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Morpheus:
Advancing Technologies for Human Exploration

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ABSTRACT

NASA's Morpheus Project has developed and tested a prototype planetary lander capable of vertical takeoff and landing. Designed to serve as a vertical testbed (VTB) for advanced spacecraft technologies, the vehicle provides a platform for bringing technologies from the laboratory into an integrated flight system at relatively low cost. This allows individual technologies to mature into capabilities that can be incorporated into human exploration missions.

The Morpheus vehicle is propelled by a LOX/Methane engine and sized to carry a payload of 1100 lb to the lunar surface. In addition to VTB vehicles, the Project's major elements include ground support systems and an operations facility. Initial testing will demonstrate technologies used to perform autonomous hazard avoidance and precision landing on a lunar or other planetary surface.

The Morpheus vehicle successfully performed a set of integrated vehicle test flights including hot-fire and tethered hover tests, leading up to un-tethered "free-flights." The initial phase of this development and testing campaign is being conducted on-site at the Johnson Space Center (JSC), with the first fully integrated vehicle firing its engine less than one year after project initiation. Designed, developed, manufactured and operated in-house by engineers at JSC, the Morpheus Project represents an unprecedented departure from recent NASA programs that traditionally require longer, more expensive development lifecycles and testing at remote, dedicated testing facilities.

Morpheus testing includes three major types of integrated tests. A hot-fire (HF) is a static vehicle test of the LOX/Methane propulsion system. Tether tests (TT) have the vehicle suspended above the ground using a crane, which allows testing of the propulsion and integrated Guidance, Navigation, and Control (GN&C) in hovering flight without the risk of a vehicle departure or crash. Morpheus free-flights (FF) test the complete Morpheus system without the additional safeguards provided during tether. A variety of free-flight trajectories are planned to incrementally build up to a fully functional Morpheus lander capable of flying planetary landing trajectories. In FY12, these tests will culminate with autonomous flights simulating a 1 km lunar approach trajectory, hazard avoidance maneuvers and precision landing in a prepared hazard field at the Kennedy Space Center (KSC).

This paper describes Morpheus' integrated testing campaign, infrastructure, and facilities, and the payloads being incorporated on the vehicle. The Project's fast pace, rapid prototyping, frequent testing, and lessons learned depart from traditional engineering development at JSC. The Morpheus team employs lean, agile development with a guiding belief that technologies offer promise, but capabilities offer solutions, achievable without astronomical costs and timelines.

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1. INTRODUCTION

NASA's strategic goal of extending human activities across the solar system requires an integrated architecture to conduct human space exploration missions beyond low earth orbit (LEO). This architecture must include advanced, robust in-space transit and landing vehicles capable of supporting a variety of lunar, asteroid and planetary missions; automated hazard detection and avoidance technologies that reduce risk to crews, landers and precursor robotic payloads; and in-situ resource utilization (ISRU) to support crews during extended stays on extraterrestrial surfaces and provide for their safe return to earth. The Advanced Exploration Systems (AES) Program portfolio within NASA includes several fast-paced, milestone-driven projects that are developing these necessary capabilities and, when integrated with subsystem technologies developed by Science Mission Directorate (SMD) investments, will form the basis for a lunar lander project. Specifically, the Morpheus, Autonomous Landing & Hazard Avoidance Technology (ALHAT), and Regolith & Environment Science & Oxygen & Lunar Volatiles Extraction (RESOLVE) projects provide the technological foundation for lunar surface demonstration missions later in this decade, and for key components of the greater exploration architecture required to move humans beyond LEO.

The Morpheus Project provides an integrated vertical test bed (VTB) platform for advancing multiple subsystem technologies. While technologies offer promise, capabilities offer potential solutions for future human exploration beyond LEO. Morpheus provides a bridge for evolving these technologies into capable systems that can be demonstrated and tested. This paper describes the activities of the Morpheus Project, ongoing integration with ALHAT in FY12, and expectations for the future, with the goal of developing and demonstrating these human spaceflight capabilities with robotic missions to the lunar surface.

The Morpheus Project provides a liquid oxygen (LOX)/liquid methane (LCH4) propelled vehicle that, leveraging subsystem designs developed by other vertical testbeds (VTB) such as the Marshall Space Flight Center's (MSFC) Pallet Lander, may be developed into reusable platforms for in-space transit and/or lunar landing for multiple missions and payloads of various sizes. Such platforms could support robotic missions and eventually manned missions with safer, "greener" propellants that, relative to hypergolics, should better support cryogenic storage in space and integration with life support and fuel cell consumables and ISRU systems.

The LOX/methane propulsion system is one of two key technologies that Morpheus is designed to integrate and demonstrate. The Morpheus LOX/methane propulsion system can provide a specific impulse during space flight of up to 321 seconds; it is clean-burning, non-toxic, and cryogenic, but space-storable. Additionally, for future space missions the methane could be produced in situ on Mars, and the oxygen is compatible on-board with life support systems and power generation. These attributes make LOX/methane an attractive propulsion technology for a lander of this scale.

ALHAT, the primary Morpheus payload, provides the second key technology: autonomous landing and hazard avoidance. When landing autonomously on any planetary or other surface, the vehicle must be able to identify a safe landing site that is free of large boulders, rocks, craters, or highly sloping surfaces. Morpheus is designed to carry ALHAT sensors and software supporting tests that will demonstrate an integrated vehicle capability to perform these tasks.

2. SYSTEM DESCRIPTION

The VTB system elements include the flight test vehicle, ground systems, and operations.

Vehicle

Morpheus design and development began in June 2010, primarily by an in-house team at NASA's Johnson Space Center. Morpheus is a "quad" lander design with four tanks and a single engine. The primary structure consists of welded aluminum box beams, machined parts, and aluminum plate. The landing struts have honeycomb crush pads in the feet to attenuate landing loads. The propellant tanks are made of welded 5059 aluminum hemispheres. The avionics and guidance, navigation and control (GN&C) components are located on a plate that spans the top deck of the primary structure.

The propulsion system uses an impinging element-type engine design, with liquid oxygen and methane as the propellants. The engine is film-cooled and operates as a blow-down system producing up to 4300 lbf of thrust. Two orthogonal electromechanical actuators (EMAs) gimbal the engine to provide thrust vector control of lateral translation and pitch and yaw attitudes. Cold gas jets provide roll control using the pressurized helium in the propellant tanks. Varying the engine throttle setting provides vertical control of ascent and descent rates.

The avionics and power subsystems include the flight computer, data recording, instrumentation, communications, cameras, and batteries. The flight computer is an AITech S900 CompactPCI board with a PowerPC 750 processor. Up to 16 GB of data can be stored on board. Data buses include RS-232, RS-422, Ethernet, and MIL-STD-1553. Multiple channels of analog and digital inputs are used for both operational and developmental flight instrumentation, including temperature sensors, pressure transducers, tri-axial accelerometers, and strain gauges. Wireless communications between ground operators and the vehicle use a spread spectrum frequency band. Two on-board cameras provide views of the engine firing during testing. Eight lithium polymer batteries provide vehicle power.

The GN&C sensor suite includes a Javad Global Positioning System (GPS) receiver, an International Space Station (ISS) version of Honeywell's Space Integrated GPS/INS (SIGI), a Litton LN-200 Inertial Measurement Unit (IMU), and an Acuity laser altimeter. The vehicle is able to determine position to less than one meter, velocity to less than three cm/second, and attitude knowledge within 0.05 degrees.

The vehicle software is architected around Goddard Space Flight Center's (GSFC) Core Flight Software (CFS). GSFC designed CFS as a set of reusable software modules in a flexible framework that can be adapted to various space applications. Morpheus software developers built upon CFS by adding custom application code unique to the Morpheus vehicle and mission design.

The initial Morpheus VTB 1.0 configuration was tested from April 2011 through August 2011. In late 2011 and early 2012, the team began upgrading the VTB to the Morpheus 1.5 configuration, including sequentially higher performance HD4 and HD5 engines, an improved avionics and power distribution design, the addition of LOX/methane thrusters for roll control, and the incorporation of the ALHAT sensors and software. This vehicle configuration is currently in testing as described in later sections.

ALHAT Payload

One of the primary objectives of the Morpheus project is to demonstrate and advance the Technology Readiness Level (TRL) of precision landing and hazard avoidance capabilities developed by the ALHAT system. The ALHAT project has been developing 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. This payload project has been conducted with a team of technical experts from JSC, Draper Laboratory, Jet Propulsion Laboratory (JPL), Langley Research Center (LaRC), and the Applied Physics Laboratory at Johns Hopkins University.

ALHAT is using an 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 area of approximately 100 x 100 meters. This cross-cutting technology is also being employed by commercial ISS supply companies and NASA's 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 interpret this information and determine the safest regions to land without hazards. To avoid interference from surface dust while descending to a safe region, the ALHAT design supplements the flash LIDAR with a Doppler LIDAR velocimeter, an IMU, and software to ensure precise measurements of lander attitude, altitude, and velocity are available at all times during the final phases of landing. These surface relative measurements provide the onboard navigation system with sufficient accuracy during last 30 seconds of the descent phase to navigate to the chosen safe region regardless of any dust disturbed by the descent engine.

Ground Systems

The VTB flight complex (VFC) includes 20' x 20' concrete pads located on a section of the JSC antenna range near an old Apollo-era antenna tower. About 2000 feet away is the Morpheus control center for on-site field testing at JSC, the small 2-story building 18 that was formerly used for rooftop GPS testing and storage. The main upstairs room has a window that looks directly out onto the test area, making it highly suitable as the operations "front room," configured with three rows of computer tables for operator workstations. An adjacent room serves as the "back room" for support personnel.

The operator workstations use GSFC's Integrated Test and Operations System (ITOS) ground software. Like CFS, ITOS was developed as ground control and display software for GSFC space vehicles and has been made available to other projects at NASA. ITOS is individually configured on each workstation to display vehicle telemetry and information unique to each operator position.

During each test, the Morpheus Project streams mission telemetry, voice loops, and video from the testing control center to JSC's Mission Control Center (MCC) over dedicated wireless and wired networks. From there, data and video can be made available to internal and external networks for NASA personnel and the general public.

A thrust termination system (TTS) is employed both for range safety and independent test termination purposes. Closing either of two motorized valves in the TTS will shut off the flow of liquid oxygen and methane to the engine and terminate engine thrust. These TTS valves are completely independent from the rest of the vehicle systems and commanded using separate Ultra High Frequency (UHF) radios. The commands to initiate thrust termination are sent from a control unit located in the operations center during any live engine testing.

Ground systems also include propulsion ground support equipment (GSE). The consumables required for an engine test include liquid oxygen, liquefied natural gas, helium, liquid nitrogen, and gaseous nitrogen. The power GSE is a portable ground power cart that is used to supply power to the vehicle until the test procedures call for a switch to internal vehicle power. The ground power cart uses heavy duty batteries and can provide up to 72 amp-hours of power for pre- and post-test activities. The mechanical GSE includes a rented crane for tethered or hot fire / hold-down testing. For tethered tests, an energy absorber is placed between the vehicle and the crane boom arm. The energy absorber is an aluminum piston and cylinder with cardboard honeycomb material that can attenuate up to 10,000 lb. This load attenuation protects the vehicle and crane structures in the event engine thrust needs to be terminated prematurely, causing the vehicle to drop to the end of the tether.

Ground systems also include a variety of transportation assets, provided primarily by JSC Center Operations.

Operations

The final element of the Morpheus system is Operations. Nine primary operator positions are staffed by team members: test conductor (TC), operator (OPS), propulsion (PROP), avionics, power and software (APS), guidance, navigation and control (GNC), ground control (GC), two range safety officers (RSO-1 and RSO-2), and the flight manager (FM). During tests with payloads aboard, another position may be included, such as one for ALHAT. Each position is certified through specific training.

Certification is also required for three pad crew (PAD) positions. PAD-1 is the pad crew leader, responsible for communicating directly with the test conductor during operations and ensuring each procedural step is executed at the pad. PAD-2 and PAD-3 provide support to PAD-1, and conduct all handling of cryogenic fluids and most other consumables.

On test days, many other JSC and Morpheus team personnel serve in various functions. JSC riggers support vehicle transportation and crane operations. Support personnel for each subsystem monitor data or help out during testing in the “back room” of the control center. Other team members standby for potential troubleshooting if problems arise.

3. MORPHEUS TEST CAMPAIGN

Morpheus testing includes three major types of integrated tests: hot-fire, tether, and free-flight.

Hot-fire Testing

During hot-fire testing the vehicle is completely restrained from movement and the primary focus is to test the LOX/methane propulsion system. In this configuration a crane is used to suspend the vehicle above the ground to provide clearance for the vehicle exhaust plume. The vehicle is also constrained from below using straps anchored to the ground that prevent vertical and lateral vehicle motion.

Figure 1 shows the vehicle during test in the hot-fire configuration. The vehicle is suspended approximately 20’ above a concrete pad by a crane outfitted with shielding to prevent damage from flames or debris during the test firing. Additional restraints are attached below the vehicle made of nylon overwrapped with fireproof insulation.

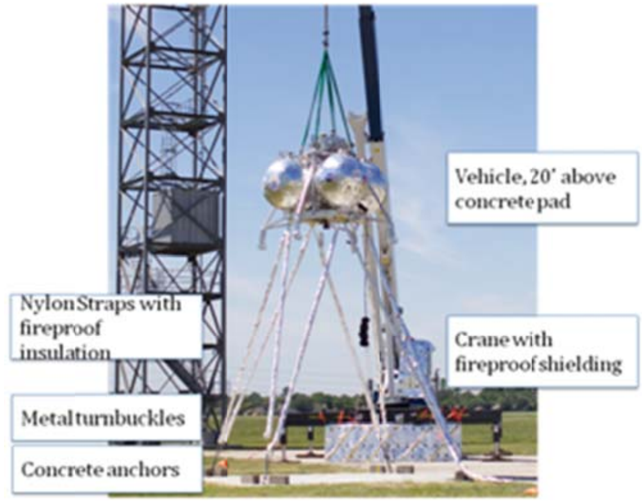


Figure 1 – Morpheus in Hot-fire Test Configuration

The objectives for hot-fire tests include demonstration of the igniter, engine ignition, performance at varied throttle settings and burn duration tests. The Morpheus project test approach limits testing on a dedicated engine test stand and emphasizes a quick transition to integrated vehicle tests. Testing on the vehicle promotes optimization of engine performance for the actual vehicle propulsion feed system instead of the test stand system. It also allows gimbal sweeps to evaluate the integrated performance of the actuators under load. The majority of engine characterization is conducted on the vehicle, essentially making the hot-fire configuration the primary engine test stand for the Morpheus Project.

Tether Testing

For tether tests the vehicle is suspended from a crane as shown in figure 2 to enable testing of the propulsion and integrated GN&C without the risk of a vehicle departure or crash. The goal of these tests is typically to ascend 5’ vertically and hover in place for a pre-programmed duration. Upon successful completion of the hover, the vehicle descends and “lands” at the end of the tether.

Due to the potential dynamic loads during tethered flight, a substantially larger 120-ton crane is used for this testing. An energy absorber in line with the tether reduces the loads on both the crane and Morpheus vehicle and help prevent damage to either asset.

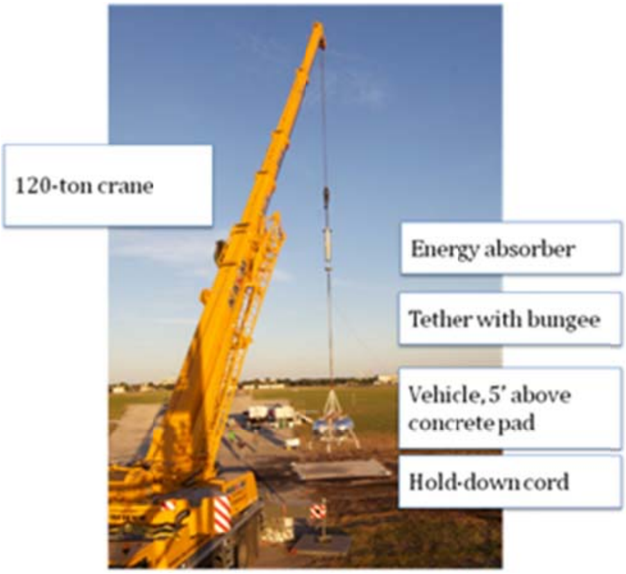


Figure 2 – Morpheus in Tether Test Configuration

Tether testing provides the first opportunity to perform integrated testing of the Morpheus vehicle with closed-loop GN&C. The primary objective of tether testing is to demonstrate 6 degree-of-freedom (DOF) GN&C for vertical translation, hover and simulated landing operations. An additional objective is to understand the integrated performance of avionics, propulsion, and GN&C. Tether testing allows rapid refinement of this integrated performance without risk of a vehicle crash.

Free-Flight Testing

Morpheus "free-flights" demonstrate the fully integrated flight capability of the vehicle with no restraints. Free-flight safeguards are automatic aborts on-board aborts, remotely commanded aborts, as well as a redundant and independent flight termination system that can be activated by spotters to visually determine trajectory deviations. A variety of free-flight trajectories can be flown to incrementally build up to a fully functional Morpheus lander capable of flying planetary landing trajectories.

4. MORPHEUS 1.0 TEST CAMPAIGN

During the Morpheus 1.0 test campaign, a series of three hot-fire tests was conducted to refine propulsion system performance. This was also the first opportunity to test vehicle hardware and software together. Due to the fast pace of development, these tests were used as verification tests for numerous software routines.

The Morpheus team completed the entire series of hot-fire tests in 8 days and successfully demonstrated all test objectives except for handover from propulsion to GN&C. The team quickly resolved all issues and confirmed solutions in subsequent tests, gaining valuable vehicle operations experience and confidence to proceed with tether testing.

Immediately following the hot-fire tests, five tether tests were conducted between April 25th and June 1st, 2011, with the primary objective to demonstrate stable 6-DOF GN&C. The rapid schedule of the first four tests was driven by a demonstration flight planned for the JSC Innovation Day event on May 4th.

The most dramatic tether test in this test campaign was TT2. Immediately upon engine ignition, an H-bridge circuit controlling the throttle valve failed, causing the valve to remain fully open (100% throttle). The vehicle rapidly ascended and an asymmetric bungee arrangement caused a pitching moment. When the ignition sequence was complete and control was handed over to GN&C the vehicle was already in a presumably unrecoverable trajectory. To make matters worse, the GN&C system also contained a 90-degree clocking error in the coordinate frame due to an incomplete vendor specification of the IMU. As a result, the GN&C could not stabilize the vehicle motion.

Figure 4 – Morpheus Tether Test 2 (TT2)

Figure 5 – Morpheus Tether Test 5 (TT5)

This uncontrolled motion continued despite on-board software and ground commands for soft and hard abort engine shutdown. These primary methods for engine shutdown all rely on the throttle valve, which had failed to full open. After 13 seconds of erratic flight the thrust was finally terminated when the wired FTS system was manually activated. Since the vehicle was tethered to the crane, no vehicle damage resulted from this test.

Despite the dramatic and uncontrolled motion seen in TT2, this test resulted in identification of the key issues mentioned above without any vehicle or property damage.

Another notable test was Tether Test 5. TT5 was conducted on June 1st, 2011, following a design review and completion of the recommended software changes. The plan and objectives for TT5 included a targeted hover time of 40 seconds. During this test the vehicle successfully completed a full duration run with nominal shutdown after 42 seconds. GN&C performance was improved and the vehicle hovered throughout the test with only a minor wobble with a period of approximately 3.2 seconds. The propulsion system performed nominally and reached steady-state engine temperatures for the first time during Morpheus vehicle testing.

Table X. Morpheus 1.0 Test Summary

Test Name	Description / Objectives	Notes
Hot Fire 1 4/14/2011	Igniter Tests	2 consecutive successful igniter tests. Flight software errors found
Hot Fire 2 4/19/2011	Igniter Tests Engine firing test	29 seconds burn time
Tether Test 2 4/27/2011	Hover test	13 sec burn time Stuck throttle and tether forces caused dynamic uncontrolled motion. Flight terminated
Tether Test 3 5/3/2011	Hover test	20 sec burn time Soft abort due to cable snag and software issue
Tether Test 4 5/4/2011	Hover test	29 sec burn time Attitude rate issue; terminated flight early
Tether Test 5 6/1/2011	Hover test	34 sec burn time; good hover Minor control wobble
Tether Test 6 8/31/2011	Hover test	11 sec burn time Engine burn-through

5. Morpheus 1.5 Test Campaign

The Morpheus 1.5 test campaign began in February 2012. To date, two hot fire tests and six tether tests have been performed, and the HD4 engine has been fired for over six minutes. The six tether tests have been opportunities for the design team to continue to characterize and improve the interaction between the GN&C and propulsion systems. Tether Test 10 is shown in Figure 6. Table X lists the test summary for Morpheus 1.5.

Add summary / results on Morpheus 1.5 testing.

Figure 6 – Morpheus Tether Test 10

Table X. Morpheus 1.5 Test Summary

Test Name	Description / Objectives	Notes
Hot Fire 5 2/27/12	Engine firing test	40 sec burn time
Tether Test 7 3/5/2012	Hover test	30 sec burn time
Tether Test 8 3/13/2012	Hover test	55 sec burn time Good 40 sec hover with GN&C oscillations
Tether Test 9 3/16/2012	Hover test	47 sec burn time Guidance and control algorithm issue
Hot Fire 6 4/2/2012	Short hold-down test on pad	5 sec burn time Footpads overheated
Tether Test 10 4/4/2012	Hover test	62 sec burn time GN&C altitude issue
Tether Test 11 4/11/2012	Hover test	56 sec burn time Stable altitude but lateral oscillations
Tether Test 12 4/18/2012	Hover test	69 sec burn time 45 sec hover (longest yet) Still lateral oscillations

6. LEAN DEVELOPMENT TENETS

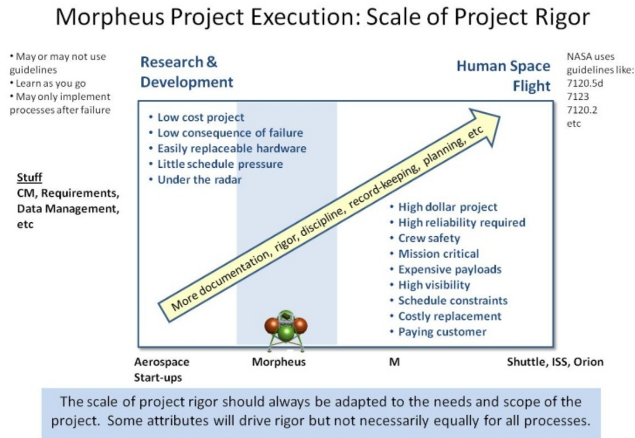
In addition to the technological advancements, another objective of the Morpheus Project is to change perceptions and attitudes about what can be done, what should be done, and what is possible. It is about a return to the fundamental engineering design practices. It is about building and developing 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. As a result, Morpheus strives to:

- Provide hands on work to civil servants and some key contractor partners
- 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 project leverage technology work in the Agency that has been ongoing, partnerships that have been in place for many years, and facilities and resources that already exist. Integrating into a flying demonstration platform provides a means to mature those leveraged technologies and thereby enable more cost effective human space flight.

Project Rigor

The real trick to sustainable lean development is finding the right level of rigor and discipline appropriate for the particular project under consideration. The following graphic illustrates the concept further as applied to the prototype Morpheus lander.



The X-axis of the graph shows some representative programs, projects, or organizations, while the Y-axis represents rigor in the form of configuration management, requirements development and flow down, safety reviews, decision board hierarchy, or any other number of mechanisms and processes used to add rigor, repeatability, redundancy or discipline into the execution of a spaceflight mission.

In human spaceflight, there has not been the opportunity for decades to develop completely new systems until the Constellation Program was formulated. NASA has gone a generation since building a piloted spacecraft. Many of the best talent in the Agency have spent their entire careers in the sustaining or operational phase of the Shuttle and ISS Programs. Because of these factors it is difficult for our workforce to move toward the left of Figure 1. It actually helps to work with some of the aerospace startups in order to see the other extreme and enable intelligent choices as to the "right" rigor for a development or prototype system. Ultimately however there is no formula for determining the "right" level of any of these attributes; it must be agreed on by the project leadership. "It is not about having process or not having process, it is about the right level of process at the right time".

Risk Acceptance

Also key to lean development is accepting appropriate risk. The project must be very clear about what risk is acceptable. For early development and testing of engineering prototypes, accepting the complete loss of the prototype or engineering unit may be appropriate. It doesn't mean the project doesn't act responsibly and professionally, it is a realization that the reason you build prototypes is because you don't have all the answers and testing and trying different designs leads to the answers. But sometimes those tests will fail and sometimes fail spectacularly. The project must manage the appropriate risk.

Partnering

Specifically partnering with external non-traditional partners can be beneficial. Those partners bring innovation and new methods. Non-traditional partners validate your own good processes and shine a light on your inefficiencies. It is often difficult to see how to improve your own processes when that is all you know. Even when improvements can be identified they are often incremental and seldom revolutionary, because all the data is grounded in the process the team knows. Partners can often help show other ways and other possibilities.

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

Build Engineering Prototypes

- *If you wait to build the perfect thing, you won't get to, and it won't be perfect anyway*
- *Engineering prototypes are for learning and failing quickly*
- *Build, fail, improve, repeat*

Create a Sense of Urgency

Every day matters. Every meeting is important or don't have it. Products are good, but products delivered quickly make all the difference. A sense of urgency makes the team intolerant of inefficiency. It drives innovation and spurs other ways of doing business. It excites and motivates. The milestone needs to be barely achievable. If it is too far away we tend to think too much. We take time to plan and analyze and re-analyze. We debate and consider. We work on things in Stephen Covey's quadrant of important-but-not-urgent and when you have a lot of time the list of "important" becomes long. We develop elaborate organizational constructs.

Given too little time we don't commit. We don't believe, we know the schedule will slip and we try only to not be the system that publicly causes the slip. We don't try to be the fastest camper running from the bear; we only try to be a bit faster than the slowest.

The key is a believable but challenging and audacious time constraint. Then we innovate and maximally leverage our capabilities. It is then when we break down barriers, work our best as a team, and truly do great things.

"Home Depot" Engineering

NASA often forgets our roots in building prototypes and performing relentless testing. For lean development it is imperative to foster and encourage "Home Depot" engineering - the act of building prototypes and engineering tests with simple hardware at hand. This allows quick and cheap understanding of the physics, how things go together, or cheaply evaluates competing concepts.

The Morpheus example is of a slosh test. For a lunar lander two thirds of the mass of the lander is propellant, so propellant slosh is important to understand and manage. The first prototype the project built did not have slosh baffles in the propellant tanks (because we were using existing tanks). For the current vehicle, however, we wanted to have baffles as that would be closer to the flight vehicle configuration. Engineers on the team were trying to understand slosh for our four tank configuration, developing a computer simulation, and planning a full scale slosh characterization test on the first lander prototype. The team developed a quick prototype shown below with $60 worth of Home Depot hardware. A series of tests were run which provided data to anchor the computer simulation, evaluate competing techniques for performing the full scale test, and more importantly gave the engineers an intuitive feel for the dynamics which led to an elegant design for the baffles for the Morpheus vehicle.

7. CONCLUSIONS

The Morpheus project has provided an opportunity for a mostly civil servant team to conduct end-to-end vehicle flight operations in a terrestrial vertical test bed, and to further advance integrated technologies that will benefit human spaceflight. Each flight test opportunity provided valuable insights, even when the primary test objectives were not met.

Tether Test 2, for example, had multiple failures that led to an unplanned swinging trajectory on the end of the tether. The team would likely never have planned a test with those test conditions, yet the "test failure" provided a good training opportunity for the team to execute an abort under safe conditions for both personnel and the vehicle. After the test, the throttle valve driver electronics design was reviewed and improved significantly, allowing the closing of previous discrepancies that had been unresolved. The GN&C subsystem team was able to review navigation data for dynamic conditions that would not have otherwise been obtained, and discovered a frame transformation error that was not observable during static testing. Lessons were learned, problems were fixed, and the team turned around the vehicle for another test less than one week later. This is in part due to a project culture that recognizes the value of testing, failing, and recovering quickly to move forward and test again.

The project successes have been enabled in part by purposefully considering an appropriate use of rigor in the processes and methodologies executed by the team during the ramp up to flight testing. Because of the fast pace and small Morpheus team size, this required innovative solutions for team collaboration and communication, as well as a project management culture that expected any process or "overhead" activity to buy its way into the project based on good rationale and benefit.

Partnering with commercial partners such as Armadillo Aerospace, which is a very small and relatively new company on the space scene, provided the NASA team with visibility into their approach to project execution and systems engineering, and they in turn gained more insight into the NASA safety and project management cultures. Commercial space companies use a wide range of approaches for their projects, as do the different NASA organizations and projects. By considering a full range of options, the result for Morpheus is a tailored approach that has more rigor than typically employed for a "technology development" project but less than that used for "human space flight."

8. SUMMARY

NASA's Morpheus Project has developed and tested a prototype planetary lander capable of vertical takeoff and landing designed to serve as a testbed for advanced spacecraft technologies. The Morpheus vehicle has successfully performed a set of integrated vehicle test flights including hot-fire and tether tests, which will ultimately culminate in a 1km slant range surface approach trajectory. This development and testing campaign has been conducted on-site at the Johnson Space Center (JSC), with initial tests occurring less than one year after project start. Designed, developed, manufactured and operated in-house by engineers at JSC, with a number of partners, the Morpheus Project represents an unprecedented departure from recent NASA programs and projects that traditionally require longer development lifecycles and testing at remote, dedicated testing facilities.

In early FY12, Morpheus made a number of upgrades and improvements to the vehicle and ground subsystems, including integration of the Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project's hardware and software components. These upgrades will provide improved performance, expanded capabilities, and better robustness for an extended test campaign that will culminate in high energy trajectories that simulate a lunar landing approach. The initial test campaign will be conducted at the Johnson Space Center, and will be followed by high energy trajectories at the Kennedy Space Center.

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. The Morpheus Project provides a focus and an opportunity to demonstrate the technologies in a relevant flight environment. Too often, technologies are not developed 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. The large scale development programs, by definition then, are only incremental, fail to fully drive the state of the art in space systems, and are not as 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.

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.

Following the terrestrial flight tests with a successful space demonstration (i.e. safe landing on the Moon) of the targeted technologies, LOX/Methane propulsion and 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.

BIOGRAPHIES

Jon B. Olansen, PhD *– Dr. Olansen serves as the Project Manager for the Morpheus Project, He began his career as a Space Shuttle flight controller, supporting 32 missions and logging >4200 hours in Mission Control. Jon earned his B.S. in Aerospace Engineering and M.S. in Mechanical Engineering from the University of Notre Dame. He obtained his Ph.D. in Mechanical Engineering (Biomedical Focus) as a National Instruments Fellow at Rice University, where he specialized in biomedical experimentation in electrophysiology and cardiopulmonary hemodynamics. He has published several journal articles related to his research and authored a reference book on biomedical instrumentation. He returned to NASA to represent the Astronaut Office in the design, development, and operation of human life sciences experiments destined for* *the International Space Station. Dr. Olansen has since held a number of positions of increasing responsibility including tours in Safety & Mission Assurance, the Shuttle Program Office and the Exploration Systems Mission Directorate at NASA Headquarters, before undertaking his current role.*

Jennifer D. Mitchell - *Ms. Mitchell graduated from Texas A&M University with a Bachelors Degree in Aerospace Engineering. She has worked at NASA JSC for 19 years in the Aeroscience and Flight Mechanics Division, working on guidance, navigation and control systems in both technical and management roles. She recently transferred to the JSC Engineering Directorate's Systems Architecture and Integration Office. She currently serves as the systems engineering and integration lead for Project Morpheus.*