

Lunar and Planetary Surface Landing Research Vehicle (LPSLRV)



*Design and Testing of a Terrestrial
Based Reduced Gravity Landing
Research and Training Vehicle*

A Technical paper submitted to the NASA Exploration Systems Mission Directorate (ESMD) Higher Education Project for consideration by the 2010 Space Grant Systems Engineering Paper Competition Committee



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Project Introduction

Human and robotic missions beyond low earth orbit (LEO) are key components of NASA's currently emerging strategy for space exploration. These missions will inevitably include human-crewed lunar and planetary surface landings. Trips to near-earth asteroids are also in the incipient planning stages. A permanent presence on the surface of an extra terrestrial body like Mars or the Moon will require many landings by both human-crewed and robotic spacecraft.

Planetary and lunar surface landings are inherently dangerous undertakings, and successful landings are indeed rare events. Since the end of the Apollo era with the completion of the Apollo 17 mission in December 1972, only five successful soft-landings have been achieved on the lunar surface, with the last landing being Luna 24 in 1976. During that same period there have been only six successful Martian surface landings with nearly as many failures. Although surface geology was a secondary consideration in selecting the Apollo landing sites, a primary consideration was crew safety and mission success. Thus all of the Apollo landing sites occurred in a narrow equatorial strip, near the lunar basaltic plains or "Maria." These landing sites were mostly free of significant surface hazards. Martian surface landing sites have been selected for similar benign surface terrain characteristics.

With a long term human extra-terrestrial surface presence, scientific objectives will become increasingly more important, and the landing site terrain will become increasingly more diverse. Correspondingly, as these surface landing sites become more "interesting," they will also become more hazardous. Thus, the development of a research and testing platforms allowing "pin-point" autonomous landing systems to be evaluated, refined, and matured is essential. Only a free flying-platform can develop surface landing technologies to a sufficient technology readiness level (TRL) to be considered for ultra-expensive, extra-terrestrial missions. Additionally, as was demonstrated during the Apollo era, the development of a flying human-pilot training vehicle for extra-terrestrial surface landings will become a long-term exploration necessity.

Background

Powered landings on the lunar surface presented several difficult challenges to the astronauts with regard to situational awareness and visual cues. Because of the lack of atmosphere, the surface lighting was particularly difficult, and astronauts had little or no ability to see into areas that were enveloped in surface shadows. To train astronauts to deal with this lighting effect, special facilities like the NASA Langley Lunar Landing Training Facility (LLTF) that used severe lighting and night training were constructed.¹

Even more significantly, because of the $1/6^{\text{th}}$ -g lunar environment (compared to a 1-g terrestrial environment), the physical orientation of the lunar module required an extreme pitch angle for a given amount of horizontal acceleration. Figure 1 demonstrates this g-effect on pitch attitude.² Because a vehicle in $1/6^{\text{th}}$ g requires only a fraction of the vertical thrust component required to hold altitude as a terrestrial-based vehicle, the required pitch angle for a given amount of horizontal acceleration is significantly greater. A pitch angle of 5° on earth is equivalent to 28° on the moon.

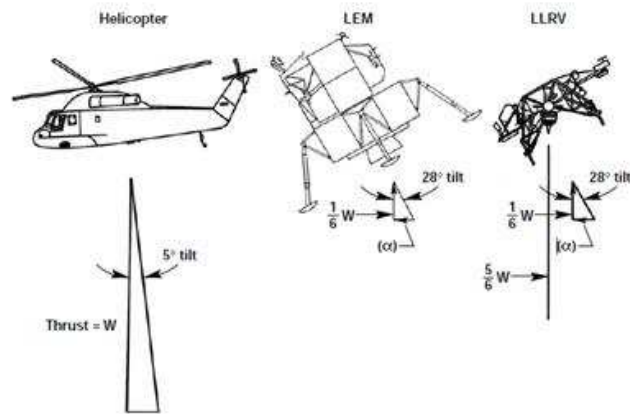


Figure 1. Pitch Angles required by terrestrial and lunar vehicles to obtain same horizontal thrust

It was believed that this significant difference in visual cues would be very disorienting to the astronauts; thus, several methods to train them to anticipate this effect were developed. The previously described LLTF modeled the $1/6^{\text{th}}$ -g environment using a complex series of mechanical pulleys and cables. While providing a good visual simulation of the landing environment, the LTF never successfully produced the required fidelity, and duplicating the piloting “feel” was significantly artificial.³

A more risky, but higher fidelity free-flying vehicle designed to simulate the $1/6^{\text{th}}$ -g lunar environment was developed at the NASA Flight research center (later to become DFRC). This vehicle, the Lunar Landing Research Vehicle (LLRV), used a single General Electric CF700-2V jet engine mounted on a gimbal. The engine was hydraulically driven to point in the vertical direction, and thrust was adjusted to offset the $5/6^{\text{th}}$ of the vehicle weight. Hydrogen peroxide thrusters were used to maneuver an outer platform. Collectively, these apparatus presented an accurate simulation of the lunar landing event to the pilots. Figure 2 shows the LLRV used as the original development platform on the tarmac at FRC. The jet engine, pilot cabin and maneuvering thrusters are clearly visible.

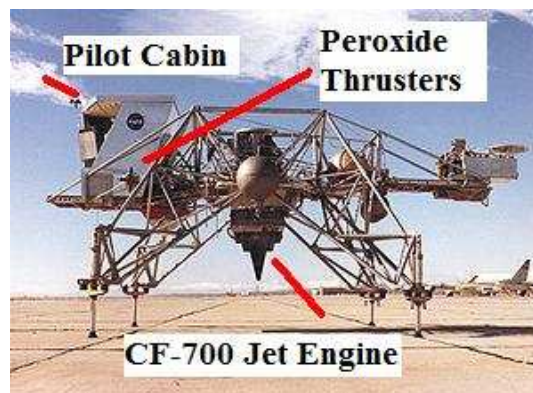


Figure 2. The Lunar Landing Research Vehicle

The LRV, once developed, was adapted for pilot training and five Lunar Landing Training Vehicles (LLTV) were delivered to NASA Johnson Space Center (JSC) for crew training. The LLTV was a difficult vehicle to fly, and the analog control systems available at the time were insufficient to control the vehicle under all flight conditions including cross winds. Three of the five original vehicles were crashed before the end of the Apollo program. Emergency ejection and parachute systems prevented any significant injury to the pilots. There were also issues with hydrogen peroxide leaking from the thrusters' fuel tanks and burning the pilot's skin. Despite the sizeable risks involved in flying the LLTV, seven of the nine astronauts who trained for lunar landings using the LLTV testified that the vehicle was a key enabler for the lunar landing missions.⁴

Project Purpose

This project seeks to design and build a free flying research vehicle that reproduces many of the capabilities demonstrated by the 1960s-era Lunar Landing Research and Training Vehicles (LLRV/LLTV). The LLRV was used to develop lunar landing control-system technologies and surface landing strategies. The LLTV was later used to train Apollo astronauts for the actual lunar surface landings. The approach for this project is – whenever possible – to replace 1960s-era analog designs with proven and reliable modern digital computer-aided technologies. This sub-scale (~1/10th full scale) vehicle simulates the reduced-gravity (i.e., lunar or planetary surface environment) using a vertically-thrusting jet engine to partially offset the vehicle weight. Although this vehicle will be remotely piloted, the design is intended as a scalable configuration. The design only uses technologies that can potentially be scaled to a size capable of carrying a human crew. The vehicle is formally designated as the Lunar or Planetary Surface Landing Research Vehicle (*LPSLRV*).

This project includes elements of all four of the critical technology thrusts identified by ESMD as key for the future of space exploration. These areas include spacecraft systems, propulsion, lunar and planetary surface systems, and ground operations. The complexity of the design – building an actual flying vehicle – required a large interdisciplinary team to be assembled. The size of the team – 7 graduate research assistants, 19 undergraduate student design team members and a faculty mentor – required that system requirements and team roles and responsibilities were clearly defined. Formal systems engineering techniques were applied to facilitate this progress.

Programmatic Level Requirements

Top-Level design requirements were defined by the NASA technical points of contact.* There are five NASA-defined requirements:

- 1) The design must be free flying.
- 2) The design must account for a reduced gravity environment.
- 3) The terminal stage of descent may be flown either autonomously or remotely piloted.
- 4) The vehicle shall be a platform for sensor evaluation.
- 5) The vehicle shall be designed and constructed within the constraints of a one-academic year senior design course.

The first three requirements were based on the top-level requirements laid out for the original LLRV design (Ref. 2). The fourth requirement was mandated in order to provide sufficient design breadth to

* Mr. John Kelley, Exploration Systems Program manager, NASA DFRC. Ms. Gloria Murphy, NASA KSC Office of Education.

support other NASA technology development efforts like the Autonomous Landing and Hazard Avoidance (ALHAT) program.[†] The final requirement is mandated by the NASA Space Grant senior design program. All other requirements for the vehicle design were derived in order to achieve these three primary objectives. Table 1 Lists the initial (top level) and derived requirements used to drive the overall vehicle design. Requirement and designation numbers are listed in columns 1 and 2. Sources and verification methods are listed in columns 3 and 4.

Table 1. Initial and Derived Project Requirements

Requirement	Number	Source	Proof of Achievement
Vehicle shall be free-flying	0.PRJ.1	NASA DFRC	Entire vehicle shall lift off the ground on its own power
Vehicle shall simulate lunar landing on Earth	0.PRJ.2	NASA DFRC	Video
Vehicle must be remotely controlled by trained pilot	0.PRJ.3	NASA DFRC	Flight test, pilot input
Vehicle shall be a platform for sensor evaluation	0.PRJ.4	NASA JSC	Data from onboard sensors
Vehicle design shall be conducted within constraints of one academic-senior design course	0.PRJ.5	NASA ESMD Office of Education (Customer)	Final functional test completed by May 8, 2010 and project within budget
Vehicle shall be reusable and capable of multiple flights	0.PRJ.6	Derived from 0.PRJ.2	Successful completion of second flight test
Mission shall be completed in 5 minutes or less	0.PRJ.7	Historical; 0.PRJ.2	Mission shall be timed
Vehicle design shall be compatible with environmental and safety constraints of operating within a university environment	0.PRJ.8	USU Risk Management Office	Risk Management sign off on flight testing

0.PRJ.1 Vehicle shall be free-flying

Apollo astronauts stated that training in free-flying simulators was vital for the success of the lunar landings, as it provided visual and physiological cues that tethered simulators did not (Ref. 3). The end result of this project per the NASA ESMD Space Grant funding will be a free-flying vehicle.

0.PRJ.2 Vehicle shall simulate lunar landing on Earth

Per customer requirements the vehicle must be able to simulate the initial approach, final approach, and landing phases of a lunar landing. The landings will be recorded on video and compared to the modified lunar landing profile as outlined in the Design Reference Mission (Figure 4) to determine if this requirement has been fulfilled.

0.PRJ.3 Vehicle must be remotely controlled by a trained pilot

The customer requires that the vehicle be operated either remotely or autonomously. Since this is the initial design, the vehicle will operate remotely. Future work would include the development of an autonomous program.

0.PRJ.4 Vehicle shall be a platform for sensor evaluation

[†] Email and phone correspondence with Chirold Epp, NASA JSC ALHAT Program Manager, June 12, 2008.

The LPSLRV's primary purpose is to develop concepts for a Lunar Landing Training Vehicle. A secondary purpose is to test sensors that are more technologically advanced than those used on the Apollo era LLTV to see what use they might be to the vehicle. The customer requires sensors for vehicle evaluation.

0.PRJ.5 Vehicle design shall be conducted within time and budget constraints of a typical senior design course

The LPSLRV is a senior design project and, therefore, must be conducted within time and budget constraints of typical senior design projects – about nine months and \$18,000. Moreover, since this project is a “beta” case for a NASA sponsored, university level engineering competition, it would necessarily be conducted within university class time and budget constraints.

0.PRJ.6 Vehicle shall be reusable

To be an effective training device the vehicle must be able to be used multiple times. This requirement states the vehicle must be capable of multiple flights after servicing of subsystem components.

0.PRJ.7 Mission shall be completed in 5 minutes or less

In order to simulate a lunar landing as best as possible, a mission time of 5 minutes was chosen to represent the time scale of an actual lunar landing. The project manager also stated that this was the maximum amount of time the vehicle could be in the air to show proof of concept.

Hazard Assessment and Mitigation

Through comprehensive checklists and emergency procedures, the risk of human injury and vehicle failure is greatly reduced. For actual test flight, safety positions have been created so that, in the event of an emergency, there should be order in handling the situation. Months before jet engine and prototype testing began, safety rules and guidelines were put in place to ensure the well-being of everyone involved. Proper clothing was worn, including safety goggles, and earplugs, gloves and hardhats were necessary. A first aid kit and fire extinguisher were always on hand in the event of injury or fire.

The Risk Management Office (RMO) at Utah State University was involved in much of the decision making process for this project and drove several of the initial decisions that affected the overall system design. To satisfy RMO mandated hazard reporting requirements, a formal system of risk assessment was developed for this project. For this analysis a hazard matrix was developed to determine and classify the hazard level of an anomaly. The hazard levels ranged from low to extreme based on likelihood of occurrence and the magnitude of damage that would ensue if a hazard was realized.

Figure 3 presents the hazard assessment matrix used for this project. To navigate this matrix, select a risk and determine how likely it is for the event to happen, and then assess how much it will affect the project. For example, the possibility of a person getting a paper cut during the duration of the project was fairly high but the *Magnitude of Failure* is negligible. Therefore, a paper cut is listed as a level-6 hazard. Level 6 is considered to be an acceptably low level of risk and can be “carried” without formal mitigation processes. On the other hand, consider the jet engine failing during flight. The *Likelihood of Failure* would be “unlikely;” however, the Magnitude of Failure would be “catastrophic.” This hazard corresponds to a level 16, or extreme, hazard. Extreme hazards (level 13 and above) are unacceptable and require additional mitigation plans.

		Magnitude of Failure					
		Negligible	Marginal	Critical	Catastrophic	Hazard level	Color
Likelihood of Failure	Certain	11	15	19	20	Low	
	Likely	6	10	14	18	Moderate	
	Possible	5	9	13	17	High	
	Unlikely	2	4	8	16	Extreme	
	Rare	1	3	7	12		

Figure 3. Example Hazard Assessment Matrix

This assessment matrix was applied to every identified risk to determine if the level of risk is acceptable. If the risk was deemed unacceptable, then the design was modified or processes were developed to mitigate the hazard. Table 2 lists some example hazards identified by the project. The table lists the numerical hazard level, potential causes and consequences, and describes what mitigation process, if any, are required.

Table 2. Example Hazard Tracking List

Hazard Level	Hazard	Causes	Preventative Measures
16	Engine Failure, causing an inability to keep vehicle in air	Debris Weather Temperature	Screen on jet intake, Check flying conditions, Pre-flight checklist Pre-flight and in-flight systems check
9	Human Injury	Burns from Jet Engine Exhaust Blowing debris Low-Voltage Electrical shock	Wear protective equipment, Designate “Keep out” zones, No power during maintenance, Follow manufacturer’s recommendations, Follow checklists
8	Electronics Failure, causing a loss of power to rotors	Communication loss Communication interference Electrical shorting	Pre-flight and in-flight systems check
8	Vibration Effects, causing the vehicle to become unstable or components to become loose	Rotors rotating near Resonance	Pre/Post assembly testing
4	Fuel Leakage, forcing the time of the mission to be reduced	Bad seal on Fuel Tank, Improper filling of Fuel Tank	Quality check, Pre-flight checklist

System Level Requirements

In addition to the project requirements, each system of the vehicle derives its own set of top level requirements that must be fulfilled but do not apply to the project as a whole. The system requirements were derived from the project requirements. Initially, the Concept of Operations and the Design Reference Mission are key to defining these system-level requirements.

Concept of Operations

A key enabler a successful design is to develop an early Concept of Operations (CONOPS) so that each of the subsystem design teams can scope the level of efforts required by their designs. For this design the initial CONOPS was for the vehicle to be composed of two platforms. The vehicle design features a two-axis gimbal system that allows the inner gravity-offset gravity offset system on the inner platform to move independently in two degrees of freedom from the outer maneuvering platform. Stability of each platform is to be controlled independently by separate control systems. The final propulsion systems selected for the inner and outer platforms are the result of trade-study assessments.

In order to meet project requirement 0.PRJ.8 (environmental safety), the decision was made very early in the program to eliminate the hydrogen peroxide maneuvering thrusters employed in the LLRV/LLTV design. Using a corrosive and toxic mono-propellant would require extraordinary safety and handling procedures that are incompatible with an “open” university design project. Similarly, developing a state-of-the art “green-propellant” bi-propellant thruster system is far beyond the scope of what can be accomplished in a one-year senior design project. Cold-gas thrusters were quickly eliminated because there was insufficient lift requirement to meet project requirement 0.PRJ.7 (5 minutes flight duration). Thus, the lift thrusters were replaced by a propeller-powered quad-rotor system. “Going with” quad rotor system was a key programmatic design decision that drove many of the down-stream design decisions. Figure 4 compares the LPSLRV design CONOPS to the LLRV.

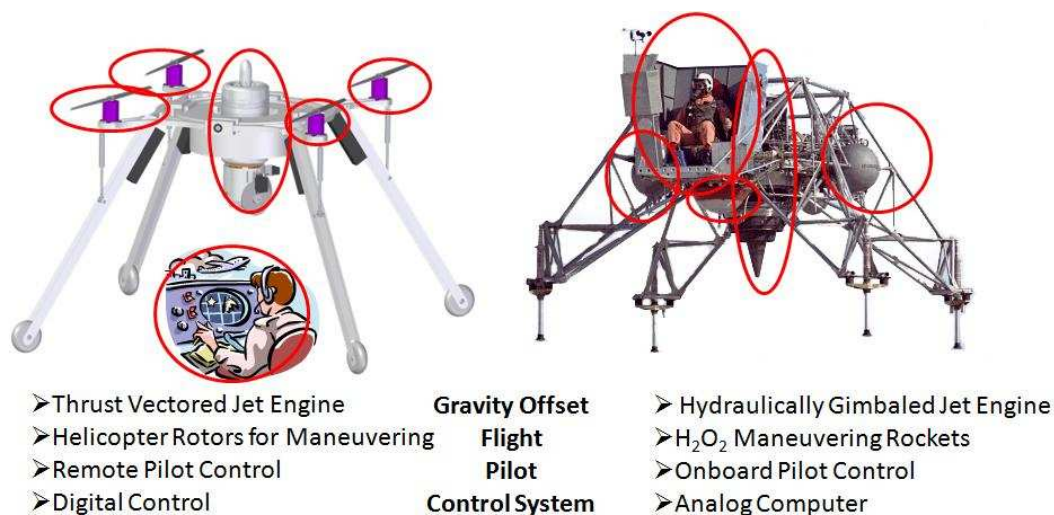


Figure 4. Comparison of LPSLRV and LLRV Concepts of Operations

Design Reference Mission

One of the key enemies of a successful program is “mission creep.” Mission creep more often than not leads to a program stalling or collapsing under its own ponderous weight. Because of limited resources

and limited experience of design team members, student design projects are especially susceptible to mission creep. A “tried and true” way to keep a program on track is adherence to a Design Reference Mission (DRM). A well-defined DRM accomplishes top-level program requirements but limits scope of design and restricts unnecessary requirement growth. The design reference mission for this vehicle attempts to reproduce as many elements of a lunar landing mission as is feasible within the schedule and budget constraints of a single year undergraduate student design project.

Figure 5 shows the three phases of the Apollo landing profile.⁵ Pictured are the in-orbit Keplerian maneuvers (5a), the powered descent phase (5b), and the final approach and descent phase of the landing (5c). Two key waypoints are shown on the approach trajectory; *high gate* – where the vehicle transitions from the powered descent to approach, and *low gate*[‡] – where the vehicle transitions from approach to the vertical descent.

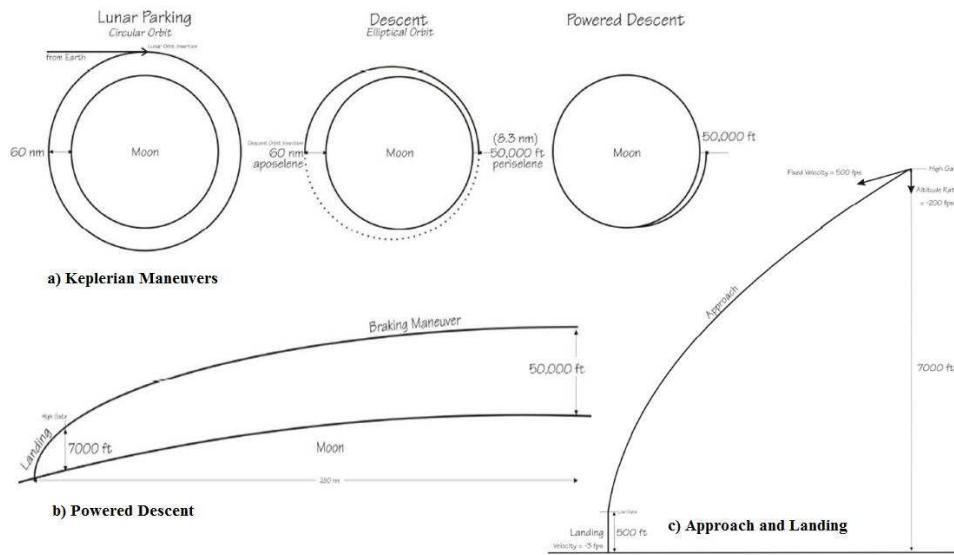


Figure 5. Phases of the Apollo Lunar Landing Profile

For this design project the DRM attempts to simulate the approach and landing phases of the mission (as did the LLTV and LLTV). To achieve a simulated lunar landing approach, the vehicle climbs, maneuvers horizontally to get onto the proper approach trajectory, then begins the powered descent before hovering for a vertical landing. An initial systems check will be performed when the vehicle is at a 1 m hover. Figure 6 depicts this design reference mission. Velocity and altitude markers were scaled from actual mission profile to keep the vehicle within the available testing range.

[‡] The terms *high gate* and *low gate* were inherited from the Apollo program and are derived from naval aviation terminology for aircraft carrier landings.

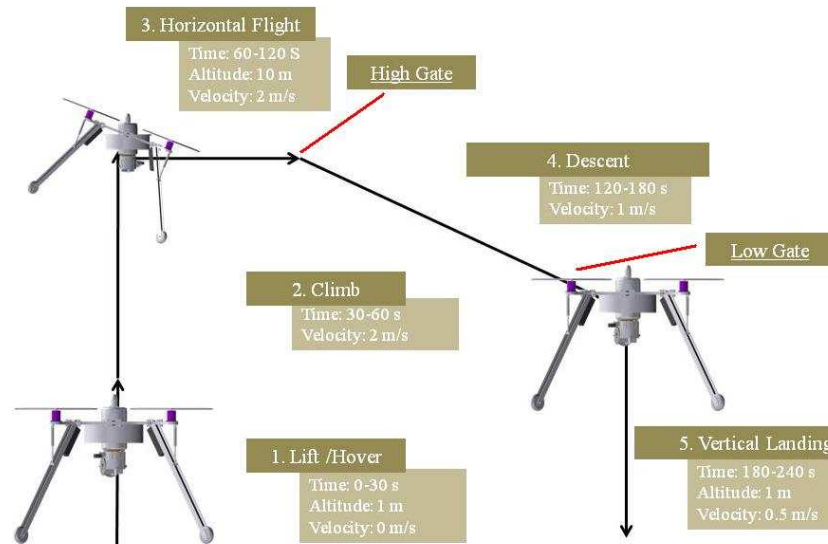


Figure 6. Design Reference Mission

Initial Trade-Off Assessments

The primary initial trade assessments performed by the LPSLRV design were selection of the appropriate power plant technologies for the inner and outer platforms. This subsection describes the top-level trade studies that were used to select the most appropriate lift-technologies. Detailed procedures used to select the final power-plant systems design will be presented later in the “Vehicle Development” section.

One of the major components of the LPSLRV is the gravity offset system that enables the vehicle to respond in the Earth’s gravity field as it would on the Moon. Several options were considered for this system, including rocket motors, electric ducted fans, rotors, and a small jet engine. A formal trade study was conducted to select the best choice for the gravity offset system power-plant. This trade study was a formal deliverable for the design class.

Rocket motors were determined to be unsuitable for the same environmental and safety reasons presented earlier. Additionally, ability to precisely control and modulate a rocket system for gravity offset is very limited. Finally, the amount of propellant required on-board would cause a prohibitive vehicle weight.

The electric ducted fans of the type used on remote control vehicles also proved to have prohibitive weight requirements. Ducted fans are very power intensive, and for this design would have required the entire structure to be built out of batteries to provide enough power for the 5-minute mission. Gas-powered fans in the size compatible with this vehicle size are not readily available.

Jet engines, the final choice for this system and the type of gravity offset system used on the LLRV, are readily available with a wide variety of vendors and size options. Fuel and power requirements were reasonable, and preliminary analysis showed that interactions with the rotors would be acceptable. In fact the propeller-wash from the maneuvering platform likely has the effect of improving the jet performance. Therefore, a jet engine was chosen for the gravity offset system. Once jet engine technology was selected, a secondary trade study was performed to select the jet engine size, features, and lift capacity. As mentioned earlier in this sub-section, the detailed jet-engine trade assessment is presented later in the “Vehicle Development” section.

As discussed earlier, the only two feasible options for the maneuvering system were cold gas thrusters and a quad-rotor system of blades. The cold gas rockets, although more closely approximating the control effectors for the actual landing spacecraft, were eliminated due to insufficient lift capacity. The low specific impulse of the cold gas system required a prohibitive amount of propellant to be stored on the vehicle. Thus the primary trade to be performed was deciding on the type of rotor system to be used. Available options included direct-drive, pitched fixed-mount aircraft propellers, low-pitch articulated rotors. As mentioned earlier in this sub-section, the detailed rotor-selection trade assessment is presented later in the “Vehicle Development” section.

Subsystem Requirements

The decisions to go with a rotor-based maneuvering system for the outer platform and a jet-engine for the inner gravity-offset platform drove many of the subsequent sub-system design requirements. The sub-system particular requirements, their designation numbers, the source of the requirement, and the verification methods are listed in Table 3.

Table 3. Sub-System Requirements

Requirement	Number	Source	Proof of Achievement
GRAVITY OFFSET			
Gravity offset system will provide enough thrust at 80% RPM to offset necessary amount of vehicle weight	0.SYS.1	0.PRJ.2	Thrust at 80% throttle is greater than or equal to 5/6 of the vehicle weight. Determined by static test
Thrust vectoring system shall keep gravity offset system opposing local gravity vector at all times in flight	0.SYS.2	0.PRJ.2	Measure the deflection angle using onboard sensors
MANEUVERING			
Maneuvering system shall provide enough thrust to offset necessary vehicle weight at 80% RPM	0.SYS.3	0.PRJ.2	Thrust at 80% is greater than or equal to 1/6 vehicle weight. Determined by static test
Maneuvering system shall provide enough differential thrust to allow correct maneuvering angles to be achieved	0.SYS.4	0.PRJ.2	Measure available differential thrust on test stand. Analytically verify that given thrust will allow angles to be achieved
STRUCTURE			
The vehicle structure shall be designed so the vehicle can fall from a height of 0.3 m without damage	0.SYS.5	0.PRJ.6	Analytic calculations/ testing

0.SYS.1 Gravity offset system will provide enough thrust at 80% RPM to offset necessary vehicle weight

The mission of the LPSLRV is to simulate lunar landing on Earth. Since Earth’s gravity field is stronger than the Moon’s, some amount of the Earth’s gravity will need to be offset. This offset will be performed at 80% power, or MIL-spec power, to provide some buffer for emergency situations, variability in vehicle weight, and fuel savings.

0.SYS.2 Thrust vectoring system shall keep gravity offset system opposing local gravity vector at all times in flight

For an effective lunar simulation and to ensure vehicle stability, the gravity offset system must oppose the local gravity vector at all times during vehicle flight. The thrust vectoring system shall provide the control necessary for this to be possible.

0.SYS.3 Maneuvering system shall provide enough thrust to offset necessary vehicle weight at 80% RPM

The mission of the LPSLRV is to simulate lunar landing on Earth. Since the gravity offset system will be countering 5/6 of Earth's gravity in lunar simulation mode, the rest of the vehicle weight must be offset by the maneuvering system. This shall be done at 80% RPM or less to provide a buffer for emergency situations, vehicle weight variability, and power savings.

0.SYS.4 Maneuvering system shall provide enough differential thrust to allow correct maneuvering angles to be achieved

Due to the lower gravity on the Moon, higher excursion angles are required for maneuvering (Figure 1). The LPSLRV must be able to achieve these angles to properly simulate a lunar landing. Differential thrust is the method chosen to change the maneuvering angle of the vehicle, so the differential thrust must be sufficient to achieve this.

0.SYS.5 The vehicle structure shall be designed so the vehicle can fall from a height of 0.3 m without damage

A systems check shall be done at a height of about 0.3 m before the landing simulation takes place. Should the gravity offset or maneuvering system fail, the vehicle shall be able to fall from this height without being damaged.

System Engineering Processes

As mentioned in the introductory section, the size of the team and the highly interdisciplinary nature of the design being attempted required that formal systems engineering techniques be applied to the design process. This section will highlight some of the design systems engineering processes that were used during the project.

Review Item Disposition

A Review Item Disposition (RID) procedure was developed to ensure fluid communication between sub-teams as well as provide a means of formal documentation for actions performed to complete the project (See Appendix A). This process is modeled on the formal processes widely used within NASA and the aerospace industry. During this process anyone on the team can initiate a Request for Action (RFA) or Request for Information (RFI) and assign it to a specific person or sub-team with a desired date of completion. An RFA assigns a specific task to be performed and documented, while an RFI asks for information about a system that is critical for the development of the project. At each team meeting, the RIDs that are due are presented in a two slide PowerPoint presentation, allowing the entire team to understand the progress being made. If the action or information was sufficient, the RID is formally closed by the Systems Engineer (SE). RIDs can be extended if more time is necessary for satisfactory completion.

Information Tracking

All RIDs are tracked on the student-built website. This website also presents formal documents that have been created such as trade studies, presentations, and test reports. In addition to keeping formal

documents on the website, an online “wiki” was developed for easy uploads of information and to provide a quick reference for other team members. This wiki will also preserve knowledge gained this year for future teams.

Document Control

A document control system, using primarily Google Docs, was created to track the variety of documents created during this project. Each sub-team was assigned a number (Table 4), which acted as the first two numbers of the document number. The next three numbers were chosen chronologically. For example, the reference number 01-001 represents the Management team. The -001 means this is the first document from this group.

Table 4. Document Control Numbering Scheme

Sub-Team	Associated Number
Top Level Management	01
Aerodynamics	02
Propulsions	03
Structures	04
Safety	05

Vehicle Development

Figure 7 shows the design sequence that was used to close on the overall vehicle design. This approach is similar to the classical design process for spacecraft and starts with the power-plant selection.⁶ Since the gravity offset system was key in fulfilling the primary mission requirement, selection of the gravity offset system was the starting point for vehicle design. Once the available thrust is known, a maximum allowable vehicle mass can then be calculated as $6/5^{\text{th}}$ of the lifting capacity of the jet engine. This total vehicle mass then determines the required thrust needed from the rotors. The lifting capacity of the rotors drives the power requirements for the battery systems, etc. Using subsystem simulations based on component performance testing, the process is iterated until an acceptable design is closed on.

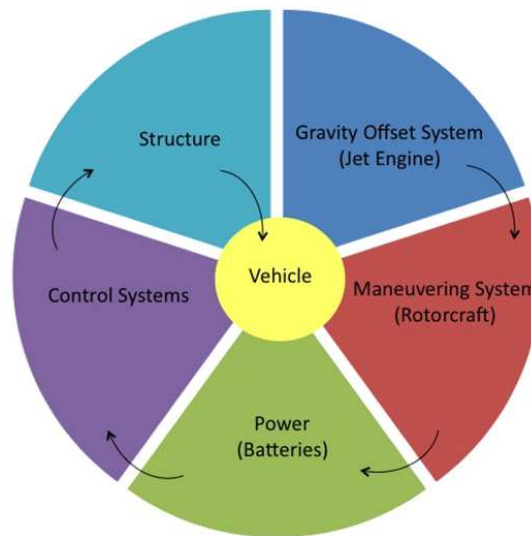


Figure 7. Vehicle Design Process

Interfaces

Figure 8 shows a functional block diagram of the overall vehicle design. The primary components are listed with arrows showing the flow of information and overall functional interdependence.

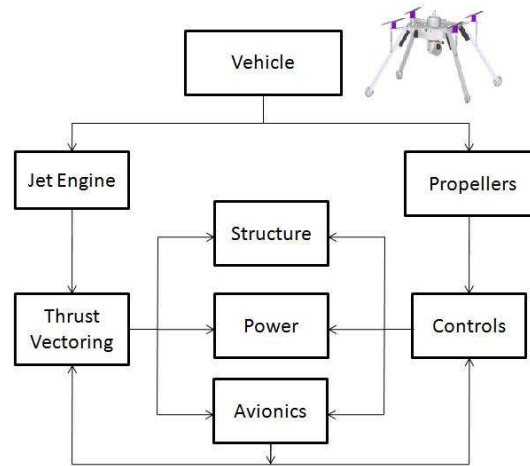


Figure 8. Vehicle Functional Diagram

Table 5 shows a detailed interface chart used to track the impact of changes on one sub-system to other sub-systems on the vehicle. Each sub-system is listed in a “yellow box.” If there is an interface between two subsystems, an M (for mechanical) or E (electrical) is written in the corresponding box. A mechanical interface is defined as a hardware connection between the two, whereas an electrical interface is defined as a software or electrical connection between the two. For example, the outer platform has mechanical interfaces with the inner platform: the quad rotor system, the required instrumentation and avionics, and the batteries providing power. Likewise, the Power system has an electrical interface with the outer platform, the jet engine, Gumstix (flight Computer), and Instrumentation and Avionics, providing power for each.

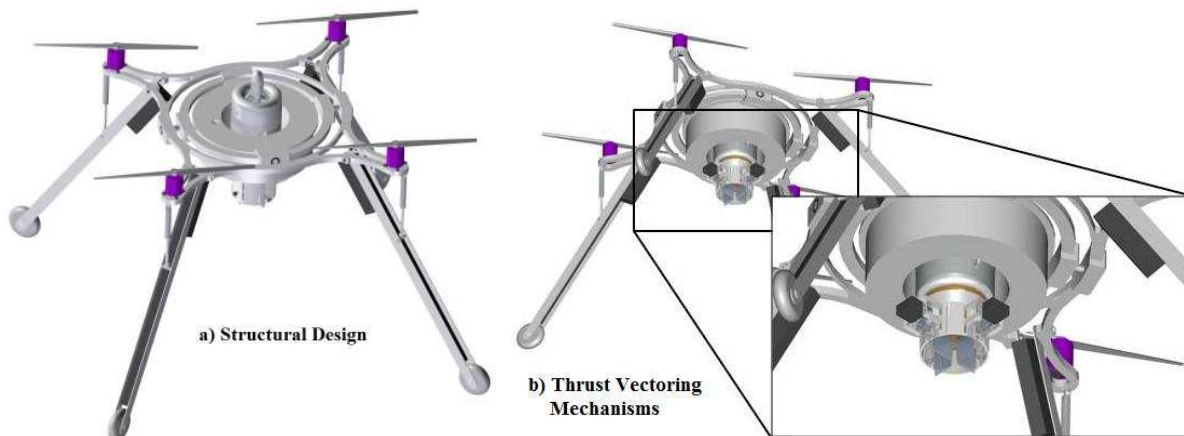
Table 5. Interfaces with Vehicle Sub-Systems

Outer Platform	M			M, E	M, E	M, E		E
	Inner Platform	M	M, E		E	M		
		Jet Engine	E		E	E	E	E
			Gumstix		E	E		
				Quad Powered board				
					Avionics	E	E	
						Power		
							Software, Ground Computer	M
								Pilot

Final Design Description

Figure 9 presents the final design for the LPSLRV. Figure 9b shows the structural configuration that features an optimized outer platform designed with the aid of structural optimization programs provided free of charge by Altair Engineering.⁷ The landing gear are hinged at the root and angled at 45° to avoid the maximum downwash velocity area produced by the rotors. Small spring-loaded shock-absorbers are used to reduce landing loads. The batteries and auxiliary components are all attached onto the outer platform.

A quad rotor system is mounted to the outer platform and features counter-rotating propellers on alternate corners, each driven by direct drive-brushless DC motors. The motors are matched with electronic speed controllers (ECs) that control the power delivered to each motor. The ECs are powered by four 11.4 Volt Lithium Polymer (LiPo) batteries. The LiPo Batteries provide approximately 14 amp-hrs of total energy and provide approximately seven minutes of flight time on a single charge. A computer-controlled gyro board (featuring a proportional integral-derivative (PID) rate damping control) system is used to stabilize the outer platform during flight.



The gravity offset system features a Jet Central™ JF-170 Rhino⁸ centrifugal turbine engine. The engine produces 36 lbf of thrust at full throttle (117,000 RPM).⁸ The fuel tank for the gravity offset engine is integrated into the inner platform. The inner platform pitch and roll angles are controlled by a thrust vectoring system featuring exhaust turning vanes. A miniature inertial measurement unit⁹ provides feedback to a PID control system implemented on a Gumstix™ micro-computer.¹⁰ The jet engine is mounted on brackets that allow a 1.125 in. range of positioning, so the center of mass can be changed.

Design Products

There were three major design reviews for this project. These reviews, listed in Table 6, were presented to departmental faculty as well as outside reviewers from NASA and the aerospace industry. Several members on the Utah American Institute of Aeronautics and Astronautics (AIAA) section attended the preliminary and critical design reviews. Peer evaluations were collected after each review. These reviews were webcast and recorded for future reference. Two formal trade studies were also performed. These trade studies selected the gravity offset (jet engine) and quad-rotor drive components. Portable Document format (PDF) copies of these trade studies and design reviews may be found on the LPSLRV

⁵ Extensive ground testing performed by the student design team has verified this thrust level.

student website.¹¹ Weekly technical interchange meetings (TIM) were held amongst the design team members. Two hours per week were dedicated to formal classroom lectures by the faculty mentor.

Table 6. Summary of Formal Design Reviews

Review	Description	Date	Target Audience
Conceptual Design Review	Student Presentation to USU Dean of Engineering, Department Heads	October 13, 2009	USU Internal, College of Engineering, Student Design Team
Preliminary Design Review	Peer review by USU Faculty, NASA Sponsors, Technical Monitors, Industry Professionals	December 8, 2009	NASA Sponsors, Industry Reviewers
Critical Design Review	Same as above	March 25, 2010	Same as above

Intrinsic Merit

This project includes elements of all four of the critical technology thrusts identified by ESMD as key for the future of space exploration. These areas include spacecraft systems, propulsion, lunar and planetary surface systems, and ground operations. The complexity of the design – building an actual flying vehicle – required a large interdisciplinary team to be assembled. The design experience closely mirrored the process that students would encounter during a “real world” industry or NASA design cycle. As such the educational experience is invaluable and not reproduced by any other aspect of the undergraduate education.

Deliverables

This project’s students have designed, built, and tested a small-scale prototype of a terrestrial based lunar landing simulator. The project is an outcome of a senior design course being developed as a partial requirement of a NASA Office of Education grant. As such every aspect of the project has been logged, and more than three giga-bytes of information will be archived and documented for future use. A significant final outcome will be a packaged senior design course that can be incorporated by other universities across the nation. It is anticipated that the vehicle will remain in flight for some time after the completion of this design course, with the long term goal of developing a world class research platform for evaluating planetary landing technologies or mission concepts.

Schedule

This project began in August of 2009 and will culminate in May 2010. See Appendix C for Gantt Charts showing the development schedule of the vehicle.

Budget

Because this project is to be conducted as a senior design project, the finances were required to be tracked. See Appendix D for the final budget tracking sheet.

Appendix A: Mass Budget

The vehicle mass budget began by allocating an adequate percentage of the maximum vehicle mass, as defined by the jet engine, to each group. As the project progressed, the distribution of weight was updated to accommodate each group's needs. To keep track of the mass contributed by each team, a document was created and saved onto subversion that allowed each team to include each component with their respective weight.

Table A1 presents the original mass allocation. Table A2 shows the mass distribution of the final design. Some of the mass allocation categories changed as the vehicle design matured. For example, the recovery system was analyzed and determined to be too mass costly and expensive. It was thus deleted from the overall design. Amazingly the mass percentages changed only slightly and the final mass (32.87 lbf) is under the total allowable mass of 34.56 lbf. The 34.56 lbf is the maximum vehicle weight that the JF-170 engine can off-set 5/6th g at the 80% thrust level.

Table A1. Original Mass Allocation for Vehicle

Team	Percent/Group	Mass (kg)	Mass(lbm)
Structures	21	2.5	5.51
Safety	8	1	2.21
Controls	8	1	2.21
Instrumentations	8	1	2.21
Power	21	2.5	5.51
Aerodynamics	18	2	4.41
Buffer	16	1.87	4.12
Total (Less Motor and Fuel)	100	11.87	26.17
Maximum Total Allowable		15.53	34.24

Table A2. Final Mass Distribution for Vehicle

Subsystem	Percent	Mass (kg)	Mass(lbf)
Structure	40.58	6.05	13.32
Controls	3.35	0.50	1.10
Instrumentations	6.71	1.00	2.21
Power	11.00	1.64	3.60
Quad-Rotor	7.98	1.19	2.65
Jet Engine Acces.	8.79	1.31	2.88
Engine	10.46	1.56	3.50
Fuel (5 min @80%)	11.13	1.66	3.67
Total	100	14.91	32.87

Appendix B: Review Item Dispensation Procedures and Forms



Initiate RFA/RFI (Anyone)	Download the RFA/RFI Form from the website and fill in the top portion. Email the form to the team lead of the subgroup the information is needed from. Also copy the lpsrv.usu@gmail.com email.
Tracking (SE and Webmaster)	Once the form has been received, a tracking number and due date of one will be assigned (unless otherwise specified). The form will be uploaded to the class website with a link to the document on subversion.
Delegate Request (Team Lead)	The team lead will receive the email and decide who will complete the task.
Fulfill Request (Actionee)	Action or Information must be completed or provided as soon as possible, since the rest of the process will depend on that action or piece of information. After the action has been fulfilled, the lower section of the form must be filled out on subversion.
Review RFA/RFI (Review Board)	Regular meetings will be held to determine if the action/information was sufficient. If the requestor is satisfied, the RFA/RFI will be closed.

LPSRV/01-002 A



Request for Action or Information (RFA/RFI) Form

☐ RFA ☐ RFI

TITLE: *

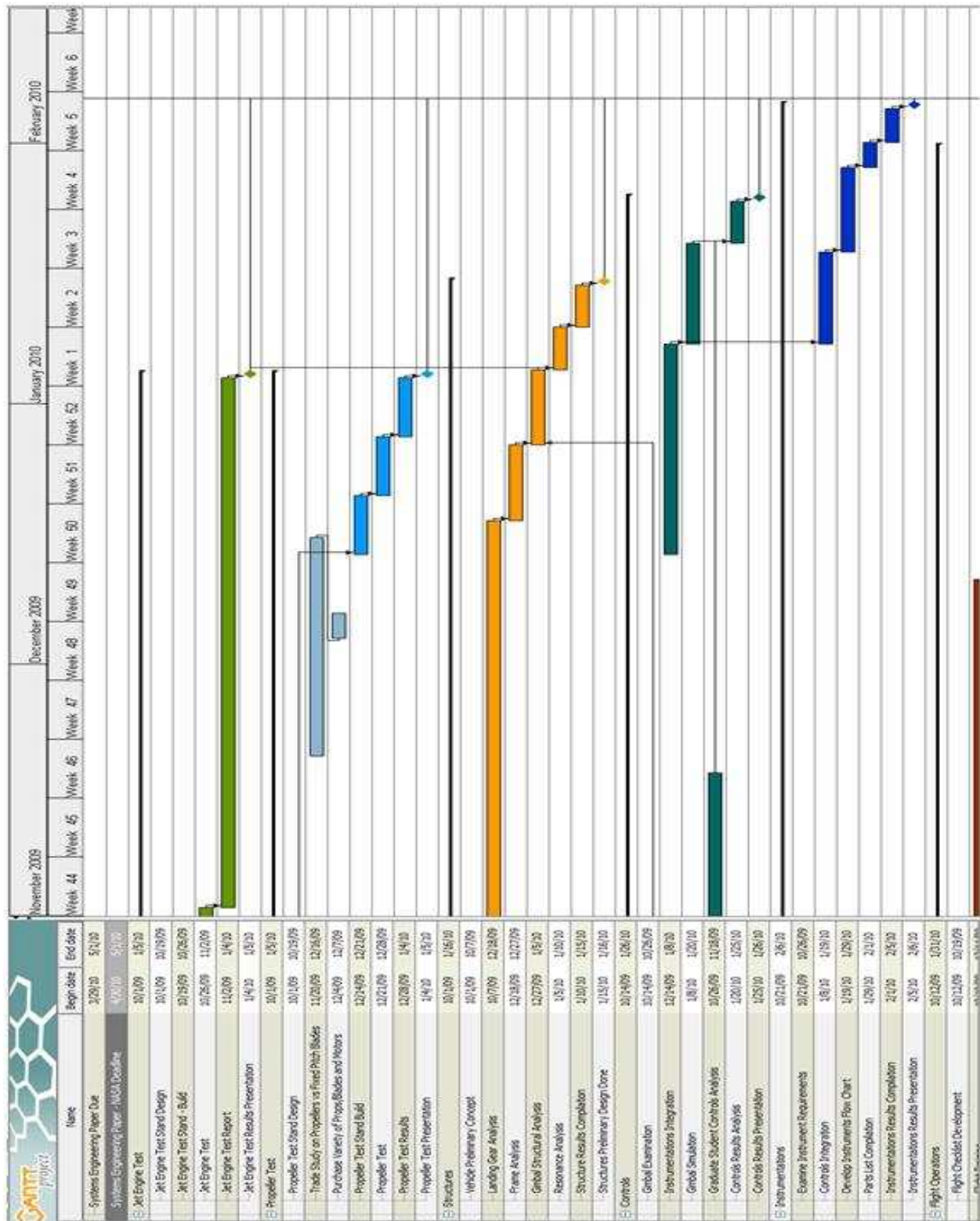
RFA/RFI Tracking Number: 00*	SPECIFIC REQUEST *	
Submission Date: yyyy-mm-dd		
Due Date: yyyy-mm-dd		
REASON/COMMENT: *	Action Requested: <input type="checkbox"/> Email <input type="checkbox"/> Face to Face Explanation <input type="checkbox"/> Test Completed <input type="checkbox"/> Other:	
SUBMITTED BY: Y.NAME SUB TEAM	SUBMITTED TO: OTHER SUB TEAM LEAD NAME SUB TEAM	
RESPONSE:		
ACTIONEE: _____		
DETAILED DESCRIPTION OF ACTION TAKEN: 		

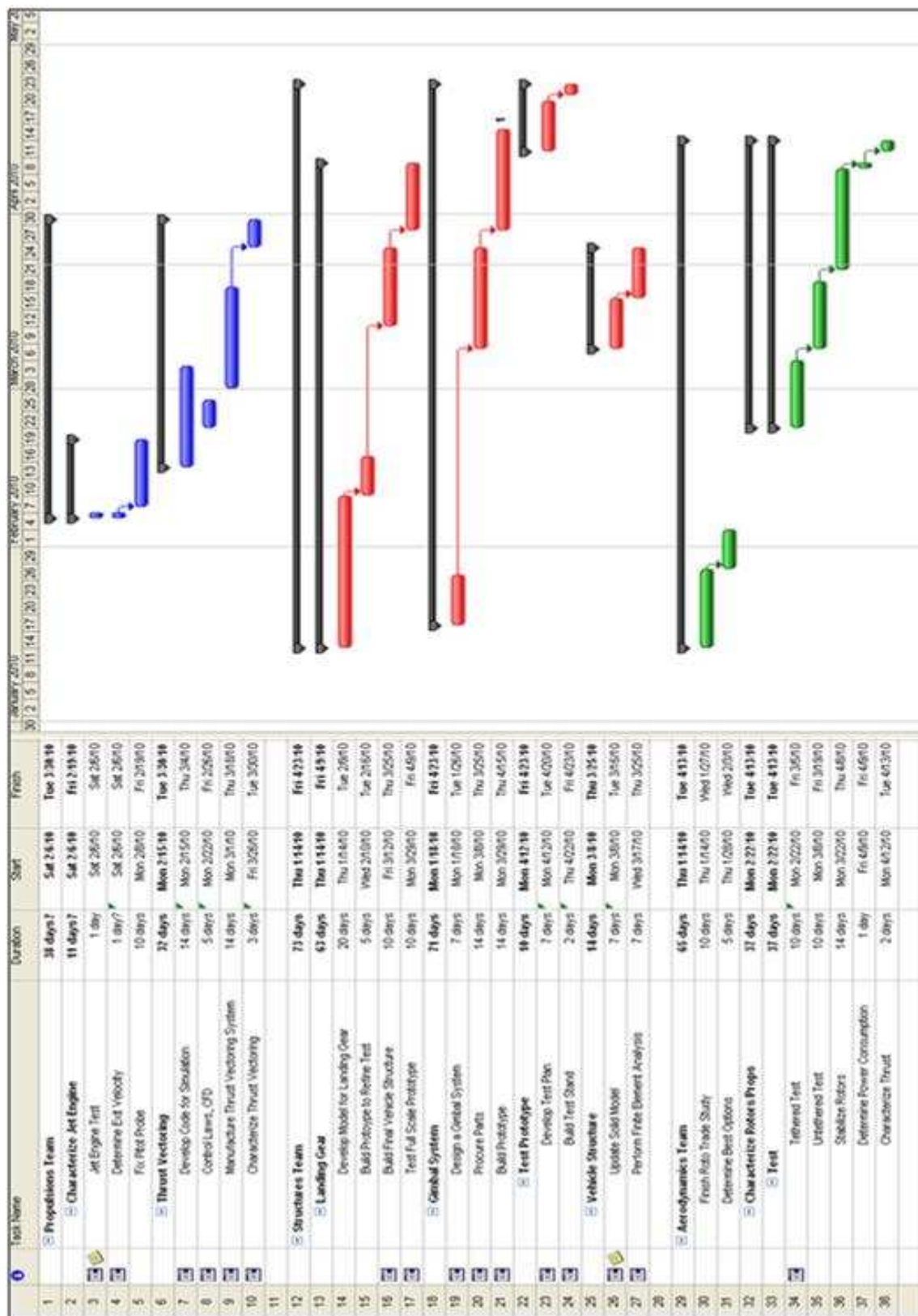
☐ RFA / RFI Closed _____

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Appendix C. Program Schedule





Appendix D: Financial Budget

Project funding sources included cash donations from the USU Space Dynamics Laboratory, the Utah AIAA section, the USU College of Engineering, the NASA Space grant Higher Education Project, and re-allocated salary from the faculty mentor. Altair Engineering of Draper Utah donated two student license seats to its HyperworksTM structural optimization computer code. Petersen Engineering of Logan Utah donated more than 100 hours of machine shop. Both non-cash contributions were considered essential to the success of this project. Amazingly the project came in under the original budget allocation.

Incoming	
From	Total Amount
NASA	\$5,000
SDL	\$5,000
College of Eng	\$5,000
AIAA	\$1,500
Whitmore-Research Salary	\$1,500

Budget	
Amount Received:	\$18,000.00
Amount Spent:	\$15,445.61
Total Remaining:	\$2,554.39

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