Landing a Humanoid Robot on the Moon in a 1000 Days
"Project M"

May 3, 2010

In 1958 NASA was formed to address issues of strategic and technological importance to the Nation. In its storied history NASA has undertaken and delivered on the most difficult and daunting challenges. The Apollo moon landings cemented our Nation's position of dominance in the strategic high ground of space and the program demonstrated to the world our unmatched technological prowess. The Space Shuttle may well be remembered as the finest single example of technological expertise the country ever produced. And the Space Station is the largest space construction project ever accomplished and serves as the quintessential example of international engineering cooperation.

While those achievements exemplify NASA's technological contributions on behalf of the United States, they also illustrate its ability to marshal, organize, and manage the human resources, institutions, and organizations necessary to produce some of the greatest engineering achievements of the last half century.

But the world is not the same as it was in the days of Apollo, or Shuttle, or even the beginnings of the Space Station. There are many nations now vying for dominance of space. Many nations recognize the importance of this, not only the technology spin-offs that it drives or the strategic value, but the intangible benefits of inspiring its youth and instilling pride in its citizens.

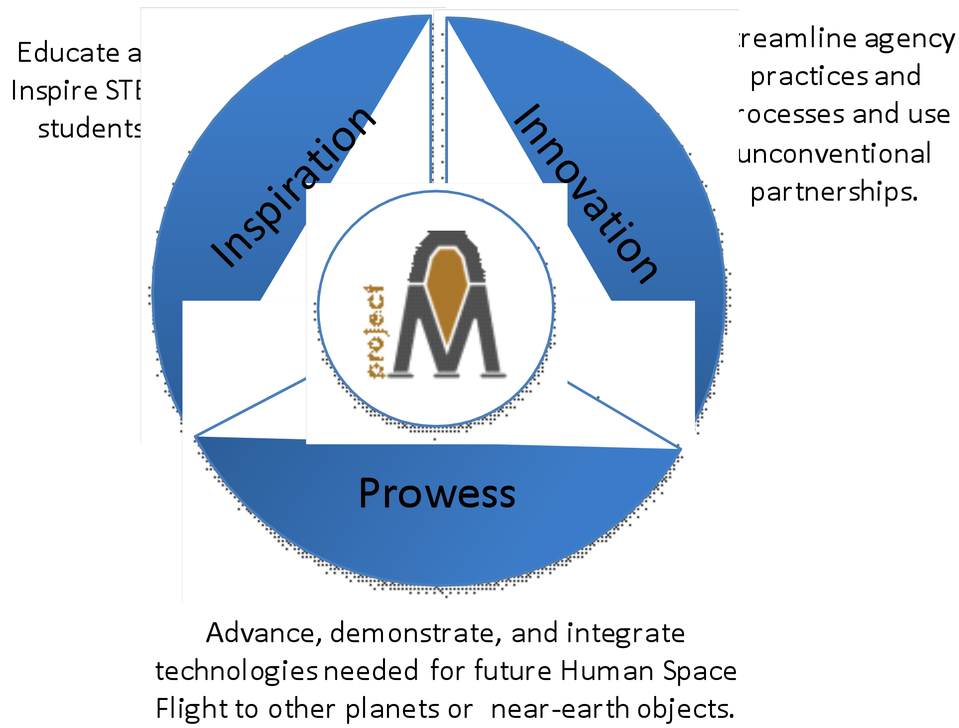
The United States is still confronted with issues of strategic and technological importance. Technology and innovation will always drive a nation's economy. Now more than ever it is important and necessary to have a technically educated society. Keeping students interested, engaged, and graduating with degrees in technical disciplines is imperative for a modern society to thrive.

A nation is only as great as the challenges it undertakes. Solving the great challenges of our time defines our collective future by inspiring students, leading our children to dream of even greater achievements, and enhancing the United States standing among the world community. A modern NASA is the unmistakable place for the country to invest in these challenges that drive the engine of innovation and ultimately the Nation's economy and prosperity.

Concept Summary

The proposition is simple: land an operational humanoid robot on the moon in 1000 days. The humanoid will travel to the moon on a small lander fueled by green propellants, liquid methane and liquid oxygen. It will perform a precision, autonomous landing, avoiding any hazards or obstacles on the surface. Upon landing the robot will deploy and walk on the surface performing a multitude of tasks focused on demonstrating engineering tasks such as maintenance and construction; performing science of opportunity (i.e. using existing sensors on the robot or small science instruments); and simple student experiments.

The mission is also about inspiration, streamlining agency practices and processes and using unconventional partnerships, and building a workforce and demonstrating technologies to enable the continuation of human exploration beyond low earth orbit.



This mission will change perceptions and attitudes about what can be done, what should be done, and what is possible. It is about a return to the fundamental engineering design practices. It is about building and developing a workforce that will have the skills and capabilities to build the next generation of spacecraft and space systems to enable human exploration beyond low earth orbit.

- Provide hands on work to civil servants and some key contractor partners (roughly targeting a 75%/25% CS to contractor split)
- Understand the underlying engineering trades and drivers through simple analysis and testing
- Build prototypes early and often to drive out design issues, operational concepts, and flight requirements

- Test relentlessly
- Take smart risks
- Strive toward simple designs
- Accept the risk of test failures in order to learn, iterate, and advance more quickly
- Encourage openness and curiosity regarding new design and analysis techniques
- Leverage off existing facility and institutional capacity
- Leverage and coalesce existing efforts and technology
- Build and manage a coalition of innovative and traditional partnerships

The design, development, test, and operations of this mission will leverage technology work in the Agency that is already ongoing, partnerships that have been in place for many years, and facilities and resources that already exist. Additional partnerships will be required and much additional engineering work is ahead, but the project will leverage and coalesce a tremendous amount of previous work. An integrated technology demonstration is necessary to mature those leveraged technologies to enable more cost effective human space flight.

The project will team with key partners in industry (including emerging aerospace companies), academia, within NASA, other government agencies, and international partners. All teaming arrangements will be based on the technology, hardware, or expertise that partner brings to bear. The project will also seek innovative and unconventional non-aerospace partnerships.

Technology

The mission is a technology demonstration and will be managed as such. The project will mature four primary technologies applicable to human exploration. These technologies are already at Technology Readiness Levels (TRL) of 5 or 6, but an integrated flight demonstration is required to fully enable them for human space flight. The technologies will be discussed in greater detail in later sections but a summary is provided below:

Technology	Why?	Projects Leveraged
Lox/Methane Propulsion	• Space storable • "Green" propellant • ISRU potential at Mars • Enables easy and safe testing	Exploration Technology Development Program (ETDP) • Cryogenic Fluid Management (CFM) • Propulsion and Cryogenic Advanced Development (PCAD)
Autonomous Landing and Hazard Avoidance (ALHAT)	• Precision landing • Hazard avoidance • Applicable at any destination • Synergistic with autonomous rendezvous and docking	Exploration Technology Development Program (ETDP) • ALHAT
Radiation Hardened by Design	• First space use of RHDB	Multi center consortium

(RHBD) Processor	• Becomes the ubiquitous processor for any spacecraft and spacecraft application	
Dexterous Humanoid Robot	• Working side by side with the crew • Capable of doing work when the crew is not present • Performs tasks risky or hazardous to the crew • Symbol of technological prowess	NASA/GM Project Robonaut 2 Exploration Technology Development Program (ETDP) • Human Robotic Systems

Why a Humanoid?

NASA is interested in a humanoid form for many reasons. The primary reason is a dexterous anthropomorphic robot can use the same tools and work in the same work space as a human, eliminating the need to develop specialized tools. A dexterous hand able to manipulate objects nearly as well as a human makes the robot more versatile to perform tasks that were not anticipated when it was developed. R2 is designed with certain intrinsic technologies and safety features that make it safe to work side by side with a human. A humanoid is more intuitive for an operator to train to do a task. For example, an operator can wear a set of gloves that are mapped to the robot's hands and the operator can then perform the task while the robot records those movements.

There are many options for mobility on a planetary surface, NASA has investigated several in the past including putting Robonaut 1 on a Segway and on a four wheeled base called the Centaur. Legs are certainly challenging and the engineering required to solve that challenge is formidable. The advantage to legs are in climbing ladders and steps and very difficult terrain such as rock piles. Legs are lighter than a wheeled based. There is some data that indicates for some conditions on a surface of low gravity like the moon, legs may actually provide higher speed locomotion than wheels.

There are some public engagement reasons for a bi-pedal robot also. There is a natural human instinct to have empathy and to relate to the human form. The other reason is because it is challenging and therefore demonstrates NASA and the country's technological prowess.

Finally, robotics will be the defining technology of this century. A humanoid robot will the iconic symbol of the culmination of that technology. A humanoid robot will be to this century what the automobile, the television and the personal computer were to the last century. Modern manufacturing is enabled by robotics. Future prosthetics for amputees will be an important application of advanced robotics. The nation that leads the industry of robotics, the nation that designs, produces, and markets robots, will dominate the global economy in this century. The United States through NASA, with this mission, can begin to lay claim to this critical element of our future.

Why 1000 Days?

A thousand days creates a sense of urgency in the workforce, which is a compelling motivation and force multiplier. It stresses our process and tools, generating new approaches, and uncovering inefficiencies. A thousand days has the promise of changing the conversation and attitudes about what is possible.

Within the Agency, there is a compelling case to be made for maturing these key technologies as rapidly as possible so that they can be ready for human space flight programs, regardless of destination.

Finally, the span of 1000 days nearly parallels a student's high school or college interval. Project M seeks to inspire a generation of students, and it is important to set a target launch date that is near enough in the future that they can expect to see it through over its lifecycle.

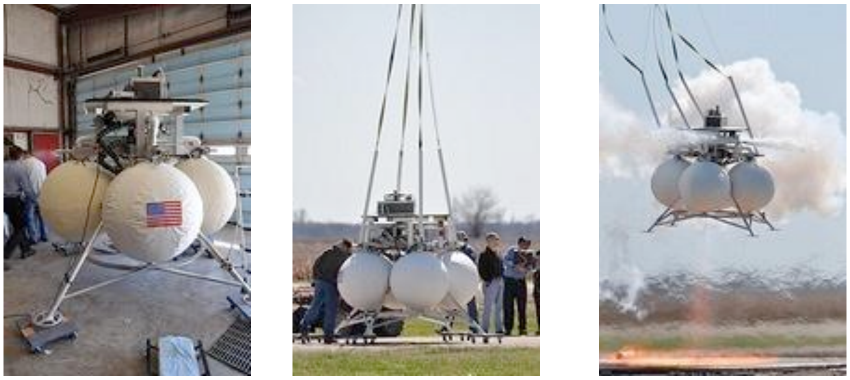
Project Overview

The Engineering Directorate at the Johnson Space Center has been considering and developing this idea since November of 2009. In the period since a small engineering team at JSC has been formed to evaluate the project and further mature the concept. The team is continuing to develop the relevant technologies and has integrated them onto the first lander prototype. The team is also developing products required by NASA's project management guidelines and is forming innovative partnerships to help fund the initial work. Some key initial project management products include Needs, Goals, and Objectives, Level 1 Requirements, Work Breakdown Structure, Initial Project Schedule, Draft Risk Database, and Initial Concept of Operations.



A number of engineering milestones have been accomplished or are underway. A prototype lander has been assembled in partnership with Armadillo Aerospace and has conducted several tethered flights. The first free flight tests will be conducted in May 2010. Another key partnership with the Institute for Human Machine Cognition (IHMC) has provided expertise and walking algorithms and software to JSC. IHMC team members working with JSC engineers have conducted the first successful tests of IHMC's leg prototype in JSC's gravity off-load facility in April 2010.

The following sections detail some of the work conducted to date.



Initial Testing of Prototype Lander

GN&C Instrument Package

Prototype Legs Walking in Active Response Gravity Offload System

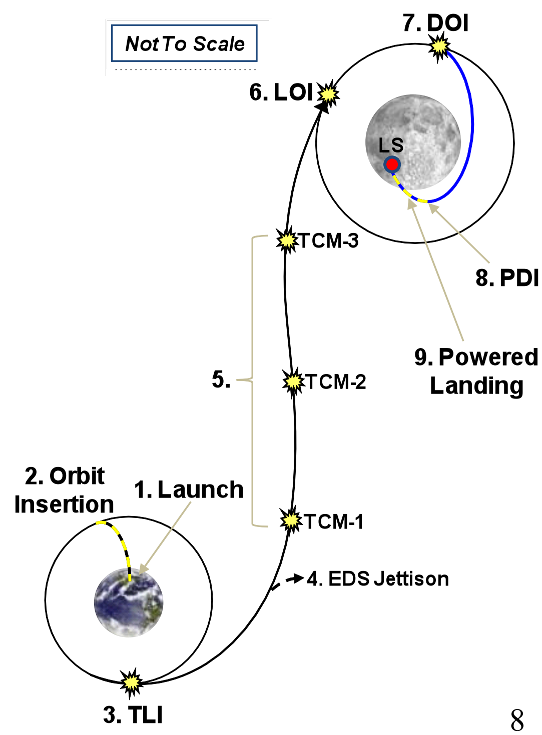
Project Needs, Goals, and Objectives

Need Statement: There is a need for a flight project that will demonstrate and integrate high risk technologies for Human Space Flight in a relevant environment and which can be used to educate and inspire the public and students in the areas of Science, Technology, Engineering and Mathematics (STEM).	
MISSION GOALS	**MISSION OBJECTIVES**
Mission Goal 1: Advance, demonstrate and integrate technologies needed for future Human Space Flight to other planets or near-earth objects.	**Objective 1-1**: Demonstrate LOX-Methane propulsion in a relevant environment.
	Objective 1-2: Demonstrate autonomous precision landing.
	Objective 1-3: Demonstrate humanoid robot walking on lunar surface.
	Objective 1-4: Demonstrate Earth-based supervised control of humanoid on lunar surface.
	Objective 1-5: Perform tasks in preparation for future human operations on the Moon.
Mission Goal 2: Educate and Inspire STEM.	**Objective 2-1**: Involve educators and students (K-12 and universities) in all phases of Project M.
	Objective 2-2: Involve and communicate to the public.
Mission Goal 3: Streamline agency practices and processes and use unconventional partnerships.	**Objective 3-1:** Revitalize the human spaceflight civil servant workforce.
	Objective 3-2: Leverage existing institutional capacity.
	Objective 3-3: Streamline processes for efficiency.
	Objective 3-4: Use unconventional partners for innovation.
	Objective 3-5: Demonstrate NASA's ability to perform lunar flight project in 1000 days.

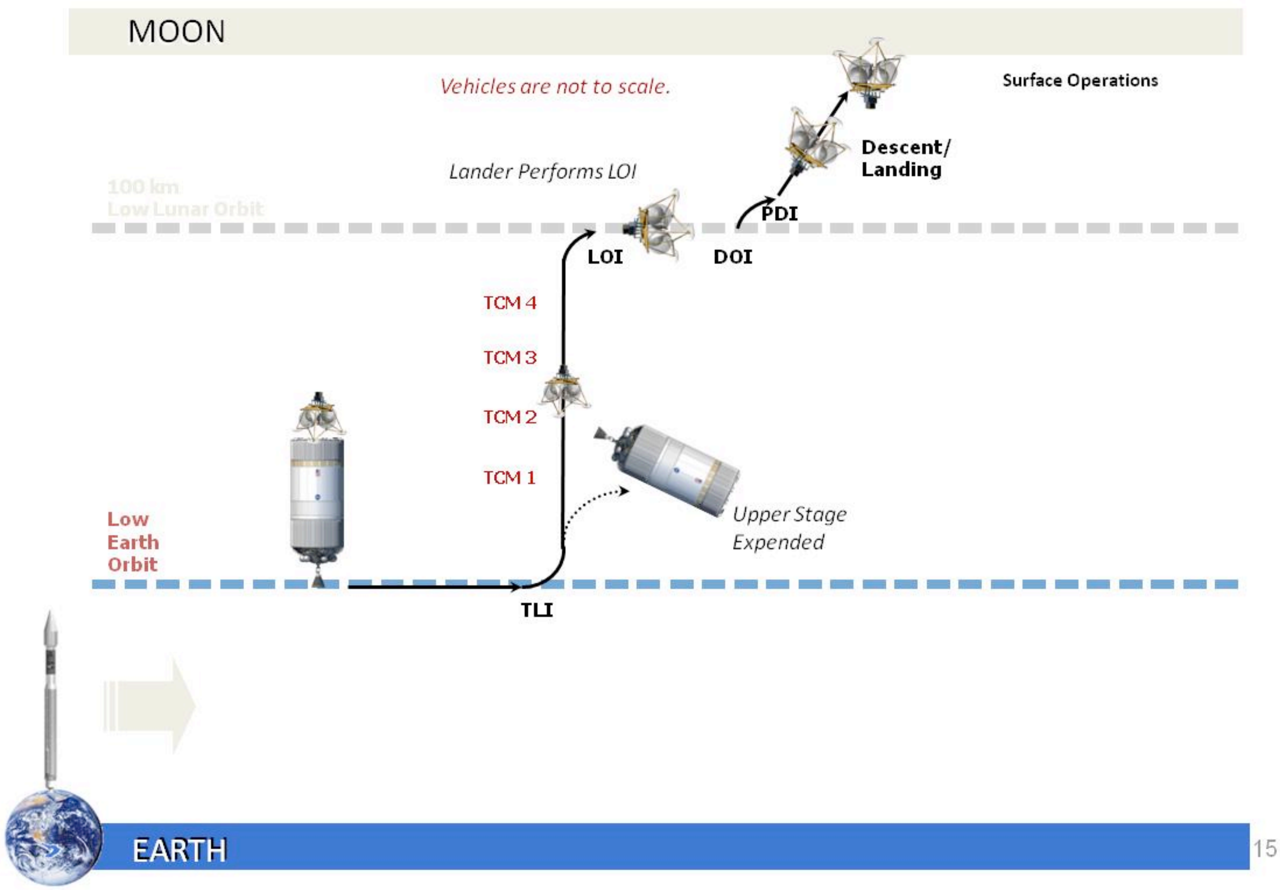
Level 1 Requirements

TECHNICAL:
1. A Robotic Humanoid shall be delivered to the lunar surface.
2. The Lander shall use LOX-Methane Propulsion.
3. The Lander shall perform autonomous precision landing.
4. The Humanoid shall walk on the lunar surface.
5. The Humanoid shall be capable of supervised control from Earth.
6. Education and scientific/engineering tasks and experiments as defined in the XXX document shall be performed while on the lunar surface.
7. The Humanoid operations on the lunar surface shall be viewed in high quality video from Earth.
8. The Humanoid shall be able to initiate and transmit verbal messages to the Earth.
PROGRAMMATIC:
1. The project shall involve educators and students from K-12 and universities in the development and operational phases of Project M.
2. The project shall involve and communicate to the public.
3. The project shall be accomplished in 1000 days from Authority to Proceed to Lunar Landing.

Mission Concept



The mission will be launched from the Kennedy Space Center on a commercial expendable launch vehicle and inserted into a trans-lunar trajectory. Mission operations will be conducted from the Johnson Space Center. Transit time to the moon is approximately 3-4 days. At the moon the spacecraft will be inserted into a low lunar orbit where it will orbit until ready to perform the entry, descent, and landing (EDL). The EDL is a powered descent using a liquid oxygen and methane engine and autonomous precision landing and hazard avoidance guidance, navigation, and control system. The spacecraft will be delivered to a landing spot within 100 meters of the target. Landing sites of interest may include, but are not limited to, an Apollo landing site or a site of scientific value such as the Aristarchus crater.



Once on the surface, checkout and deployment of the humanoid robot will begin. The deployment mechanism will be designed such that the robot limbs can be tested without the danger of the robot falling. When the robot systems are fully evaluated the robot will be released to a standing position.

The robot will be capable of operating on battery power for approximately 1.5 hours on a single charge. In the current concept of operations the robot will plug itself back into the lander for recharge using the lander's solar arrays and will therefore be able to conduct multiple sorties. The robot will be capable of performing a number of tasks on those sorties. The tasks may include performing a representative maintenance task, a science experiment, or conducting a simple experiment that could be repeated in the classroom (e.g. Galileo's famous gravity experiment). Representative maintenance and construction tasks might include deploying a solar array, deploying instruments away from the lander, constructing a thermal shield, or reconfiguring hardware on the lander.

For educational, scientific and situational awareness, one of the level one Project M requirements is to have high quality video of the Robonaut activities while on the lunar surface. Multiple camera views will be provided in near real time, such as views from both the robot's perspective and from an external (third person) view. In addition to lunar surface operations, near real time video will be available from multiple development facilities throughout the lifecycle of the project. This will ensure the involvement and interest of educators, students and the general public in the project. Given the goal to educate and inspire students of all ages, this high quality video ensures their involvement during development and lunar surface operations.

Relevant Technologies

As mentioned previously, one of the goals of this project is demonstration of a few key technologies. These technologies have been maturing separately and at their own schedule. This mission provides a focus and an opportunity to demonstrate the technologies in a relevant space environment. Too often NASA fails to develop technologies to a level at which a program or project can utilize them. Because of that the technologies often are deemed too risky to adopt by large scale development programs. As a result the large scale development programs by definition are only incremental and fail to fully drive the state of the art in space systems, and are not able to realize cost savings through innovative approaches. By focusing key technologies on a flight demonstration, those technologies are then available for a multitude of other applications.

Project M has four key technologies. Three are part of the lander:

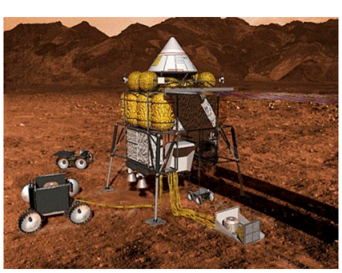
1) Liquid oxygen/methane propulsion system (LOX/CH4)
2) Precision landing and hazard avoidance hardware and software
3) Radiation Hardened By Design (RHBD) computer processor.

The other key technology of course is the humanoid robot itself. The humanoid robot has application in both the space environment and the terrestrial environment.

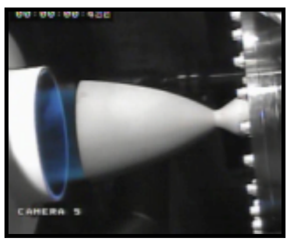
The relevant technologies are discussed in more detail below.

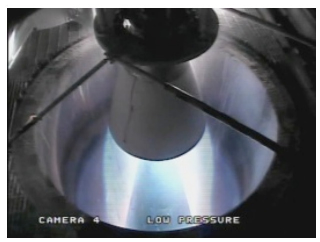
Lox/Methane Propulsion

Technology advancements are needed to robustly explore the solar system; the Apollo-era technologies and propellants for spacecraft are not sufficient. The Mars design reference mission (DRM) studies have identified a need for Liquid Oxygen (LOX)/methane in the architecture, primarily for the lander. A mission architecture can benefit from in-situ production of propellants on the mars surface, thereby reducing the number launches from earth. Oxygen and methane are both capable of in-situ propellant production on the Mars surface. In addition, these long duration exploration missions place more importance on the need for propellants that are higher density and more easily stored for long durations in space and on Mars than liquid hydrogen. The higher density and moderate cryogenic temperature also means that the engines can be either pressure-fed or pump-fed designs. Pressure-fed propulsion systems provide a higher reliability for many spacecraft applications due the simplicity of the engine cycle. The combination of high propellant performance, space storability, smaller propellant tanks, improved system reliability, and in-situ propellant compatibility means that LOX/methane is enabling to exploration. These benefits are also applicable to CEV service modules and lunar vehicles, thus providing a stepping stone to Mars.




Another pull for LOX/methane propulsion has come from the need to have non-toxic, operationally efficient propellants, as compared to the 50 year old technology using toxic (carcinogenic) propellants. Many small commercial launch vehicles have gone to LOX/hydrocarbon or alcohol propellants rather than use toxic propellants or liquid hydrogen in order to improve ground operations and reduce vehicle size and costs. Of the various hydrocarbons, methane has been identified in studies performed since the 1980's as the best propellant for reusable booster and reaction control systems in part due to its clean burning, high density, and high performance combustion characteristics. These characteristics are important for human exploration spacecraft, such as landers and service modules. For Project M, the non-toxic propellants allow operationally efficient ground and flight test to be carried out routinely. Liquid oxygen is very low cost, 4 cents per lb_m, as compared to toxic propellants costing 100 dollars per lb_m. This means that test vehicles can be flown much more often for a fraction of the cost.





Recently, LOX/Methane propulsion system tests have been performed in simulated space vacuum environments on the ground. The results have been excellent. The Exploration Technology Development Program (ETDP) Propulsion and Cryogenics Advanced Development (PCAD) and Cryogenic Fluid Management (CFM) projects, comprised of GRC, MSFC, JSC, KSC engineers, along with strong industry partners, have invested significant amount to develop and ground test liquid oxygen and methane propellant since 2005. The technology even traces its roots back to the 1980's. These ground tests have shown the demonstrated the capability for higher performance, reliable ignition, and cryogenic fluid management. Lox/Methane engines have been tested by Aerojet, ATK, Pratt and Whitney, XCOR, Armadillo Aerospace, Northrup Grumman, WASK, and others. At GRC test facilities, tests on liquid oxygen and methane cryogenic propellant have been conducted to develop technologies needed for space storage and acquisition of liquid propellants from the tanks in zero-g. Project M proposes to continue this work through its industry partners, to leverage emerging technologies through the use of SBIRs and innovative partnerships, as well as engage Universities and its students. Currently, the primary hurdle to using LOX/Methane for human missions is the lack of in-space flight experience. The Project M lander builds on the ETDP work and gains the needed flight data that would allow a program manager to use these propellants for human spaceflight. This flight experience will be critical to the risk reduction effort needed to eventually field these propellants on the lunar surface and mars for human spacecraft.

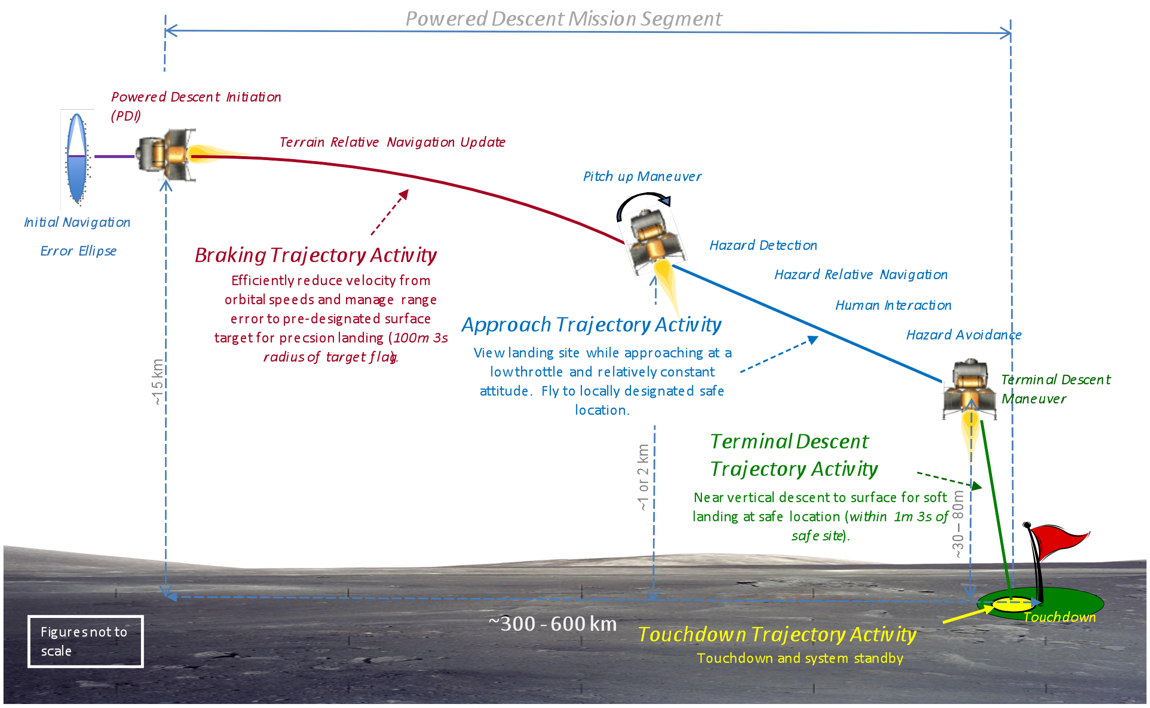
Precision Landing and Hazard Avoidance Hardware and Software

One of the objectives of the Project/Concept M is to demonstrate and to advance the Technology Readiness Level (TRL) of precision landing and hazard avoidance capabilities developed by the Autonomous Landing and Hazard Avoidance Technology (ALHAT) system. The ALHAT project is currently funded by NASA through the Exploration Technology Development Project (ETDP) and managed by the Johnson Space Center (JSC) Engineering Directorate to develop an integrated Autonomous Guidance, Navigation, and Control (AGNC) hardware and software system capable of detecting and avoiding surface hazards and autonomously guiding a manned or unmanned space vehicle, to a safe touchdown within 90 meters of a pre-designated planetary or asteroid site. The project began in 2006 and is scheduled for completion in 2012, with a team of technical experts from JSC, Draper Laboratory, Jet Propulsion Laboratory, Langley Research Center, and Applied Physics Laboratory at Johns Hopkins University.

The ALHAT project is using onboard laser altimeter and flash Light Detection and Ranging (LIDAR) for the onboard sensors to perform Terrain Relative Navigation (TRN) and Hazard Relative Navigation (HRN). A flash LIDAR flashes a very quick laser beam over a planetary surface of approximately 100 x 100 meters. This same technology is cross-cutting as it is also being employed by commercial ISS supply companies and by the NASA Orion project for automated rendezvous and docking (AR&D). The photons emitted from the LIDAR strike the surface of the target object or surface and return to a timing detector grid, giving very precise range and bearing measurements for each photon 30 times a second. These three dimensional measurements provide elevation information for each small segment of the surface, thus producing a digital elevation map that can be used to determine hazards to the landing vehicle. Software algorithms then interpret this information and determine the safe regions to land without hazards. To avoid problems associated with surface dust while descending to the safe region, the ALHAT system is being designed with sensors, such as a Doppler LIDAR velocimeter and an Inertial Measurement Unit (IMU), and software such that the lander attitude, altitude, and velocity of are precisely known at all times during the final phases of landing. The onboard navigation system uses these surface relative measurements to navigate to the chosen safe region accurately enough for the last 30 seconds of the descent phase regardless of any dust disturbed by the descent engine.

While lunar landers were used successfully during the Apollo era, there were certain risks taken with Apollo that NASA intends to reduce or eliminate in future lunar vehicles, regardless of whether these are manned or unmanned. The ALHAT technology will also allow us to safely land on various planets, moons, and asteroids at essentially any desired surface location under any lighting conditions. To achieve the necessary technology readiness level, the ALHAT sensors and software package have to be tested and demonstrated. With successful tests and demonstrations currently underway the ALHAT system can be verified to TRL 6 by August 2010. With a successful space demonstration of ALHAT system on the Project M (i.e. safe landing on the Moon), the ALHAT system can be elevated to TRL 9, and can safely be used for future manned or robotic vehicles at any destination in the solar system.

ALHAT Powered Descent with Approach Phase Highlighted



Radiation Hardening by Design (RHBD) Technology coupled with Multi-core processing

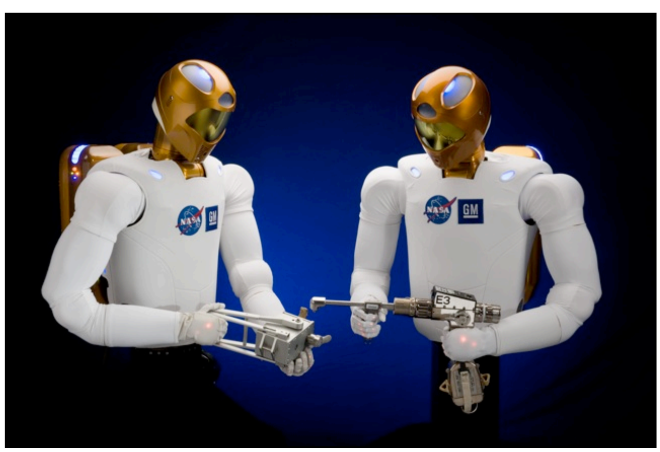
The objective of Radiation Hardening by Design (RHBD) technology is to develop and employ design techniques that allow the fabrication of radiation hardened integrated circuits using design approaches only. This is in contrast to traditional methods that rely on specific manufacturing changes in fabrication, processes, or materials in order to produce a space-rated product. RHBD would allow commercial manufactures to produce electronic components suitable to withstand the space environment more readily and with less expense and employ existing infrastructure while using common materials. There have been significant advances in this technology led by DoD efforts.

A parallel technology, multi-core processing (as opposed to a single core CPU) is becoming the standard for general purpose as well as high performance computing. In order to achieve the automation necessary for long-duration spaceflight missions, employment of multi-core processors using parallel processing software techniques is essential. Highly sophisticated computing requires high computing power, and the traditional means of increasing computing by simply adding more CPUs, card by card, into a space system is neither mass nor power nor volume efficient. Successfully using radiation hardened by design technology coupled with a multi-core processor architecture will forge a new era in space-based computer processing by allowing the growth of more sophisticated software applications with readily available hardware, and by forming the basis for future low mass/power/volume avionic and space computing system designs. Additionally, because the space and general commercial systems will share a common design and software tools, applications and infrastructure developed as a result of this technology will easily migrate to and from terrestrial applications.

Project M will employ the first civil space application of a multi-core processor designed using RHBD techniques to withstand the space environment. Project M will use a Maestro/Tilera48 processor, first available in 2010, for its automated landing and hazard avoidance vision system. Upon successful use of this technology by the ALHAT sensor system in M, a path for the full-migration of other spacecraft and robot computing and software will be established. It is envisioned that future flights of spacecraft and space robots would employ a multi-core processor system for their computing needs, taking advantage of the greatly increased distributed computing power and parallelism achievable over current means.

Robonaut 2

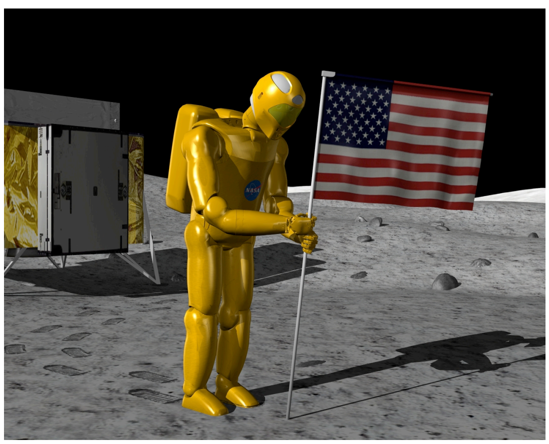
The Robonaut 2 (R2), developed by JSC Engineering in partnership with General Motors, is a state of the art anthropomorphic robot, with the payload, speed and dexterity that enables it to do work, differentiating it from other humanoid robots. Like its predecessor Robonaut 1 (R1), R2 is capable of handling a wide range of EVA (astronaut) tools and interfaces, but R2 is a significant advancement over its predecessor. R2 is more than four times faster, is more compact, is more dexterous, and includes a deeper and wider range of sensing. Advanced technology spans the entire R2 system and includes: optimized overlapping dual arm dexterous workspace, variable stiffness series elastic joints, extended finger and thumb travel, highly integrated electronics, miniaturized 6-axis load cells, redundant force sensing, ultra-high speed joint controllers, extreme neck travel, and high resolution camera and IR systems. Currently 36 patents have been filed based on the R2 design.



Robonaut 2 – Upper body systems with EVA tools

Several lower bodies were developed as part of the R1 series: a single leg for stabilization in space, a 2 wheel indoor mobility platform and a rugged 4 wheel mobile base for navigating planetary analog environments. For mobility on the moon, the advanced electro-mechanical joint technology that has proven itself out in the R2 upper body will be leveraged to yield the first set of Robonaut legs. NASA will team up the non-profit Institute for Human and Machine Cognition (IHMC) located in Pensacola, Florida and adapt their world class walking algorithms to produce gaits that will give R2 mobility in the 1/6 G lunar environment. When completed the resulting humanoid robot will have an unprecedented capability to navigate and perform work on the moon.

While putting the first humanoid robot on the moon is a great engineering feat in itself, the benefits extend into many areas. A dexterous robot, equipped with human size arms, hand and legs has the unique ability to test out systems in space for future human missions that is not possible with any other robot, providing early performance data that can be utilized to improve designs, enhancing crew safety and mission performance. After proving itself out on its first Lunar mission, Robonaut will be well positioned to prepare future human sites and act as a caretaker for lunar assets in-between missions. Additionally, humanoid robots are exciting and inspirational. A technology savvy American public, especially young students, can identify with a humanoid robot engaging them in NASA's missions, and highlighting the importance of science and technology education.



Concept of Robonaut Planting a Flag on the Moon

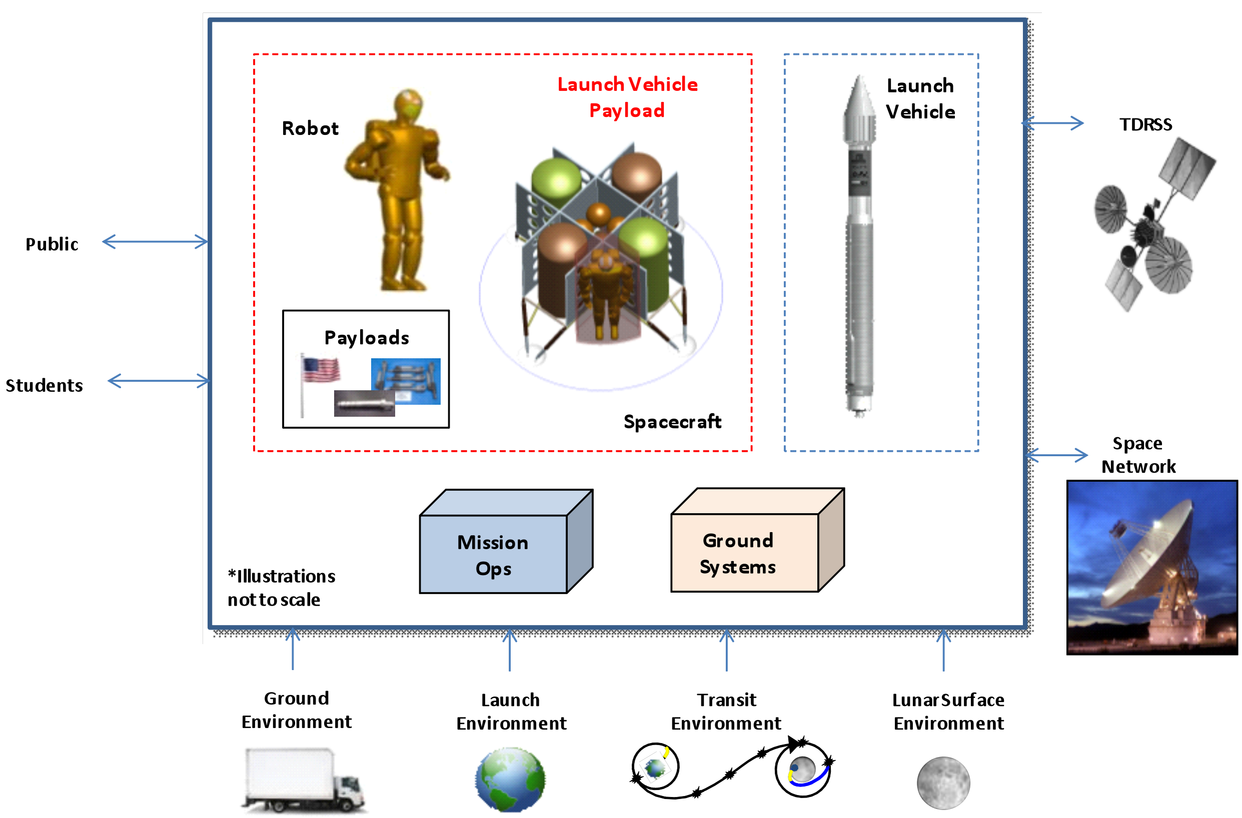
The NASA partnerships have helped identify that Robonaut and its technologies have numerous applications here on Earth. Even before launch, GM is exploring the utilization of R2 technologies to improve product and manufacturing safety, product quality, and manufacturing efficiency. GM and NASA are also exploring how R2 technologies can be used in spinoff applications. NASA is currently working with Purdue University to optimize motor designs that are applicable not only to robot legs, but also other high performance systems: automobiles, electrical machinery, etc. The Robonaut team has established a partnership with Boston Power, Inc. that will accelerate "Green" battery technology to not only provide efficient energy storage in space but also less waste in our landfills. Robotics is essential to modern manufacturing. Also future prosthetics for amputees will be an important application of advanced robotics.

R2's advanced technology yields impressive performance, but its greatest advantage is the breadth and depth of work it can perform, setting it apart from its predecessor and other robotic systems.

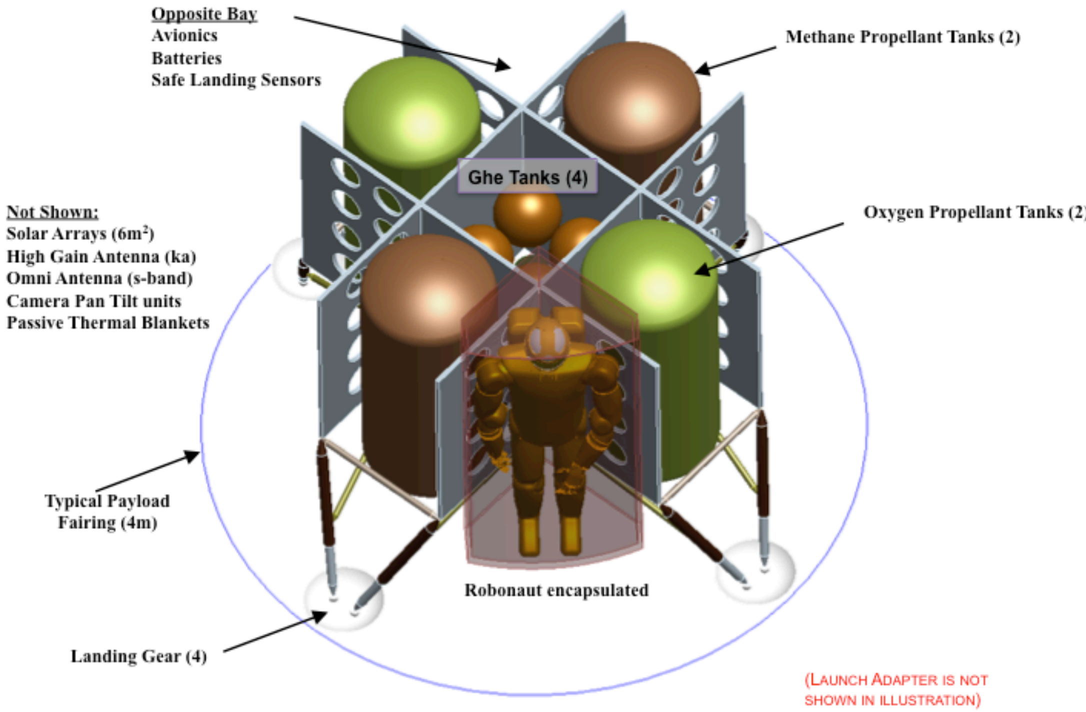
Technical Design Overview

The spacecraft design has a few key driving requirements that influence the basic layout. These include launch and landing center of mass, sensor location and field of view, power and thermal pointing and payload access to the surface. Since the propulsion system consumes most of the volume and mass, consideration must be made to packaging the propellant tanks and how the primary structural load is transferred to the launch adapter. Two basic configurations have emerged: four tanks and two tanks. Within the two configurations multiple sub trades of tank support and tank static loading have been investigated. A series of Risk Reduction free flying vertical test beds will be built to help down select the number of configurations and generate a baseline for the flight vehicle. This design a little, build a little, test a little approach significantly buys down programmatic risk early. The tangible benefits include a fast paced streamlined development cycle and visible progress relative to the stakeholder community.

In the overall context of the Project M system, the Robonaut and secondary payloads are integrated with the spacecraft, which is integrated with the launch vehicle. Both of which require interfaces with Mission operations and ground operations. The external interfaces include network assets, natural and induced environments and stakeholder engagement.



The major components of the spacecraft system are the liquid oxygen and methane propulsion subsystem, the structure and mechanisms subsystem, the Avionics/Communication/Power subsystem, the Guidance, Navigation and Control subsystem, and the Robonaut Payload. A conceptual layout is illustrated in the following figure.

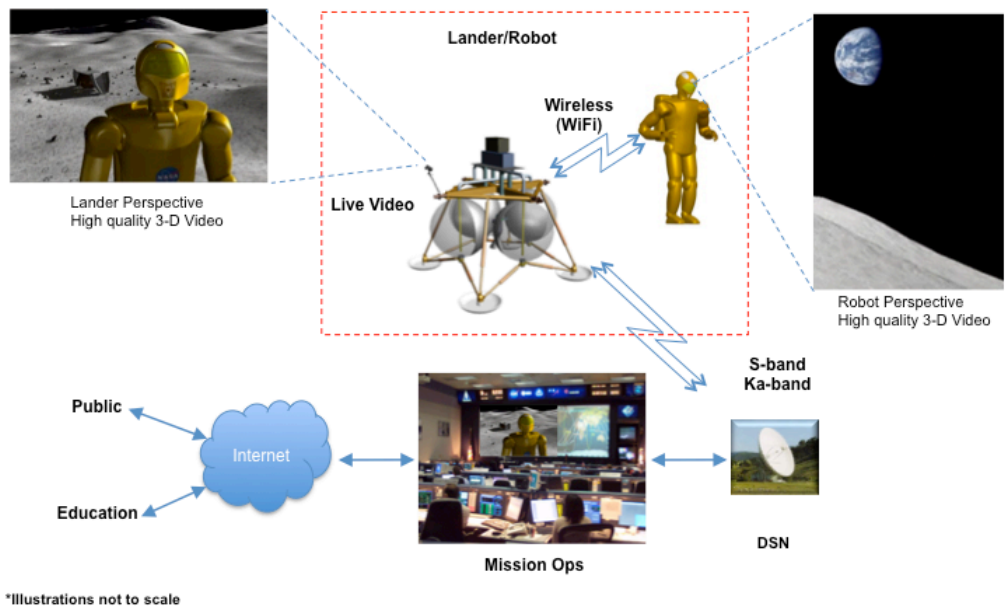


Conceptual layout for a full-scale lunar flight vehicle

The propulsion system is driven by the need to provide attitude control and course correction maneuvers during transit as well as a throttled 2000 lbf main engine that provides lunar orbit insertion, de-orbit, powered descent and soft touch down on the lunar surface. The total delta velocity is just over 3 km/sec, which makes the propellant mass fraction just over 65% of the spacecraft wet mass. There are opportunities to refine the trajectory and realize increased engine Isp performance that could significantly reduce the mass fraction to the benefit of added payload to the surface.

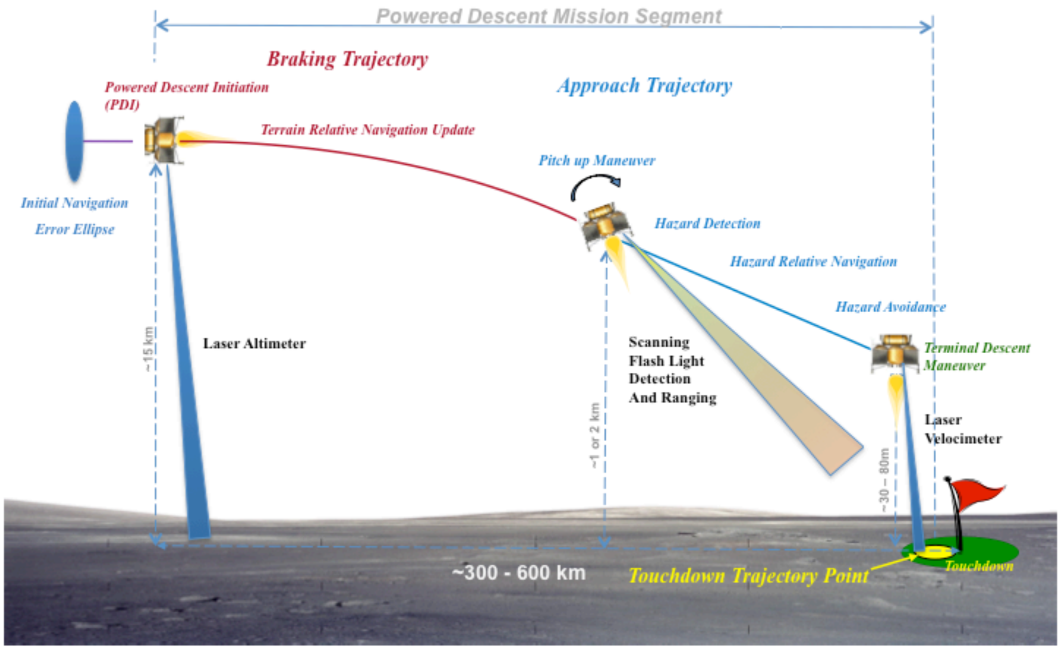
The structure and mechanism subsystem is responsible for sizing the structure for the static and dynamic loads over its lifecycle. The mechanisms development includes the payload restraints for Robonaut and associated deployment of solar arrays and cameras. Part of the structures and mechanism subsystem design effort is to package the secondary structure elements and determine the optimum blend of manufacturing materials and processes to produce a light weight, cost effective structure. A significant ongoing trade for structures is the use of composite materials and the determination of the right balance and implementation to provide a realizable spacecraft.

The avionics, communication, and power subsystem provides all command and data handling, software development, and power distribution and storage for the spacecraft. The architecture relies heavily on using proven flight computers and software reuse to speed development time. The communication architecture is driven by the need to transmit high bandwidth video from the surface of the moon. This necessitates the use of Ka band communication that was pioneered by the Lunar Reconnaissance Orbiter (LRO) and leverages the same ground infrastructure. The software architecture uses the GSFC developed Core Software Tool suite as its core modules.



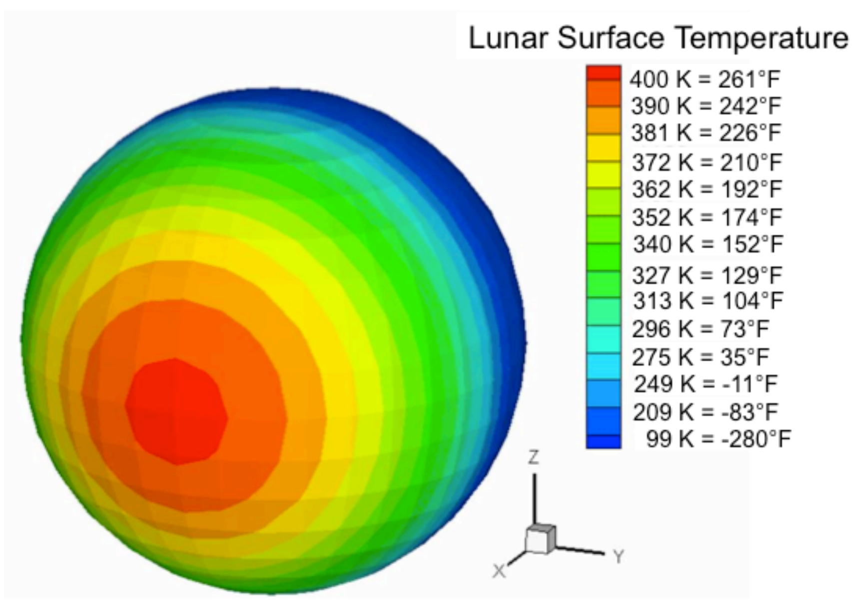
Communication architecture

The Guidance, Navigation & Control (GN&C) subsystem has two distinct phases of operation: in space transit to the moon and lunar surface safe landing. The transit portion relies on a state of the art inertial measurement unit updated by both commercial star tracking cameras and RF transponders. Once de-orbit to the lunar surface has commenced a laser altimeter supplements navigation knowledge and guides the spacecraft to the landing area. About a kilometer away from the landing site, a new safe landing system will be demonstrated for the first time that uses a flash LIDAR camera that scans the landing area for hazards and guides the spacecraft to a safe area to land. A second safe landing system will use a laser velocimeter to ensure a soft touch down. A pictorial of the landing phase is show in the next figure.



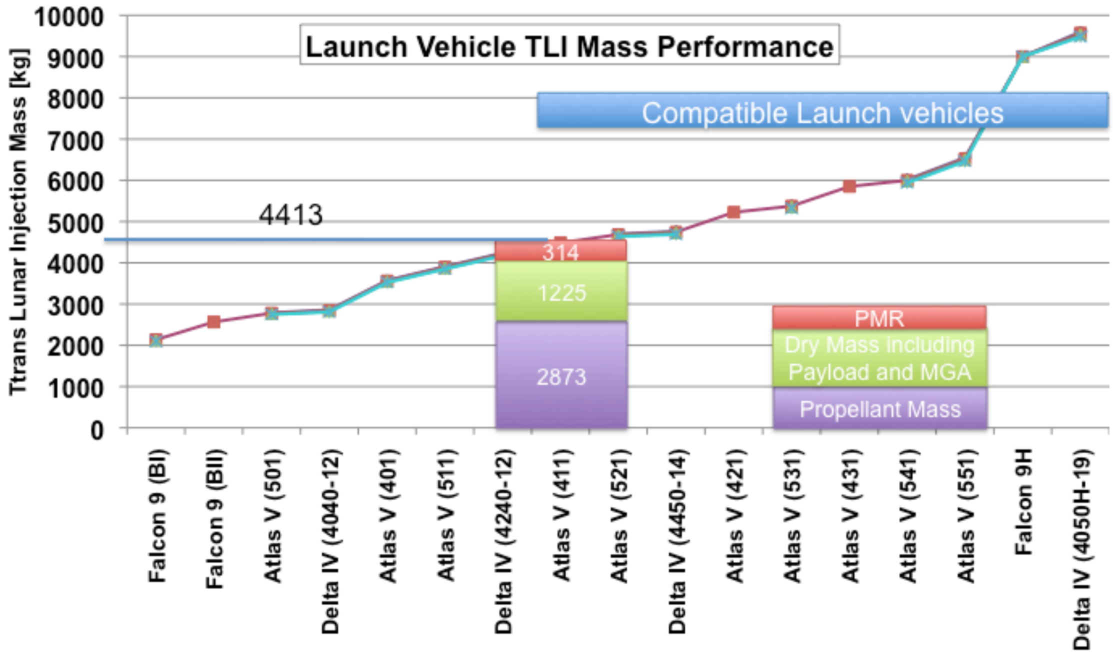
ALHAT Landing System

The overall integration of the Robonaut payload completes the spacecraft description. One of the major integrated system challenges for mid latitude landing sites is the thermal environment. Special consideration for extreme hot and cold cases will necessitate creative passive thermal designs. The lander and robot operations will be restricted to the early morning and late afternoon when the sun is low on the horizon. Robonaut will have to seek shelter during the peak of the day and before nightfall to maintain electronic components and batteries within the acceptable storage temperature limits. Survival through the night may not be feasible based on thermal and power storage requirements.



Lunar day and night temperatures (radiative sink temperature)

The spacecraft design follows established guidelines and NASA standards for the design factors of safety and qualification of the end-to-end system. The mass and power are margined according to life cycle phases. The pre Phase A mass statement for the spacecraft has approximately 20% mass growth allowance and 15% project manager reserve. A comparison of launch vehicle capability versus spacecraft translunar injected mass is show in the following figure and suggests that the spacecraft will require a launch vehicle with a payload capacity of an Atlas V (411) or larger.



Pre phase A mass statement compared to launch vehicle performance

The lunar lander spacecraft has enormous potential for technology advancement by integrating new green propellants and state-of-the-art hazard avoidance and landing controls, but also by exploring recent innovations in structural materials. Recent advances in cryogenic tank composite materials and the manufacturing and processing of such material structures has progressed intensely so as to create a lighter-weight vehicle that maintains all the structural integrity of much heavier lander design predecessors. This material property advancement has such a tremendous weight advantage that it is expected to be integrated into either the first lander design or else one of the immediate successive lander designs in the flow.

The deployment mechanism that lifts and sets the robonaut gently onto the lunar surface in a vertical standing position is directly incorporated into the lander, as well as the protective launch and landing restraints for the robonaut. The restraint and deployment will include proper vibration and shock attenuation, power, data, and communication connections. After robonaut deployment onto the lunar surface, the lander will also provide a power recharge station for the robonaut as well as accessible thermal conditioning to ensure proper protection from the immediate lunar surface temperatures which, dependent on precise landing location and time, are likely to range from -100F to +250F. Thermal protection will also be provided for all other subsystems during necessary operational and non-operational timeframes.

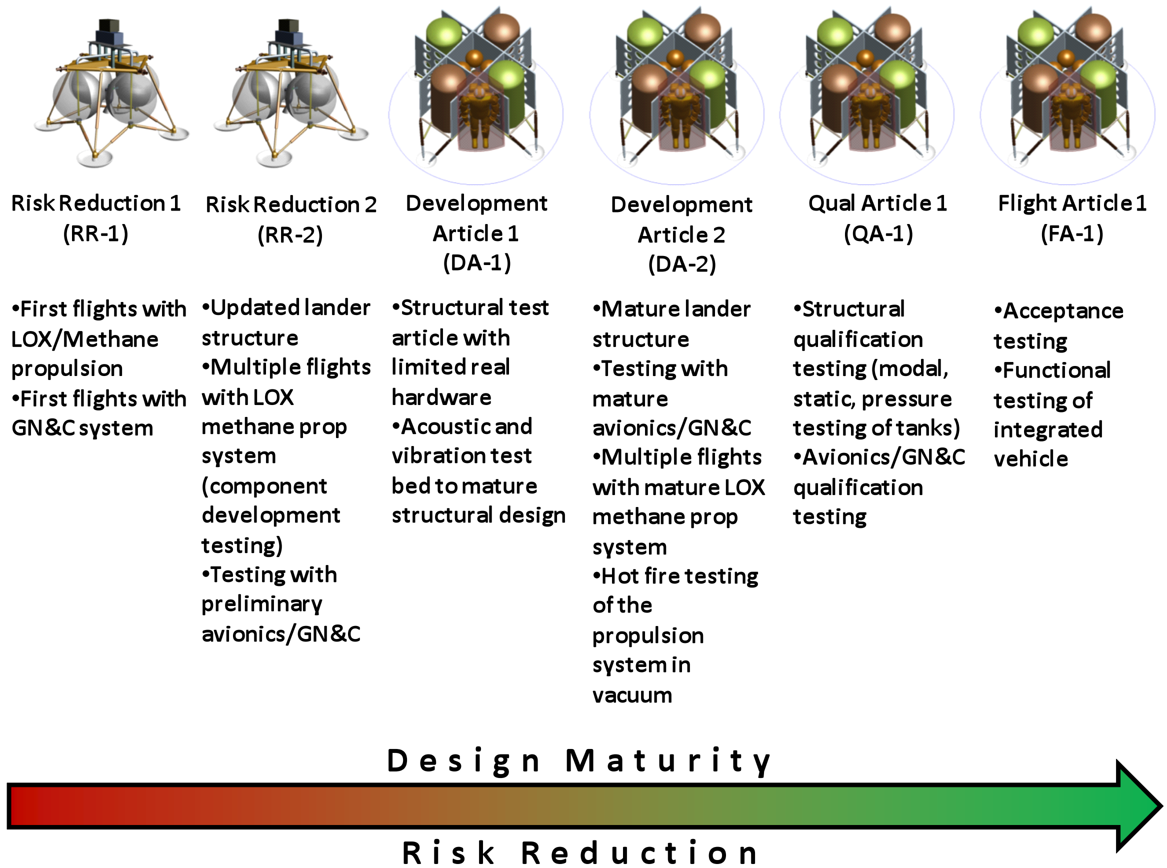
Lander power will be supplied by a combination use of batteries and solar arrays. The solar arrays will remain stowed safely for launch and then deployed after lander spacecraft separation from the expendable launch vehicle main engine. The solar arrays will continue to supply power for the approximately 4 travel days leading up to lunar descent, at which time they will be retracted until landing is complete. Re-deployment of the solar arrays after landing on the surface will occur with a different orientation based on solar orientation at the landing time of day.

Test and Verification Approach for Project M

Mission reliability is established through rigorous testing and analysis to ensure (or certify) the vehicle design performs as intended. The testing and analysis requires the definition of loads and environments to which the spacecraft is exposed. The systems that comprise the Project M spacecraft (the major elements being the lunar lander and Robonaut 2) will mature through cycles of design, development testing and finally a series of qualification tests.

The philosophy for design and testing of the Project M spacecraft is to quickly execute several cycles of design and tests and analysis iterations. Components will be tested in the laboratory where several options may be evaluated via many tests conducted cheaply and quickly. For example, the liquid oxygen (LOX)/methane propulsion system team will conduct many thruster and valve tests in a small facility allowing for inexpensive, quick and controlled data collection. This will enable an efficient down select to a credible system design. System teams will build engineering evaluation units of each system for bench level evaluation and flight testing.

The team has envisioned a suite of lander test vehicles, or vertical test beds, which will be flown in Earth's atmosphere to incrementally demonstrate spacecraft performance. As each system progresses in maturity it is added to the lander which is currently in test. The following figure shows the suite of six lander vehicles the team intends to build, test and fly, with an associated overview of test objectives. The RR-1 lander is being assembled for testing the end of February 2010.



Project M suite of test vehicles and objectives

This design and test approach will allow the team to evaluate each system design (e.g. propulsion; guidance, navigation and control; avionics; and structure) in a timely fashion as soon as the design is mature enough for assessment. Testing the maturing spacecraft early and often will inform the design process in a much more rapid fashion than traditional serial process of design to final configuration and only then test the spacecraft.

In parallel with the lander design and testing activities, the robotics team intends to take a similar approach to design and test. A total of four R2 robots will be fabricated to develop and certify the system. A fifth R2 will be fabricated for educational outreach activities while a sixth R2 will fly to and operate on the lunar surface. Three of these units (built with engineering development unit fidelity) are envisioned for developing the algorithms and techniques for walking on the lunar surface, getting up from a possible fall, and understanding the effects of lunar soil and flight environments.

Engineers will test R2 extensively in the Active Response Gravity Off-load System (ARGOS) at JSC. The facility allows R2 to operate while suspended from a cable and actuator system that monitors and tracks the R2 position allowing continual off-loading of 5/6 of the R2’s weight.

Much like astronauts utilize a swimming pool to simulate the weightless environment of space and train for complex activities outside their spacecraft, R2 will train in ARGOS to simulate the one sixth Earth gravity of the moon. Through field testing on a simulated lunar surface complete with rocks, boulders and dirt the team will establish confidence in R2's ability to perform its mission on the moon.

The integrated lander/R2 spacecraft system will be exposed to a range of environments and loads including but not limited to:

- transportation and handling loads,
- launch static, vibration and acoustic loads,
- stage separation shock loads,
- thermal extremes and radiation exposure during the transit to and while on the surface of the moon,
- landing loads at touchdown with the lunar surface.

All of the components that comprise the M spacecraft will be certification tested for environmental loads at the lowest appropriate level (e.g. flight computers, robot motors, lander structure). Additional tests are envisioned at the integrated spacecraft level where understanding the interaction between systems is important (e.g. electromagnetic interference and thermal testing). Furthermore, it is critical to the success of the mission to test the functional performance of the vehicle's many components and at the integrated spacecraft system level.

Through the test and verification strategy described above, the Project M spacecraft will achieve a high reliability design while meeting the 1000 day launch schedule.

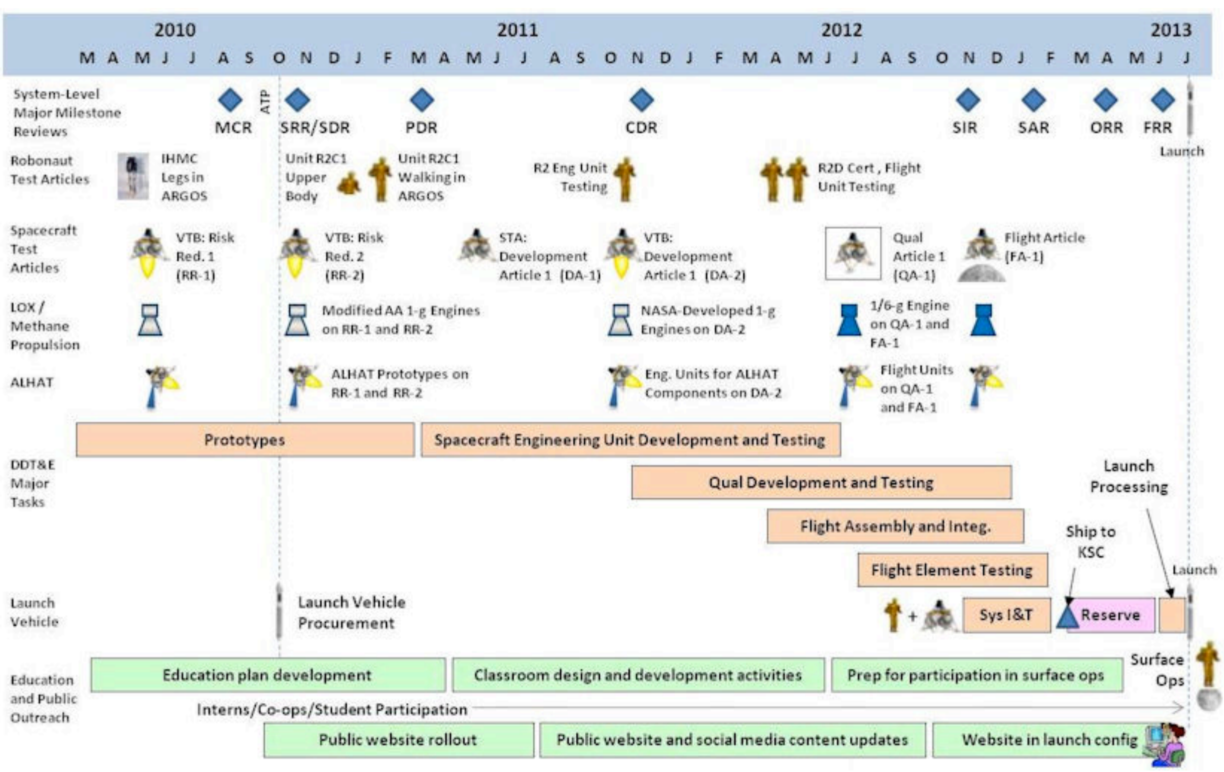
Additional Accomplishments to Date (as of April 1, 2010)

Subsystem	Accomplishments to Date
Propulsion System	• Hot fired RCS jet at ESTA • Pixel lander converted to LOX Methane • Several tethered flights conducted • Preparing for free flight testing
Command and Data Handling Camera and Video Power Communications	• Built initial C&DH hardware prototype for software development capability • Notional Avionics/Power/Communications/Video architecture completed • Identified the Avionics Integration Evaluation Lab for Project M GNC/software development
Structures and Mechanisms	• Compiled, reviewed, and screened numerous lander concepts with blue-ribbon panel as well as Project M community having all skill mixes • Emerged with two general concepts from which to develop various versions for feasibility assessment • Produced CAD and finite element models of both concepts • Performed early c.g. assessment, loads analysis, landing stability assessment, and minimum frequency checks • Manufactured mock-ups of both concepts • Initiated iterative assessment to populate structure with robonaut, remaining payloads, and secondary structure to optimize for R2 deployment, recharge, and thermal protection with adaptive solar-array configurations • Produced and screened numerous R2 deployment concepts to target versions for further assessment and prototyping
GN&C	• Initial end to end mission design • Developed RR1 GNC integration plan and procured hardware • Initiated refurbishment of NSTL with expected operations in March • Completed fabrication and testing of integrated GN&C package • Completed transit and LLO tracking navigation analysis study.
Software	• Identified software components, sizing, reuse and associated staffing needs • Chose target processor boards and allocated software components to processors • Received & assessed GSFC/LRO software for spacecraft reuse • Established software development tool chain and strategy for both Robot and Spacecraft
Thermal	• Initial thermal environment analysis complete

The 1000-Day Schedule

The figure below shows the high level project schedule over 1000 days. The schedule shown assumes a project authority to proceed on March 25, 2010 and a launch date of December 19, 2012. The timeline will naturally shift as the ATP date matures. Key features of this schedule include:

- System-level milestone reviews from Mission Concept Review (MCR) through Flight Readiness Review (FRR)
- Robot test articles for key test activities, and Robot PDR and CDR that are separate from (and earlier than) the System PDR and CDR
- Spacecraft test articles for risk reduction and flight system development
- LOX/Methane propulsion development milestones
- ALHAT development milestones
- System Design, Development, Test and Evaluation major tasks up to launch
- Key activities for education and outreach



Enabling a 1000-Day Schedule

There are many factors that affect a NASA project's ability to meet planned schedule. The GAO report released in February 2010, "Report to Congressional Committees: NASA Assessments of Selected Large-Scale Projects" provided an assessment of the cost and schedule performance for selected NASA projects. The authors identified six challenges that contributed to "cost and schedule growth in these projects: technology maturity, design stability, contractor performance, development partner performance, funding issues, and launch manifest issues."

The Project M mission is a technology demonstration mission. However, the key spacecraft technologies have been in development over three years or more. Furthermore, the technologies have been in development specifically for space applications, so there is a natural transition from the heritage technology development to a space flight demonstration. None of the spacecraft technologies have a Technology Readiness Level lower than a 4, and most are at 5 or better. All spacecraft technologies have plans to be at least a TRL of 5 by PDR and 6 by CDR. The plans include early environmental testing at the component level and development of multiple prototypes in order to perform parallel testing at multiple test facilities.

The Robonaut dexterous upper body has been in development for over ten years, and the current version, R2, has been in development for over three years and has reached a TRL of 6. The leg walking software is being developed in partnership with IHMC, and is already at a TRL of 5. All Robonaut technologies have plans to be at least a TRL of 5 by PDR and 6 by CDR. As for the spacecraft, the technology maturation plans include early environmental testing at the component level, and development of multiple prototypes in order to perform parallel testing at multiple test facilities.

Design stability was identified by the GAO report as a challenge that affects schedule. As per best practices, the project is planning to have at least 90% of the drawings complete by CDR. In addition, a rigorous test program is planned to increase design maturity prior to CDR.

The GAO's report listed contractor performance as a challenge, and Project M does not have a prime contractor. Development partner performance was listed as a concern; Project M does not propose any major partnerships but instead a number of smaller, innovative partnerships throughout the project. The team plans to have fall-back plans defined for any partnerships that are expected to result in products that are on the critical path.

The last two challenges called out in the GAO report, funding and launch manifest, are less in the control of the project. However the team plans to develop and maintain a detailed and phased cost estimate and schedule in order to request the level of funding needed to maintain the 1000-day schedule. Additionally, launch vehicle service provider integration will begin as soon as the project receives authority to proceed, and the team will stay closely aligned to the launch vehicle's integration schedule tasks and milestones.

In addition to the factors identified by the GAO report, there are many other enabling factors that will help Project M to achieve the 1000-day goal:

- Careful management of requirements and vigorous management of scope. This includes not pushing performance beyond the customer's requirements at the expense of cost or schedule.
- Ability to draw on recent experience and expertise with spacecraft and lunar lander vehicle development specifically for a mission to the Moon during the Constellation Program.
- Use of streamlined processes such as model-based configuration management for hardware
- Definition of frequent points of synchronization for the design team and careful management of the vehicle configuration at each of these points
- Early and frequent live dynamic testing to increase design fidelity and reduce design surprises later
- Simplification of milestone reviews and more frequent peer reviews to strengthen design
- Use of industry, NASA and academic partnerships to leverage existing tools, capabilities, skills, processes
- Continuous identification and management of risks
- Utilization of a team that is mostly in-house and co-located

Costs

The concept team developed three costs estimates for comparison. The team has used the traditional NASA and DoD costing models and developed a bottoms up cost estimate based on a resource loaded integrated master schedule. Because we are heavily leveraging technologies that have been in work for some time, leveraging innovative partnerships, and because we are focusing on a rapid iterative design model that quickly drives to good engineering solutions, we believe this mission will cost less than comparable previous missions, and will enable more cost effective human space flight in the future.

Outreach and Education

One of the fundamental goals of Project M is to inspire the next generation while enhancing Science, Technology, Engineering and Math education throughout the Nation. That inspiration is achieved not only by completing a successful mission but also by connecting the public to the project throughout its development.

Through Project M, NASA intends to show how the technological innovations detailed in this proposal become reality. To convey the message of inspiration, an education and outreach team will be integrated with the engineers on the project. Embedding team members will allow information about the project to flow out to the education and outreach channels in a more efficient manner. The project will pull back the curtain and show engineers turning bolts, designing models, and coding software. The project will document failures as well as the successes to further highlight the engineering process and encourage the kind of innovation that only comes through bold progress. Showing only the end result is not enough –real time updates throughout the entire life of the project are required.

Education

STEM education is the overarching purpose of Project M. The project team will work closely with the education offices across NASA to promote STEM education in K-12 classrooms, universities and professional training arenas. Partnerships are being pursued between NASA and the Department of Education, universities, school districts and professional organizations to advance this activity and to create an environment of participatory exploration.

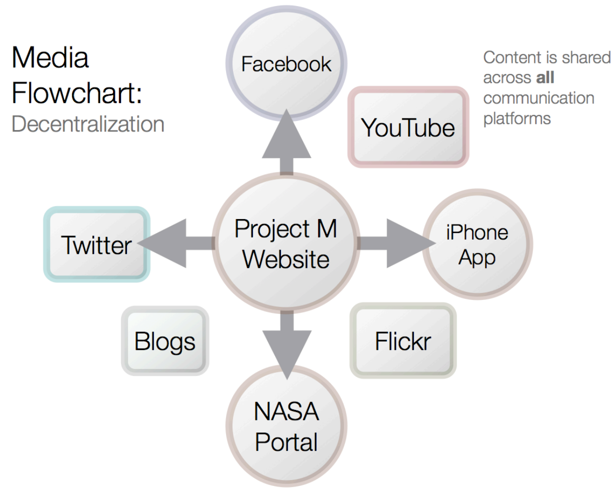
Within the K-12 environment, students may be engaged through interactive classroom activities before and during the mission. The project has a unique opportunity to reach out and interact with students. The humanoid robot will be capable of walking in a 1g environment. The robot actually visiting classrooms provides a tremendous opportunity for NASA. The robot visiting events such as the FIRST Robotics competitions offers another example of reaching thousands of students in a very unique way.

Enormous potential exists for Project M to leverage university partnerships. Collaboration opportunities and sponsored research are two obvious means to pursue. The project can also serve as a basis for curriculum development, student design projects, or even the possibility of student flight projects. Most effectively, Project M provides the perfect work environment for coops and internships, with undergraduate or graduate students or with shared faculty.

Professional training is facilitated by fully documenting this project as case study in engineering development and project management. The openly public nature of the project ensure that those to follow will learn from all the decisions made, just as the project team will learn from its own mistakes as it progresses towards the mission.

Outreach

Content will include documentary style images and video released at consistent intervals. Timing of these intervals will vary depending on the platform.



The project will use a decentralized method to flow content to all possible channels. In order to reach the largest number of people possible we must push content to the places that they visit. We will take advantage of all the latest social media and content distribution platforms including but not limited to the NASA Portal, Facebook, YouTube, Twitter, and Flickr. Each platform has its own specialty and content will flow based on that niche.

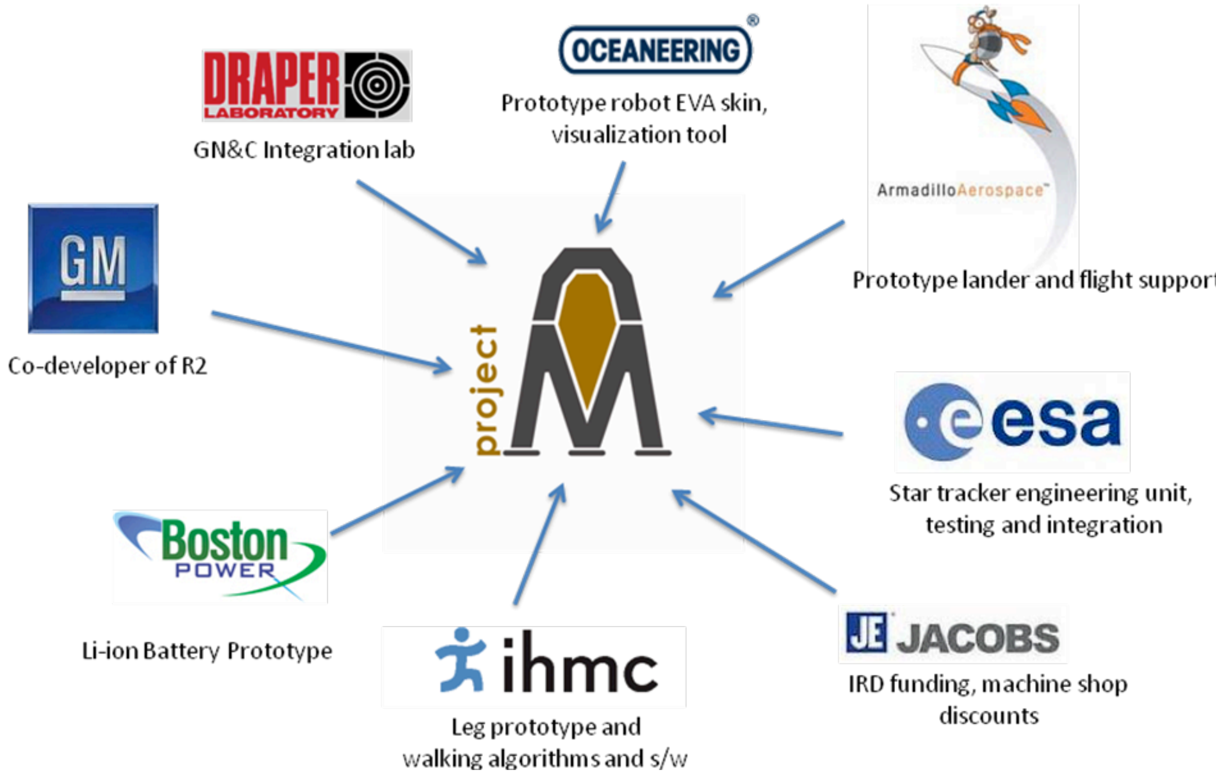
In addition to the social media sites, there will also be a project website. This website will grow and change as the project matures. It will be the central repository for all information and content. Content posted into social media platforms will flow back into the website using the same subscription technologies (RSS, ATOM, and others) that the audience will use as well. Approximately 4 weeks before launch the site will be converted from project to mission documentation.

The content generated for these platforms will also flow into education to engage future engineers. Seeing people engaged in cutting edge engineering will drive more students into technology and engineering fields. It is critical for the future of American education to see a future in these fields. By showing the progression of the project across the entire 1000 days we can highlight each aspect of the project. By partnering with existing education organizations we can provide content that they can then use in their specific application.

In addition the project will encourage engineers on the project to capture their experience and lessons learned in blogs and other discussion forums so that others in the NASA community can benefit from their experience.

Partners (as of April 2010)

A number of participating companies and organizations have been part of the project conceptual development. All the organizations shown here are providing some valuable service, hardware, or facilities at no cost or as in-kind contribution to the project.



Other Centers Collaborations

The project has benefited greatly from the successful Exploration Technology Development Program (ETDP) managed out of the Langley Research Center. The ETDP has been a well managed and stable source of outstanding technology funding for the Agency. JSC leads a number of ETDP tasks and supports a number of others led by other NASA centers. The following are the relevant ETDP tasks that Project M is leveraging.

- Human Robotic Systems (HRS)
- Autonomous Landing and Hazard Avoidance Technology (ALHAT)
- Propulsion and Cryogenic Advanced Development (PCAD)
- Cryogenic Fluid Management (CFM)

Since the project is in the early conceptual formulation stage, other center participation has not been negotiated. However some discussions and collaborations have taken place. In addition JSC and JPL have a strong and energetic relationship in a number of robotic technical areas and the two centers were already collaborating on ALHAT and avionics. JPL also offered their Team X collaborative design environment and hosted the JSC core team for a three day session in January 2010. NASA center collaborations to date:

- JPL – robotics, Team X collaborative design environment, robotic vision, ALHAT hazard detection and avoidance software, rad-hard by design multi-core processor
- GSFC – spacecraft software foundation
- KSC – launch services studies
- LaRC – ALHAT sensors, composite analysis
- MSFC – LOX/Methane Engine development, thermal environment analysis (in discussion)

Future Capability

The Project M Lander and Robonaut will provide NASA the building blocks for future missions. Starting from additional missions to the lunar surface, the Lander systems can also be modified to do both in-space propellant transfers, autonomous rendezvous and docking demonstrations, as well as bringing a modified robonaut to an asteroid.

Additional Lunar missions can range from development of in-situ resource utilization technology, to more ambitious Robonaut missions, and deployment of precursor surface system technology required for a permanent Human presence. Since the initial Lander only uses a mid range Expendable Launch Vehicle (ELV), there will be a strong incentive to scale up the Lander for these future missions. It is possible to deliver at least one metric ton of payload to the Lunar surface by scaling a subset of the Lander systems and using the heavy versions of ELVs (e.g. Delta IV's Heavy, Space X's Falcon 9 Heavy, etc.). Most of the systems such as power, avionics, navigation sensors, and communications can be used as is. The experience work force gained from Project M will provide the corner stone for design of future missions. In addition, Project M is setting mid range performance and design requirements that will drive down the production cost of future Landers. Project M is taking the lessons learned from our industry partners to facilitate this alternative design approach.

For in-space propellant transfer, the Project M Lander utilizes the propellant of choice for future missions that would utilize in-space refueling and/or depots. In addition, the Lander has all the systems required for automated rendezvous and docking. With modification of the propellant and pressurization system for transfer plumbing and a docking mechanism that meets the international docking standard(in work), two Landers would rendezvous in Low Earth Orbit(LEO) and demonstrate all the key technologies required for in-space propellant transfer and storage of mid temperature range cryogenic propellants.

For an Asteroid rendezvous, the Lander would need more study, but conceptually the Lander may have most of the systems needed to attempt an Asteroid rendezvous. The precision landing system for Project M with some modification to the software could be used as is to rendezvous with an Asteroid. A delta velocity assessment would be needed to determine if a scaled up propulsion system is required to rendezvous with the selected Asteroid. In addition, modification to the Robonaut leg system may be required to maximize capability to transverse the asteroid surface in near zero gravity. The combination of human scientific tools utilized by Robonaut will greatly increase our understanding the chemical make-up of asteroids.

As a minimum, Project M provides a great jumping off point for future NASA missions tied to the flexible Architecture.

Summary

The concept of landing a humanoid robot on the moon in 1000 days is compelling. It leverages existing technology development efforts, creates opportunities (perhaps unprecedented opportunities) for student outreach, and develops skills and capabilities needed for more affordable human spaceflight. NASA has the opportunity to once again inspire the nation, amaze the world, and make the impossible possible.

Reference links

NASA Links
http://www.nasa.gov/topics/technology/features/robonaut.html
http://robonaut.jsc.nasa.gov/
http://robonaut.jsc.nasa.gov/projectm/

GM Press Release
http://publish.media.gm.com/content/media/us/en/news/news_detail.brand_gm.html/content/Pages/news/us/en/2010/Feb/0204_nasa