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GENIE Flight Test Results and System Overview

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Abstract— NASA has envisioned a suite of lander test vehicles that will be flown in Earth's atmosphere to incrementally demonstrate applicable lunar lander performance in the terrestrial environment. As each terrestrial rocket progresses in maturity, relevant space flight technology matures to a higher technology readiness level, preparing it for inclusion on a future lunar lander design.. NASA's "Project M" lunar mission concept flew its first terrestrial rocket, RR1, in June 2010 in Caddo Mills, Texas. The Draper Laboratory built GENIE (Guidance Embedded Navigator Integration Environment) successfully demonstrated accurate, real time, embedded performance of Project M navigation and guidance algorithms in a highly dynamic environment. The RR1 vehicle, built by Armadillo Aerospace, performed a successful 60 second free flight and gave the team great confidence in Project M's highly reliable and robust GNC system design and implementation. This paper provides an overview of the GENIE system and describes recent flight performance test results onboard the RR1 terrestrial rocket.

Acronym List

AFM: Autonomous Flight Manager
AGNC: Autonomy, Guidance, Navigation, and Control
ALHAT: Autonomous Landing and Hazard Avoidance Technology
CSDL: Charles Stark Draper Laboratory
EKF: Extended Kalman Filter
EML: Embedded Matlab
ETDP: Exploration Technology Development Project
GPS: Global Positioning System
GSE: Ground Support Equipment
GENIE: Guidance Embedded Navigator Integration Environment
IMU: Inertial Measurement Unit
JSC: Johnson Space Center
NASA: National Aeronautics and Space Administration
RR1: Risk Reduction 1 Terrestrial Rocket
TRL: Technology Readiness Level
VTB: Vertical Test Bed

INTRODUCTION

The GENIE was conceptualized in January 2010 to be an extensible platform capable of validating an assortment of navigation and guidance algorithms via simple software load for a variety of users. The integrated hardware and software platform was built to flight worthy completion within seven weeks via rapid prototyping effort at Draper Laboratory.

The first adopters of the GENIE platform were Project M and ALHAT. Project M is a NASA JSC conceptual design to land an operational humanoid robot on the moon in 1000 days. The humanoid will travel to the moon on a small lander where it will perform a precision, autonomous landing, avoiding any hazards or obstacles on the lunar surface. Upon landing the robot will deploy and walk on the surface performing a multitude of tasks. [1] Project M aims to quickly develop and test applicable lunar landing algorithms in an existing terrestrial rocket, named Pixel, constructed at Armadillo Aerospace. The ALHAT project, also managed by NASA JSC, seeks 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. [2] The GENIE platform proved to be the first real time implementation of ALHAT/Project M's guidance and navigation software with great success.

GENIE OVERVIEW

The GENIE, pictured in Figure 1, is an integrated hardware and software platform capable of providing real-time autonomy, guidance, and navigation solutions in a rugged environment. The GENIE, when coupled with an appropriate control authority, is capable of closed loop control to precisely and safely ascend and land a terrestrial rocket over a variety of trajectories applicable to lunar or Martian environments.

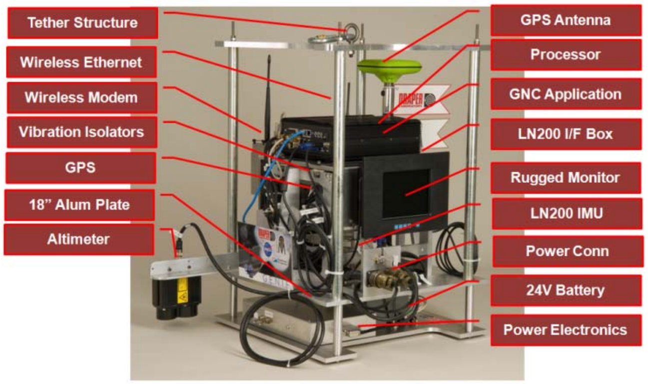

Figure 1: GENIE Components

The GENIE sensing suite consists of an LN200 IMU to measure vehicle translational and rotational rates, a Javad GPS to measure position and velocity, and an Acuity Laser altimeter to measure altitude. The GPS sensor and Pentium based microprocessor are packaged in a GENIE custom built rugged housing structure to mechanically isolate units from the harsh vibration environment encountered on terrestrial rockets. Additionally the entire structure is capable of being top lifted for easy transport and tethered type testing. The GENIE contains its own batteries, power system, and wireless communications to allow it to be completely stand alone and without the need for hard wired connectivity. The GENIE consumes approximately 48W of power when fully operational, fits within a 18" x 18" x 26", volume, and weighs approximately 50 lbs.

The GENIE AGNC software resides on a Pentium based processor running VxWorks. The flight computer has associated serial I/O to communicate with the navigation sensors and has a large solid state recording capability. A linux based laptop serves as the primary GSE performing any necessary commanding and received low bandwidth housekeeping and health telemetry High rate bandwidth data is stored internally to the GENIE solid state drive and subsequently offloaded on demand wirelessly via a GENIE supplied local wireless network.

GENIE Guidance and Navigation

The GENIE guidance software is a variant of the ALHAT guidance software that is designed to provide propulsive maneuver commands, which dictate the flown lunar landing trajectory profile [5]. These commands consist of overall trajectory burn targeting and maneuver burn guidance, or the burn direction and magnitude information needed to complete the maneuver. The ALHAT guidance software provides these maneuver commands to accomplish the lunar deorbit and the powered braking burn landing maneuvers. The GENIE RR1 guidance software was instead configured to fly a simple rectangular hop trajectory. In this software variant, guidance provided targeting and burn guidance to fly out a sequence of three phases: a vertical rise to a defined altitude, a lateral traverse to a defined target, and a vertical descent to touchdown at the target.

The GENIE RR1 navigation software is a derivative of the ALHAT navigation algorithm that was utilized in the JPL ALHAT helicopter Flight Test campaign in the summer of 2010. The underlying navigation algorithm is an extended Kalman filter (EKF). The primary responsibility of GENIE navigation is to provide estimates of the vehicle state to guidance and control. Navigation processed external sensor measurements (altimeter and GPS position and velocity) aided by a strap-down LN200 IMU. In addition to estimating the inertial state of the vehicle (position, velocity, and attitude), navigation also provided real-time estimates of the sensor biases which were used to adjust the measurements accordingly. Finally, the navigation algorithm also maintained estimates of quantities such as the accumulated delta velocity in order to provide downstream processes (i.e. guidance) with required information.

RR-1 Flight Vehicle

In late 2009, NASA's Project M began working with Armadillo Aerospace as a consultant for

Liquid Oxygen (Lox) Methane engine development [3] Project M has identified Lox/Methane propulsion as a key enabling technology and has adopted it as part of their mission concept to gain valuable in-space flight experience. Additionally, Project M hired Armadillo Aerospace to provide a lox/methane based terrestrial rocket to begin a series of risk reduction activities to mature the AGNC algorithms and sensors. The first risk reduction activity planned and completed was an open loop GENIE configuration to assess mechanical integrity and performance of navigation, sensor, and guidance subsystems. The objective of the Pixel vehicle was to provide a stable flying terrestrial rocket capable of flying additional payload and independently logging vehicle truth data.

To meet the objective, Armadillo provided a single thrust vector control, four tank configuration terrestrial rocket known as the Pixel initially developed for the X Prize Cup. [4] The vehicle has its own avionics and communication system and is completely capable of free flight independent from the GENIE. A picture of the GENIE integrated onto the Pixel terrestrial rocket is shown in Figure 2.

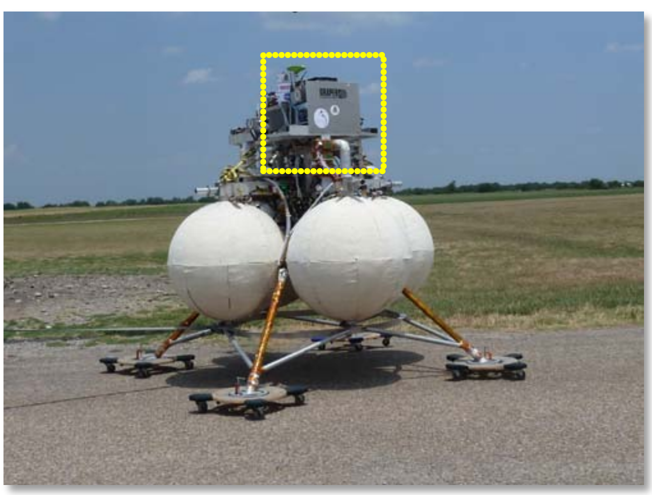

Figure 2: GENIE Integrated onto Armadillo Aerospace Pixel Terrestrial Rocket also known as RR-1

RR1 Flight Test Results

In June 2010, the GENIE successfully demonstrated a high performance embedded guidance and navigation solution on a free flying terrestrial rocket.

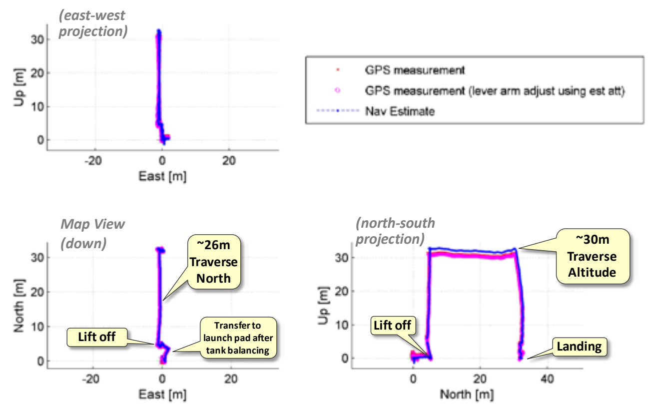

Figure 3: GENIE Onboard Navigation Position Solution During RR-1 Hop Flight

Figure 3 shows some trajectory data logged onboard GENIE during this hop maneuver. The maneuver was planned to be a 30-meter ascent, 26-meter lateral traverse, and a 30-meter descent to the landing pad. Each subplot in the figure shows a different perspective of the three-dimensional trajectory data (i.e. east-west projection, down projection, and north-south projection). The GENIE navigation state solution is shown in blue, while the raw GPS position data is shown in magenta and red. This plot shows good agreement between the navigation solution and the raw sensor data and between the planned and flow trajectory. A small discrepancy is visible between the blue and magenta curves in the north-south projection. This is due to the more accurate navigation altitude estimate (utilizing the GENIE altimeter) as compared to the lower accuracy GPS altitude measurement.

Figure 4 shows the onboard GENIE estimated altitude (blue) and the raw altimeter measurements (magenta & red) versus mission elapsed time. In this data, you can see noisy altimeter data during the lift off. This was caused by the dust kicked up during the first few seconds of flight, visible in the photo (Figure 5). Several times during the flight anomalous altimeter measurements were provided to the navigation software and were properly edited out to avoid corrupting the state estimate. Several small anomalous measurements are visible in the figure below. During descent, the vehicle lowered its altitude quickly to about 7-meters altitude, and then paused before the final descent to touchdown.

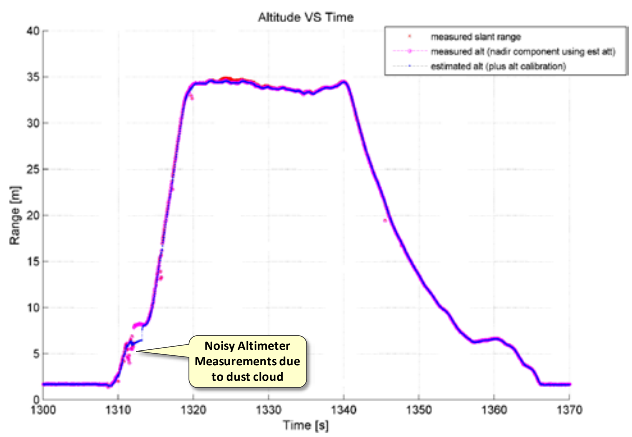

Figure 4: GENIE Onboard Navigation Altitude Solution During RR-1 Hop Flight

In general, the GENIE performed very well as a real-time, embedded test platform for the guidance and navigation software. The internal data logging system captured all the raw IMU, GPS, and altimeter data, with no data loss, which is invaluable for post-flight testing and further analysis. The real-time execution of the guidance and navigation software onboard GENIE was also flawless. Output from this software was also logged onboard for post-flight evaluation. The evaluation of this logged data has shown that this guidance and navigation software performed correctly in this real-world test, building confidence in the software's design as it moves on to the next stage of flight-testing.

Figure 5: June 2010 RR1 GENIE Flight Test in Caddo Mills, Tx

RR-1 FLIGHT LESSONS LEARNED

One beneficial strategy for the GENIE development effort was to utilize the Matlab autocoding tool for the some of the key algorithms onboard the flight computer. This approach allowed the algorithm developers to focus primarily on the proper functional nature of the algorithm in development and allowed them to efficiently test the functional performance in the convenient Matlab environment. Then using the Matlab EML autocoding tool, these algorithms were quickly converted into C-code, which could then be compiled into the GENIE flight computer. As the algorithms matured, enhancements or bug fixes quickly and easily flowed from the original Matlab expression of the algorithm into the real-time VxWorks environment in the GENIE system.

Another beneficial software development strategy for the GENIE platform was to create for each of the AGNC algorithms a top-level software "executive layer" that surrounds the individual A, G, N, or C algorithms; these are known as the "functional layer". Using this construct (figure 6), the AGNC algorithms were given a standardized software interface to the VxWorks system that simplified integration with the rest of the flight software. Within the executive layer, any unique aspects of executing the algorithm could reside. This approach also enabled previously developed, legacy software to be easily introduced into the GENIE flight software system without necessarily requiring rework of the underlying software, or changing the GENIE flight software paradigm. In this scenario, the executive layer fills the software gap between the standardized GENIE flight software setup and the heritage software. This approach was shown to be highly effective and efficient when the GENIE navigation software was used concurrently in an ALHAT helicopter field test. To support these two flight test efforts, the navigation executive layer was modified so as to toggle between the GENIE flight software paradigm and the ALHAT field test computer paradigm with only a recompile. The underlying "functional layer" navigation algorithm was identical and performed well in both applications.

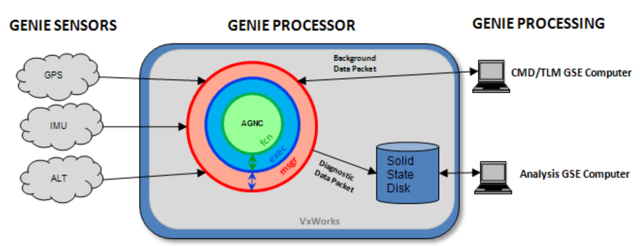

Figure 6: GENIE software layering supports extensibility

To help mitigate risk of the actual flight, a series of ground tests were executed prior. Starting in the laboratory environment, the GENIE was assembled and tested on a static table to measure Earth rate and simple accelerations. This proved out the end-to-end connectivity and allowed the GSE to be fully developed. Next, a series of cart tests were executed at a prior surveyed parking garage to demonstrate that the GENIE would initialize properly outside and perform within expectations. This included manually lifting the GENIE to mimic take-off, translating it via a cart, and the placing the GENIE back on the surface to best mimic the planned hop, albeit at relatively small altitudes. To stimulate higher altitudes, the GENIE was places on a crane and moved within a 3 dimensional volume. Designers checked that navigation solutions behaved properly while being subject to pendulum tests and multiple rotations on the crane. Finally, prior to the final flight, a tethered test was achieved on the actual rocket to ensure that the GENIE mechanical structure would properly hold together and that operations were sufficiently planned out. A good lesson learned here is the value of the tether test that most closely approximated the free flight experience. Not only did it verify mechanical integrity, it clearly demonstrated that what we planned for operationally during the free flight was cumbersome and untimely, making the team revamp and focus on only critical operations for the highly dependent free flight operation.

FUTURE PLANS

Since the successful flight of GENIE in June 2010 on the Armadillo Pixel vehicle, a significant effort has focused on applying the extensible system to demonstrate closed loop control on at least two independent terrestrial rockets. The first is a NASA owned, Armadillo derived, terrestrial rocket known as Morpheus. Fundamentally Morpheus is a larger and more capable Pixel vehicle to be used as a general testbed, including validation of ALHAT approach phase trajectory execution via the GENIE platform. The second is a Masten Aerospace terrestrial rocket capable of both ALHAT approach phase trajectories and Martian approach phase trajectories. The Armadillo Aerospace Pixel and Masten Aerospace Xombie, pictured in Figure 7, are the basis for future NASA derived GENIE customized vehicles that allow full closed loop control to best validate a host of applicable space landing technologies.

Both GENIE enabled vehicles will incrementally raise associated technology readiness levels of suitable lunar and martian next generation technologies through closed loop payload testing. Potential payloads include ALHAT derived velocimeters, altimeters, terrain relative navigation sensors, hazard detections systems, and associated algorithms applicable to the Moon, Mars, or Near Earth asteroids. As each system progresses in maturity through repeated terrestrial flight, the desire is that the now TRL 6 advanced technology will be more readily adopted in future near term space missions, giving the spacecraft designer more capability and technology options to choose from.

Figure 7: Armadillo Aerospace Pixel (left) and Masten Xombie (right) Terrestrial Rockets

In the 2012 timeframe, GENIE AGNC software aims to autonomously fly the terrestrial rocket by determining vehicle navigation state and calculating the when, where, and how to control the vehicle and to land using an ALHAT hazard detection system to help identify safe landing locales in the local terrain. This achievement will raise the TRL to 6 for the ALHAT System, completing the primary project mission statement.

CONCLUSIONS

The GENIE is a novel system GNC concept that was proven through prototyping and demonstration in a realistic operational environment, the RR-1 terrestrial rocket. A primary objective of a GENIE enabled terrestrial rocket concept is to demonstrate and advance the Technology Readiness Level (TRL) of precision landing and hazard avoidance capabilities developed by the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project. For example, the same navigation algorithm and hop guidance solution that was designed to be applicable in the terrestrial and lunar environment was validated on the RR-1 flight, helping validate the ALHAT system concept and raising its TRL.

The GENIE rapid prototype design and test approach allowed the ALHAT/M team to evaluate each system design (e.g. propulsion; guidance, navigation and control; avionics; and structure) in a timely fashion. Testing a maturing spacecraft early and often informs the designer in a more rapid fashion than traditional serial process of design to final configuration and then and only then testing final configuration.

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