Morpheus (VTB)

Morpheus GNC Development and Testing

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Topics

• Morpheus Background
• Tale of Two Paradigms
• Phase 1: Early GNC Development and Testing
• Phase 2: Vehicle Development and Testing
• Phase 3: ALHAT Testing
• Conclusion
Morpheus evolved from Project M mission application to become a terrestrial vertical testbed (VTB) for LOX/LCH4 and ALHAT technologies.

Key Enabling Technologies:
- LOX Methane
- Robotics
- Autonomous Safe Landing
- Radiation Hardened by Design Processor

Demonstration in a Relevant Environment:
- In-space Cryogenic Propulsion
- On-ramps ISRU: Key to power propulsion and life support
- Advances TRL of key Cryogenic Fluid Management Devices
- Robotic assistance path sustains Human Exploration
- Demo supervised autonomy with human factors and EVA tools
- Provides human scale perspective
- Hazard Avoidance Landing System
- AR&D sensor and algorithm commonality

Mission Focus on inspiring STEM Education at all levels
Transition from Project M to Morpheus

Context Feb 1, 2010
- Presidential Budget ends Cx and puts NASA in strategic replanning mode
- Very difficult to get approval for a lunar mission in this environment
- Robonaut2 focuses on ISS deployment and continued terrestrial leg development
- LOX/LCH4 and ALHAT technologies demonstration carry on in the Morpheus VTB

### Advance Exploration Systems
- **Vertical Test Bed**
  - Autonomous Safe Landing
  - LOX Methane
  - Robotics

### ISS Testing
The Morpheus VTB inherited the test-oriented development approach of ProjectM and is effectively the Project M Risk Reduction 2 (RR2) test vehicle.

Early GNC and propulsion system development was performed on the RR1 vehicle built by Armadillo Aerospace.
ALHAT Demonstration Description

**ALHAT Technologies**

- **AGNC** = Autonomous Guidance, Navigation, & Control
- **ALT** = Laser Altimeter
- **VEL** = Doppler Velocimeter
- **TRN** = Terrain Relative Navigation Sensor
- **HDS** = Hazard Detection System with Flash LIDAR

**Entry Interface**

- Entry
- Chute deploy
- Chute Phase
- Aeroshell Separation
- Begin sensing
- Powered Descent

**Precision Landing Demonstration**

- (AGNC, ALT, VEL, TRN)

**Terrain Relative Navigation**

- Morpheus powered flight to test hazard detection scenarios
- Hazard Detection Demonstration (AGNC, HDS)

**Hazard Avoidance**

- Precise, safe controlled landing
- Trajectories are not to scale and are only illustrations of phases

Commercial VTB powered flight to test both precision landing and hazard detection scenarios
ALHAT Powered Descent

**Braking Trajectory Activity**
Efficiently reduce velocity from orbital speeds and manage range error to pre-designated surface target for precision landing (100 m ± radius of target navigation)

**Approach Trajectory Activity**
View landing site while approaching at a low throttle and relatively constant attitude. Fly to locally designated safe location

**Terminal Descent Trajectory Activity**
Near vertical descent to surface for soft landing at safe location within 1 ms of safe site

**Touchdown Trajectory Activity**
Touchdown and system standby
RR-2 (Morpheus) Development Phases

**PHASE 1**
- New RR-2 Structure
- New RR-2 Engine
- Uses Armadillo’s Avionics, Remote Control and Ops

**PHASE 2**
- Same engine as Phase 1
- Uses NASA’s Avionics, Remote Control and Ops

**PHASE 3**
- Another new engine
- New prop components
- Additions to precision landing sensors

**PHASE 4**
- Capability for hazard detection and avoidance

**Caddo Mills**
- Design and Development
- System Integ & Test

**JSC**
- Design and Development
- System Integ & Test
- Flight Tests

**Flight profiles will be “short hops” on the order of 30 m altitude**

**JSC WSTF**
- System Integ & Test
- Flight Tests
- Flight Tests

**DATES**
- Oct +

**Flight profiles will include full “ALHAT”-type final approach trajectory from about ~1.6 km downrange, ~800 m altitude to landing**

**FY12**
• ALHAT MISSION STATEMENT
  – Develop and mature to TRL6 an autonomous landing GN&C and sensing system for crewed, cargo, and robotic planetary descent vehicles. The System will be capable of identifying and avoiding surface hazards to enable a safe precision landing to within tens of meters of certified and designated landing sites anywhere on a planetary surface under any lighting conditions.

• The ALHAT Project started in 2006 and has essentially completed the development of software and hardware systems
  – AGNC
  – Terrain Relative Navigation
  – Hazard Detection and Avoidance
The Project will be ready in FY12 to demonstrate the following capabilities on a Vertical TestBed

- Autonomous closed loop precision landing from approximately 500m altitude and 1000m slant range with real-time hazard detection and avoidance on the Morpheus VTB
  - Utilizes Hazard Detection System (HDS) which consists of a gimbaled flash lidar with real-time compute element and associated software. Identifies safe landing aim point in less than 10 sec
  - Utilizes Doppler lidar velocimeter and laser altimeter plus COTS navigation sensors such as IMU
  - AGNC with extended Kalman filter navigation which utilizes inputs from all of the above sensors to provide landing precision to within 3m (3σ) of the real-time determined safe landing location
  - Utilizes Hazard Relative Navigation – terrain relative navigation by tracking features and comparing to HDS determined feature location
• The Project will be ready in FY13 to demonstrate the following capabilities on a Vertical TestBed
  – Autonomous closed loop precision landing from approximately 6 km altitude using real-time Terrain Relative Navigation (TRN) and hazard detection and avoidance on a commercial VTB
    • Utilizes passive optical TRN from high altitudes to the start of the hazard detection phase followed by hazard detection and avoidance with the HDS for safe precision landing
    • Doppler lidar velocimeter and laser altimeter plus COTS navigation sensors such as IMU
    • AGNC with extended Kalman filter navigation which utilizes inputs from all of the above sensors to give landing precision to within 3m (3σ) of the real-time determined safe landing location and within 90m (3σ) of the prelaunch landing target
    • Demonstrates all of the ALHAT techniques and sensors
ALHAT Project Flow

**ALHAT System**
- FY11
  - Optical Camera/TRN Compute Element
  - HDS / 128 Flash lidar
  - Laser Altimeter
  - Doppler Lidar

**Morpheus VTB**
- FY11
  - Closed loop AGNC
  - Tethered flights
  - Hop flights
  - Extended Hop Flights

**Commercial VTB**
- As early as practical, pursue integration of Laser Altimeter and Doppler Lidar sensors

**Flight Opportunities**
- Integrate and fly GENIE system as open loop payload
- Modify control S/W
- Close loop between GENIE and VTB

**FY12**
- TRN Sensor Integration and Ground Testing
- HDS Gnd Test

**FY13**
- TRL6 Demo ALHAT System
- Integrate & Test TRN and HDS

**HDS** – Hazard Detection System
**HDP** – Hazard Detection Phase
**MDT** – Mars Descent Trajectory
**TRN** – Terrain Relative Navigation
**GENIE** – Guidance Embedded Navigation Integration Environment
Morpheus Vehicle Overview

• Vertical Take-off / Vertical Landing
  – Impulse for 60-210 seconds of flight

• Pressure Fed Liquid Oxygen (LOX) and Liquid Methane (LNG) propulsion (235 PSIG)

• Single Film Cooled Rocket engine
  – 2000 or 4000 lbf Thrust
  – Two axes Gimbaled and 4:1 Throttled

• Autonomous Flight Control
  – Nav Base : IMU (2), GPS (2), and Laser Altimeter
  – Ground Command and Telemetry through RF link

• Stand alone Flight Termination System
Tale of Two Paradigms

• Traditional spacecraft development relies on comprehensive requirements development and analysis, varying time in integrated testing early, and late integration of long lead or high value assets into a flight configuration. This approach is not risk tolerant and experiences significant performance, cost, and schedule impacts when issues are discovered at integration.

• Morpheus adopted a test oriented paradigm where a small set of spacecraft level requirements were developed to guide early subsystem design and development.
  – Metal was cut early and subsystem requirements refined in parallel
  – Integration of subsystems was performed with available/affordable assets.
  – Approach is tolerant of flight failures as test successes
Traditional vs. Test, Test, Test Development

**Traditional**
- Heavy emphasis on early trades and analysis
- Cost/schedule impacts deferred to late in project
- Serial progression
- Risk averse
- May not flight test
- Spec assets

**Test, Test, Test**
- Emphasis on rapid prototyping
- Cyclic and parallel progression
- Accepts risk early
- Uses available/affordable assets

“Flight” article is well thought out and tested at subsystem/component level. But has no “real-world” exposure.

Development, integration, and test cycles or “spirals” lead to a robust design where project energies are focused on issues discovered in testing.
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Early flight “failures” may be test “successes”
Morpheus Lean Management

• Flat organization
• Small teams / co-location
• Open source tools
• Available/affordable asset re-use and utilization
• Online collaboration through Sharepoint
• Engagement of safety/qa early as part of team
• Incremental and tangible test milestones - genie, mast demos, cold flow, hot fire, tether, vertical, hops, high energy
Phase 1: Early GNC Development and Testing

• 2-3 charts

• ALHAT analysis GNC package start  background description and rationale

• Letting the genie out of the bottle.....genie overview, purpose to test realtime feasibility of basic guidance and nav approach with basic sensors

• Commonality with ft4

• Flight details and results

• Successful distributed team collaboration

• Cart testing

• Sim development with laptop, realtime, flight processor etc support (technology simulation levels?)

• Cool pictures, movie?
ALHAT GN&C System

**Autonomy (AFM)** – Combines precise navigation, surface imaging, adaptive vehicle maneuvering outside the nominal profile, and human input to enable safe and precise lunar landing.

**Guidance** – Provides burn targeting & maneuver guidance for end-to-end lunar landing mission. Supports precision landing (dispersion correction) and hazard avoidance.

**Navigation** – Estimates vehicle states for end-to-end lunar landing mission. Dual-state filter architecture for precise vehicle delivery.

**Control** – Provides 6DOF control (RCS and main engine) for Crewed lunar landing vehicle.

**Hazard Detection System** – Provides hazard detection sensors and algorithms/software
GENIE Field and Flight Testing
Six GENIE Adaptation Steps to High Performance Flight on a VTVL Terrestrial Rocket

GENIE TEST PROGRESSION

1. Closed Loop SW Simulation
   - GENIE AGNC software working in close loop environment adapted to VTVL TR

2. Hardware in the Loop Simulation
   - GENIE AGNC embedded system performing correctly with VTVL TR

3. Open Loop Flight
   - GENIE AGNC embedded system mechanically intact and operational on flying vehicle

4. Closed Loop Tethered Flights
   - GENIE AGNC embedded system capable of flying closed loop control on flying vehicle

5. Closed Loop Hop Flights
   - GENIE AGNC embedded system capable of flying closed loop hop trajectory

6. Closed Loop Approach Flights
   - GENIE AGNC embedded system capable of flying closed loop approach trajectory

7. Adaptation Objective
   - GENIE AGNC embedded system working in close loop environment adapted to VTVL TR

Adaptation Step Completion Number
RR2 Rev1 Build2 GNC FSW Architecture

“Core AGNC FSW” retains only the blue and green layer

A = Mission Manager
G = Guidance
N = Navigation
C = Control

GNC App Function = GREEN
GNC App Exec = BLUE
GNC App Messenger = RED
I/O App = PURPLE

CFS Message Bus = ORANGE

CMD
TLM

INPUT
DISP

IP Socket I/O

GPS Sim Model
ALT Sim Model
SIGI Sim Model
GNC App Function, Executive, and Messenger

“Core AGNC FSW” retains only the blue and green layer

**CFS SW Message Bus**

a GNC *app messenger* handles the CFS specific messaging and executes the GNC app executive

The place where the CFS message subscribe, CFS message send occurs along with other CFS specific detail

a GNC *app executive* calls the GNC app function and extracts necessary data for the function call

*Literally calls the GNC app function*

a GNC *app function* performs the GNC algorithm

*Isolating the functions from particular architecture allows for extensible and reusable GNC SW development*
Phase 2: vehicle development and testing

- 3-4 charts
- Integration with CFS and flight processor, ported from genie...but maintaining genie
- Breaking up nav into rate groups
- Simplified guidance
- Added flight control
- Added AFM
- Added sigi as prime imu
- Display development
- GNC bunker, mast demo 1 ("failure"), mast 2 demo (Ethernet sim), mast demo 3 (socket sim), flat sat testing, cold flow, hot fire, tether timelines pictures and some details
Morpheus Embedded Simulation
Phase 2 Vehicle Testing at JSC

Extensive non-realtime and realtime simulations in the Morpheus Avionics/Software Testbed (MAST)
Completed Hotfire and Tether testing at the JSC VTB Flight Complex
Continuing Tether testing at the JSC VTB Flight Complex
Planned Free Flight Vertical and Hop Trajectories at JSC VTB Flight Complex

*T Scale, 1.24” = 80’ = 24.384 m

= Pads are 6m x 6m (20’ x 20’)
Morpheus Tethered Flight
Phase 3: ALHAT testing

- 1-2 charts

- Future tether test, vertical free flight, hop free flights

- Transition to high energy testing, trajectory plot?

- Integration with ALHAT

- Integration with Masten for commercial ALHAT demo
Six GENIE Adaptation Steps to High Performance Flight on a VTVL Terrestrial Rocket

- **GENIE TEST PROGRESSION**
  - Closed Loop SW Simulation
  - Hardware in the Loop Simulation
  - Open Loop Flight
  - Closed Loop Tethered Flights
  - Closed Loop Hop Flights
  - Closed Loop Approach Flights

- Adaptation Objective
  - GENIE AGNC software working in close loop environment adapted to VTVL TR
  - GENIE AGNC embedded system performing correctly with VTVL TR
  - GENIE AGNC embedded system mechanically intact and operational on flying vehicle
  - GENIE AGNC embedded system capable of closed loop control on flying vehicle
  - GENIE AGNC embedded system capable of flying closed loop hop trajectory
  - GENIE AGNC embedded system capable of flying closed lunar/mars like approach trajectory

Adaptation Step Completion Number
Big Picture – 2010 in review

Pixel Lander:
Armadillo Aerospace hardware with LOX/LCH4 engine
NASA GN&C collecting data
~20 tethered flights, 3 free flights

Morpheus Lander:
All NASA design
Constructed, assembled, and tested by AA and NASA
Flying at JSC will be all NASA team

Video Link: 2010-10-21-VerticalTestBedProgress-PowerPoint WMV - episode-.wmv
Big Picture – 2011 in review

Jan 2011
- More GN&C & Software Bunker
- Energy Absorber testing
- Tank cycle testing
- Vehicle Arrives at JSC

Feb 2011
- B220 Set-up
- Propulsion System Assembly
- End to End Wiring Checks
- NASA HD Engine test(s)

Mar 2011
- N2 Cold Flow
- Software Talks to the Vehicle Avionics for the First Time
- Power GSE plugged to Vehicle for the First Time
Conclusion

– 1 chart

– Rate of progress to date

• Test paradigm with lean management

• Forward plans with ALHAT

• Could be right back on track for lunar mission with little loss of pace...i.e. We needed to do this testing anyway!
Backup Material
SCHEDULE SUMMARY

ALHAT Technologies

AGNC = Autonomous Guidance, Navigation, & Control
ALT = Laser Altimeter
VEL = Doppler Velocimeter
TRN = Terrain Relative Navigation Sensor
HDS = Hazard Detection System with Flash LIDAR
cVTB = Commercial Vertical Test Bed

October 2012
AGNC Closed Loop Mars-like Demo on cVTB with ALT/VEL/TRN payload

August 2013
Integrated Precision Landing and Hazard Detection Flight Demo on cVTB (AGNC/ALT/VEL/TRN/HDS)

April 2012
AGNC Closed Loop Hazard Detection Flight Demo on Morpheus (AGNC/ALT/VEL)

February 2013
Precision Landing Flight Demo on cVTB (AGNC/ALT/VEL/TRN)

June 2012
Closed Loop Hazard Detection Flight Demo on Morpheus (AGNC/HDS/ALT/VEL)

September 2011
AGNC Closed Loop Flight cVTB Hop Demo

December 2011
ALHAT System Integrated Ground Test

April - September
GFY2011

October - September
GFY2012

October - September
GFY2013

2011

2013
**TRL 9:** Actual system “mission proven” through successful mission operations
Thoroughly debugged software readily repeatable. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.

**TRL 8:** Actual system completed and “mission qualified” through test and demonstration in an operational environment Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.

**TRL 7:** System prototype demonstration in high-fidelity environment (parallel or shadow mode operation) Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.

**TRL 6:** System/subsystem prototype demonstration in a relevant end-to-end environment Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.

**TRL 5:** Module and/or subsystem validation in relevant environment Prototype implementations conform to target environment / interfaces. Experiments with realistic problems. Simulated interfaces to existing systems.

**TRL 4:** Module and/or subsystem validation in laboratory environment Standalone prototype implementations. Experiments with full scale problems or data sets.

**TRL 3:** Analytical and experimental critical function and/or characteristic proof-of-concept Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated.

**TRL 2:** Technology concept and/or application formulated Basic principles stated. Experiments with synthetic data. Mostly applied research.

**TRL 1:** Basic principles observed and reported Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research.
MISSION STATEMENT

• The Project M Field Test effort aims to demonstrate high rate inertial Guidance, Navigation, and Control (GNC) with low rate representative Kalman filter updates in a free-flying terrestrial lander environment.

AA-VTB-FT1 OBJECTIVE

• The primary objective of the Project M Tier 1 FT is the open loop navigation demonstration of Project M Autonomous GNC (M-AGNC) using data from a tactical grade IMU, GPS, and altimeter with telemetry and data recording on the AA-VTB.
CSDL GENIE delivers a precise navigation state output at 20Hz and forms an embedded guidance solution for VTB vehicles.