. The oleo-pneumatic shock absorber has among the highest energy dissipating efficiency currently in the aircraft industry. Although, not typically found in light aircraft, a thorough analysis for its integration is carried out in the Oleo-Pneumatic Shock Absorber Design for Light Aircraft by Usmani and Thong[16].

The main and nose landing gears are traditionally and simply hinged for retraction. The main gear and the nose gear is first folded, due to the limited space, and afterwards retracted frontward. The Figure 12 displays the kinematics and how the retraction is achieved. The net result is a forward folding retraction, which is the most ideal situation. An aft retraction mechanism will not free-fall to the ground due to the opposing air force stream and requires more work. In case of an emergency a forward retraction saves work and energy. Figure 13 shows the three dimensional rendering of the nose and main landing gear in the Pro-Engineering CAD program.

E. Power Generation

One of the greatest obstacles in the design of a Mars Flying Robot is to generate enough power to drive all of its systems. This method of power generation should produce enough power for the propulsion system, the CFJ airfoil, the instrumentation used to collect data, a data transmitting system, landing gear extension and retraction and several other applications. As the best alternative, the MIRAGE is powered by a Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM) type fuel cell. The fuel cells will be required to produce an output load of 40 kW.

Fuel cells are more efficient since the fuel cell stack does not contain moving parts, which reduces the risk of mechanical breakdown and significantly increases energy efficiency. Some other favorable characteristics for transportation and space applications include compact size and lack of volatility. The Membrane Electrode Assembly of modern fuel cells is approximately 2.5 millimeters in thickness. The cells are connected in series with a plate containing channels for the reactants and channels to remove the water produced. As long as they are supplied with the liquid hydrogen fuel and liquid oxygen oxidizer, the PEM fuel cells function continuously. This capability also reduces the amount of power backup supplies that would need to be carried onboard the MIRAGE.

PEM fuel cells have a performance advantage of delivering high power density with a lower weight and volume than other fuel cell types. Furthermore, the PEM fuel cell was chosen since it can operate at relatively lower temperatures, an indispensable capability in order to generate power in the cold Martian atmosphere. The PEM fuel cells operate at approximately eighty degrees Celsius compared to other types of fuel cells, which operate at more than 1000 degrees Celsius. Since the temperature in mars ranges from -30 to 130 degrees Celsius, any additional heating could be provided by a relatively small heat exchanger powered by batteries. PEM fuel cells can reach the correct operating temperature quickly and thus, are able to respond rapidly to varying loads. Working in low temperature allows the fuel cell to start up more rapidly resulting in less wear and consequently, a longer life span of the system components. Furthermore, sufficient hydrogen and oxygen are supplied from storage tanks to reach the goal of three flights at one and a half hour duration each.

The material selection for the proton electrolyte membrane is a perfluorosulfonic acid polymer film. Nafion 117, transparent polymer film, is commonly used as the PEM membrane material and it is manufactured by DuPont. The material for the catalyst layer is made from a mixture of platinum, carbon powder, and PEM powder which is bonded to a conductive carbon fiber cloth. A hydrogen humidifying bubbler is used to prevent the fuel cell from dehydrating under the loading conditions. Moisture management is a crucial task for maintaining the effective productivity of the fuel cell system. On the hydrogen anode electrode, the PEM must be kept damp in order to prevent crack formations, circuit shorts or leaks. On the oxygen cathode electrode, the water produced is removed so the catalyst is not soaked and lacking enough oxygen.

After comparing the various technologies available, the lightweight, high power density fuel cell stack by Advanced Power Sources Ltd[17] is ultimately the most suitable to use in our applications. The stack has an operating temperature of 60°C and an operating pressure of 200 kPa. The performance characteristics include a power density of 2.08 kW/L a specific density of 1.41 kW/kg and a calculated volume of 0.032 cubic meters.

.

F. Scientific Instrumentaion

In order to accomplish its scientific mission, the MIRAGE incorporates an instrumentation package that has proven reliable and successful, namely, a derivative of the Athena science payload[18] currently functioning on the two Mars Exploration Rovers. Among the instruments included are:

- A Mössbauer spectrometer: It was designed to study minerals that contain iron, such as FeO (rust) and hematite, common on the Martian surface. It can determine the composition and abundance of iron-bearing minerals to a high degree of accuracy.
- A Robotic Arm with a Rock Abrasion Tool (RAT): The RAT is a tool that can create a hole 45 mm in diameter and up to 5 mm deep into rocks. A rotating brush sweeps dust away from the hole. The dust is then analyzed by the spectrometers. The robotic arm is fully deployable and maneuverable and contains other instruments within its assembly.
- A Microscopic Imager: This miniature camera is held by the robotic arm very close to the surface of rocks or soils to take black-and-white pictures of features as small as 1/10 of a millimeter across.
- An Alpha Particle X-Ray Spectrometer (APXS): It detects alpha particles and x-rays emitted by rocks and soils in order to detect the chemical composition of the sample.

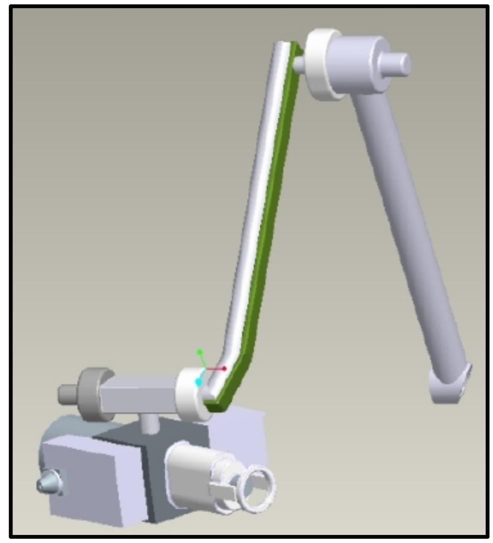

Figure 12. CAD model of Robotic arm with RAT and other instrumentation

The MIRAGE will also be the first system to integrate the AMASE Microbe Detector[19], a state-of-the-art tool that will analyze samples and detect indications of the presence of any life forms on Mars. Other standard instrumentation includes a stereo camera and an infrared spectrometer, used to assess the immediate territory, and antennas, which will transmit the data to the orbiter or relay satellite.

III. Weight Estimation

One of the first steps of the design process was a rough weight estimation based on basic preliminary calculations and historical data. Later in the design process, this calculation was refined as more design parameters were finalized. During preliminary design, it had been decided that in order to minimize weight, the main structure of the aircraft would be composed of an advanced composite material, graphite-epoxy. This material has a low density and a relatively high strength, making it ideal for aerospace applications. Conventional commercial aircraft are mostly composed of aluminum while more advanced fighter jets, such as the F-35 Joint-Strike Fighter, where costs are less of an issue, the structures are composed mostly of composite materials. These materials are expensive, but in applications such as space exploration, the costs of launch and transit far outweigh spacecraft material costs.

In order to quantify the advantages of using graphite-epoxy over metals in the construction of the aircraft, weight estimations were conducted separately for the cases of an airframe composed of graphite-epoxy and a generic alloy of aluminum. Instrumentation, fuel cell, and propeller weights were estimated based on historical data. This historical data was primarily taken form programs such as the NASA ARES aircraft and the NASA Ames AME aircraft[1 2]. For graphite-epoxy a density of 1600 kg/m^3 was used, and for aluminum a density of 2800 kg/m^3 was used. By using these rough methods, a preliminary mass of 283 kg was calculated when using aluminum and a mass of 199 kg when using graphite-epoxy. This means that by using graphite-epoxy, a weight reduction of nearly 30% was achieved. Clearly, the benefits of using graphite-epoxy instead of aluminum far outweigh the high costs, particularly in an application where costs are already expected to run very high.

When the conceptual design process was near completion, a more detailed weight calculation was then made. It was expected that the weight would be significantly increased from the preliminary calculation due to the addition of additional features such as the lift fan, the inclusion of the landing gear and fuel in the weight calculation, and the introduction of an aluminum inner structure. Once the 3-D modeling was completed by using Pro/Engineer Wildfire, it was possible to exactly calculate the aircraft's whetted surface area. This was calculated to be 13.28 m^2. Using a more accurate density of 1550 kg/m^3 for graphite-epoxy, mass of 30.88 kg was calculated for the aircraft skin. The skin thickness was estimated to be 1.5 mm based on the fact that the minimum skin thickness for a high-speed transport aircraft on Earth is 1.5 mm, because this is not a high speed aircraft, a skin thickness of 1.5 mm is therefore an acceptable assumption.

Once the design of the rib and spar support structure of the aircraft was completed, it was then possible to calculate its exact volume with the use of the model mass properties calculation capabilities of Pro/Engineer. The material chosen for the airframe structural support was aluminum 8090-T3, which is an alloy containing Lithium, Zirconium, Copper, and Magnesium in small concentrations. This alloy was developed specifically for aerospace applications due to its very low density of only 2541 kg/m^3. The low density leads to a very low weight, even for Aluminum. Using these values, a mass of 100.73 kg was calculated for the airframe structural support.

The weight of the fuel cell was simple to find once several parameters about it were known. The fuel cell chosen for this design achieved a specific power of 2.08 kW/kg and a power density of 1.41 kW/L. Knowing this, it is possible to calculate the mass of the fuel cell. The weight calculations for the liquid Hydrogen (LH2) fuel were more involved. One must take into account not only the weight of the fuel itself, but also the weight of the fuel container, including the insulation it is covered with. Because LH2 must be kept at cryogenic temperatures (some 30 K), and at high pressures (200 kPa), the storage tank must be a double-hulled, vacuum sealed, and highly insulated in order to keep the LH2 at such conditions. Because of these considerations, the LH2 storage tanks are generally very robust. The most advanced tanks available have a 17% weight percent of the fuel itself. Taking all these facts into consideration, a weight estimate can be arrived at.

We know from previous analysis that the system requires roughly 36 kW of power during cruise, so, assuming that the aircraft will need to cruise for a total of 5 hours, the work done can be calculated to be 180 kWh. This assumption is exaggerated in order to accommodate for the power that will be taken up not just by the propulsion system, but also by the CFJ pumps and instrumentation. The mass of the LH2 fuel needed for operation can be obtained because we know that the gravimetric density for LH2 is 5.57 kWh/kg, which is a property of the substance.

It is now possible and rather simple to calculate the mass of the fuel tank with insulation. The fuel tank is assumed to weigh 17% of the fuel, as is the case with advanced LH2 tanks constructed of composite materials. With these calculations, we arrive at a total fuel system mass of about 37.81 kg, which is a relatively small number due to the low weight of Hydrogen.

Now that a mass analysis has been completed for the LH2 fuel, it is necessary to do the same with the LOX (liquid oxygen) oxidizer. Fuel cells work under strict electrochemical processes. It is known exactly how many hydrogen molecules are needed to create a certain current since each hydrogen molecule will contribute exactly one electron. Therefore, for every two Hydrogen atoms consumed in the reaction, only one Oxygen atom is consumed. We know that the number of moles of Oxygen must be exactly one half of the number of moles of Hydrogen. The mass of the liquid Oxygen was calculated at 256 kg. It is important to note that even though only half the number of moles of Oxygen are used than Hydrogen, the Oxygen still weighs nearly eight times more than the Hydrogen. This is due to the fact that a hydrogen atom has sixteen times the mass of a Hydrogen atom, which is the lightest of all the elements. For this reason, the effective range of our aircraft is limited to how much oxidizer we can carry. It is possible that some day in the future, Oxygen can be recovered directly from the Carbon dioxide which makes up 95% of the Martian atmosphere, which would dramatically reduce weight and therefore increase range. However, while such systems have been proposed which use electrolysis cells utilizing yttria-stabilized zirconia to separate CO_2 into Carbon monoxide and O_2, they have never been tested nor proven effective. For this reason, such systems were not considered in our design.

The mass of the propulsion system was calculated by separating it into shafts and blades. All shafts are to be constructed of Aluminum 8090-T3 and all blades of a graphite-epoxy composite material. By measuring the volumes of these two subsystems, it was then possible to calculate the total mass of the propulsion system to be 15.55 kg.

IV. Structural Analysis

In order to support all of the loads of the aircraft, it is necessary for the aircraft to have a supporting structure of ribs and spars. These structures must be able to support the weight and loads of the aircraft without excessive bending, fatigue, or any failure. While a composite material like graphite-epoxy is desirable because of its very low density, it is a material which can only support limited amounts of loads in a give direction due to its fiber matrix construction. For this reason, Aluminum was chosen as the main structural material. Aluminum is light-weight, yet very strong. One of the most optimum Aluminum alloys for aerospace applications at the moment is the 8090-T3 Aluminum-Lithium alloy already mentioned. It was developed to be damage-tolerant and has about 10% lower density and 11% higher modulus than 2024 and 2014, which are two commonly used aluminum alloys in aircraft. It was designed for applications where damage tolerance and the lowest possible density are of critical importance, as they are in the Mars environment. Of particular importance, 8090 alloy has a higher strength and toughness than other conventional Aluminum alloys at low temperatures. Because the temperatures in Mars can range from -30 ºC at day to -130 ºC at night, this is a highly desirable trait.

The internal structure which was designed for the MIRAGE consists of six ribs, three located on each wing. These ribs were placed such that they provide proper structural support, while still interfering as little as possible with the CFJ enhanced lift apparatus which is one of the main mission features. There is also a pair of spars which run the span of the wings. These spars have an I-beam cross section for maximum support. The ribs and spars have piercings at strategic points which allow for the flow of air for the CFJ apparatus, and for the passage of ducts, wiring, and other instrumentation. Figure 15 shows the 3-D model of the internal structure for the MIRAGE.

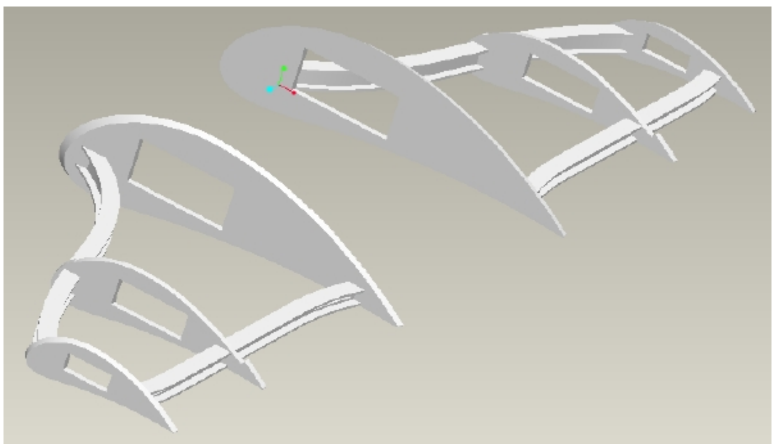

Figure 13: Internal structural support of the MIRAGE

V. Conclusion

Due to the uneven and rocky terrain, the MIRAGE has vertical take-off and landing capability by way of a lift fan. In addition, thrust is generated by a propeller of 1.40m diameter. Both propulsion systems are powered by hydrogen fuel cells, which are energy efficient and highly reliable. The MIRAGE incorporates a Co-Flow Jet (CFJ) airfoil of 25% thickness integrated into a blended wing-body airframe made of graphite-epoxy. Designed by Dr. GeCheng Zha[4], the CFJ airfoil improves aerodynamic efficiency by maintaining flow attached at high angles of attack, significantly increasing lift. The MIRAGE has a wingspan of 4.8m, a surface area of 6m^2, and an aspect ratio of 3.84. Its gross mass, including the scientific payload and fuel is of 490 kg. On Mars, this corresponds to a weight of 1839 N.

The MIRAGE has the capacity to take off, land and roam on the Martian surface, and to cruise on the lower Martian atmosphere with high aerodynamic performance. The Co-Flow Jet Airfoil, propeller, Hydrogen fuel cells, and lift fan constitute a technologically advanced and efficient propulsion system. In addition, the blended-wing body with the incorporation of the CFJ airfoil produces the desired lift. Together, these systems comprise the optimum configuration that accounts for the advantages and disadvantages posed by Martian environment, and allows for the fundamental mission of efficient Mars exploration to be accomplished. This innovative aircraft promises to gather valuable information about our neighboring planet, endowing the scientific community with a solid foundation for future manned exploration.

References

[1] Hall, D. W., Tsai, K. C., Galbraith, D. And Parks, R. W., Airplane for Mars Exploration: Conceptual Design of the Full-Scale Vehicle Propulsion System Concept, NASA/Ames Research Center, 94035-1099, 1997.

[2] Hall, D. W., Parks, R. W. and Morris, S., Airplane for Mars Exploration: Conceptual Design of the Full-Scale Vehicle; Design, Construction and Test of Performance and Deployment Models, NASA/Ames Research Center, 94035-1099, 1997.

[3] Corke, Thomas C., Design of Aircraft; Prentice Hall, 2003.

[4] Zha, G.-C., Bruce F. Carroll, Paxton, C., Clark A. Conley and Adam Wells, High Performance Airfoil Using Co-Flow Jet Flow Control, AIAA Paper 2005-1260, AIAA the 43rd Aerospace Sciences Meeting and Exhibit Conference, Jan. 10-13, 2005, Reno, NV.

[5] Zha, G.-C and Paxton, C. and Conley, A. and Wells, A. and Carroll, B. "Effect of Injection Slot Size on High Performance Co-Flow Jet Airfoil" to appear in AIAA Journal of Aircraft

[6] Aguirre, J., Wang, B-Y., Zha, G-C., Design and Study of Engineless Airplane Using Co-Flow Jet Airfoil, submitted to 25th AIAA Applied Aerodynamics Conference, 2006.

[7] Joint Strike Fighter Literature

[8] Athena Technologies, Inc ; http://www.airforce-technology.com/contractors/flight/athena/

[9] www.mh-aerotools.de/airfoils/javaprop.htm

[10] National Aeronautics and Space Administration Mars Exploration Rover Mission

[11] Chai, Sonny T. and Mason, William H., Landing Gear Integration in Aircraft Conceptual Design, Multidisciplinary Analysis and Design Center for Advanced Vehicles, Virginia Polytechnic Institute and State University NASA National Technical Information Service, 1997

[12] www.eaa.org/benefits/sportaviation/S409-LandingGearDesign.xls

[13] Hiscocks, R. D., Design of Light Aircraft, http://www.ee.ryerson.ca/~phiscock/aircraft.html, 1999.

[14] Rawdon, H., The Landing Gear

[15] Bruhn, E. F., Analysis and Design of Flight Vehicle Structures, Jacobs Pub, 1973.

[16] Wsay Usmani, M. A. and Thong G. K., Oleo-Pneumatic Shock Absorber Design for Light Aircraft, University of Putra Malaysia

[17] Davies, D. P. and Adcock, P. L., Lightweight, High Power Density Fuel Cell Stack, DTI/Pub URN 02/643, Advanced Power Sourced Ltd. for DTI Sustainable Energy Programmes, Crown Copyright 2002.

[18] Athena Science Payload

[19] AMASE - ilewg.lpi.usra.edu/meetings/lpsc2005/pdf/2173.pdf