Hover Test Vehicle

Implementation Plan and Test Results

26 February 2009

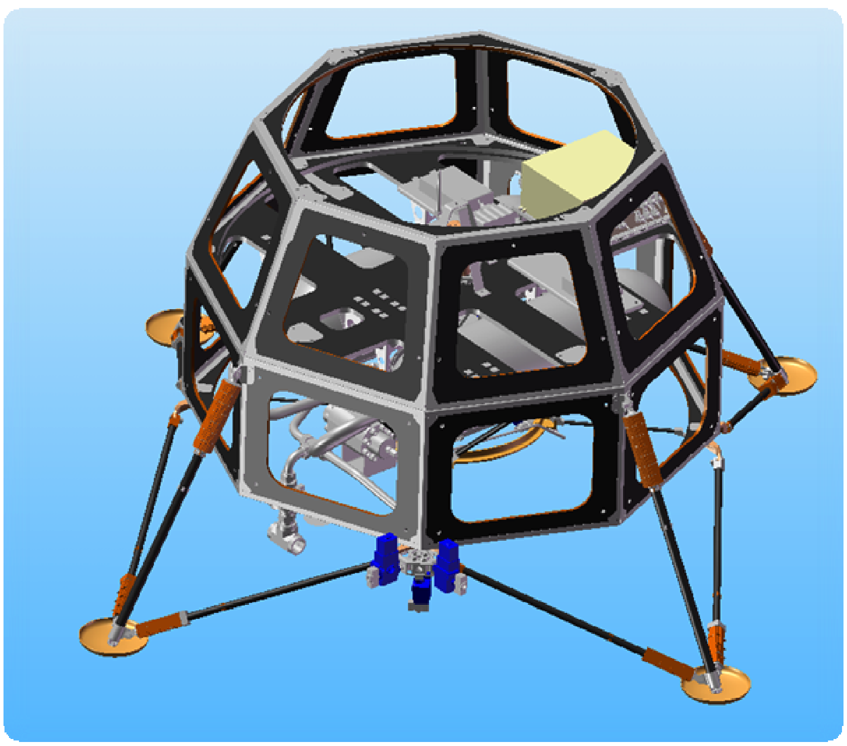

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Table of Contents

Table of Tables

Table of Figures

1. Introduction

In order to develop the capability to evaluate control system technologies, NASA Ames Research Center (Ames) began a test program to build a Hover Test Vehicle (HTV) – a ground-based simulated flight vehicle. The HTV would integrate simulated propulsion, avionics, and sensors into a simulated flight structure, and fly that test vehicle in terrestrial conditions intended to simulate a flight environment, in particular for attitude control. The ultimate purpose of the effort at Ames is to determine whether the low-cost hardware and flight software techniques are viable for future low-cost missions. To enable these engineering goals, the project sought to develop a team, processes and procedures capable of developing, building and operating a fully functioning vehicle including propulsion, GN&C, structure, power and diagnostic sub-systems, through the development of the simulated vehicle.

2. Test Objectives

The test plan is designed to test the 6 degree-of-freedom control of the HTV design using a cold-gas propulsion system. The test plan sequence addresses risk by incrementally adding complexity to each test, based upon the results of the previous test. This minimized the chances of damage to the vehicle.

The Test Sequence is composed of the following steps:

1. **Strap-down Test** – individual propulsion system components, followed by entire propulsion system, are tested in strapped-down configuration prior to integration with the vehicle
   Purpose: measure performance of the main and ACS thrusters and characterize the nozzles.
2. **String Test** - hang the vehicle from string and close the IMU-ACS control loop to stabilize the vehicle in the presence of disturbances
   Purpose: check coordinate systems, verify predicted control authority
3. **Pop-Up Test (Bungee) -** one pulse of the Main thruster to get into the air, then active ACS control on the way up and down.
   Purpose: check that we have enough ACS authority to compensate for off-axis thrust, measure any large rotations to back-out thrust vector
5. **Multi-Pop Test** (Bungee) – multiple pulses of the Main Valve with active ACS from bungee.
   Purpose: Verify prior to free flight that the Hover Test vehicle will work as planned, while still maintaining a level of safety with the bungee so that the vehicle would not be damaged.
6. **Full Hover Test –** multiple pulses of the Main Valve with active ACS with no support
   Purpose: complete 3-axis test of the attitude control system

3. Technical Plan

3.1 Reference Documentation

The following is a list of documentation that supports the Hover Test Implementation Plan.

1. Further Test Analysis and Results Documents:
    a. J. Bell, Design of a Cold Gas Propulsion System for a Hover Test Vehicle (NASA TM, in preparation)
    b. NRP 45 Building Emergency Action Plan (BEAP), Dated Oct 2007

3.2 Roles & Responsibilities

The Hover Test is a project at NASA Ames and is implemented as a technology risk reduction and team development activity. The organization chart below shows roles and responsibilities for key personnel on the team. The following outlines specific roles and responsibilities for each task and sub-task lead:

- **Director –**responsible for overall direction of the project, including customer relations, updating centre and Agency relevant management and outside entities.

- **Project Manager** –responsible for overall management of the project, including top level definition of project budget, schedule and technical objectives. The PM is also responsible for defining the level 1 objectives, major schedule milestones and budget allocation for this task.

- **Task Lead –**responsible for management of Hover Test Activities and implementing detailed task objectives within the parameters defined by the PM with respect to budget and schedule constraints. The task lead is responsible for allocating resources among the various subtasks in order to accomplish the defined objectives. The task lead is also responsible for coordinating additional resources, such as subcontractors and make or buy decisions, within and outside of Ames. The Task Lead is responsible for overseeing activities for the Hover Test Vehicle, Hover Test Facility, and Testing. Will Marshall acts as Deputy Task Lead.

- **Test Director** –responsible for oversight of all test activities in the Hover Test Facility, Building 45. Specifically, the Test Director is responsible for ensuring that Test Operations Procedure (TOP) are followed and recorded and that safety procedures are implemented so that personnel safety is not compromised. The Test Director is also responsible for ensuring safety of all personnel, such as team members and visitors.

  For un-tethered flight, the Test Director or acting Test director shall not implement test initiation unless he has concurrence from the following subsystem leads that the vehicle is safe to fly:
  1. Avionics Lead
  2. Propulsion Lead
  3. Vehicle Design lead

  In the event the Test director is not present or available, the Deputy Test Director shall act as Test Director. In the event neither the Test Director nor the deputy Test Director are available, an alternative TOP must be reviewed and approved by the Test Director prior to testing.

- **Hover Test Facility Lead -** responsible for all aspects of the Hover Test Facility. The primary responsibility is to bring Building 45 into compliance for temporary occupancy for limited use Hover Testing. This includes obtaining necessary permits and operating in compliance with the Ames Fire Marshall, SR & QA, including the Ames Safety Pressurized Systems Safety Engineer. The Facility Lead is also responsible for the Following:
  1. Controlling access to Building 45
  2. Maintaining ear & eye protection equipment
  3. Maintenance of the building including operational hardware such as the Air Compressor, Cameras, lights, etc. All maintenance activities need to be coordinated through and approved the Facility Lead.

- **Vehicle Design Lead** – responsible for the design and development of the Hover Test Vehicle including the following:

1. Maintaining Configuration Control of all drawings, including as-built configurations and related documents such as analysis and vendor specific specifications, associated with the design and manufacture of the vehicle. In addition, copies of all such material shall be archived on NX.
2. Responsible for integrating and packaging Avionics hardware into the vehicle.
3. Responsible for maintenance and repair of the vehicle and its subsystems, with exception of the Avionics Package and related hardware and software.

- **Propulsion Lead** – responsible for the propulsion system level design including the following:
  1. Developing the overall system level analysis and specification needed to design the propulsion system hardware.
  2. Responsible for coordinating pressure system safety issues with the Ames Pressure System Safety Representative.
  3. Working under the direction of the Test Director, responsible for developing and maintaining procedures for pressurizing and safing the vehicle.

- **Avionics Lead** – responsible for design and development of all Attitude, Guidance Navigation and Control Systems including all hardware and software. The Avionics Lead is responsible for determining the operational flight parameters of the test including the following:
  1. Giving final approval that vehicle is ready for flight.
  2. Setting vehicle operational conditions such as initial operating pressure and test duration, and scope of test.
  3. Setting the Pass/Fail Criteria
  4. Determining criteria for aborting a test
  5. Developing and maintaining the avionics aspects of the TOP

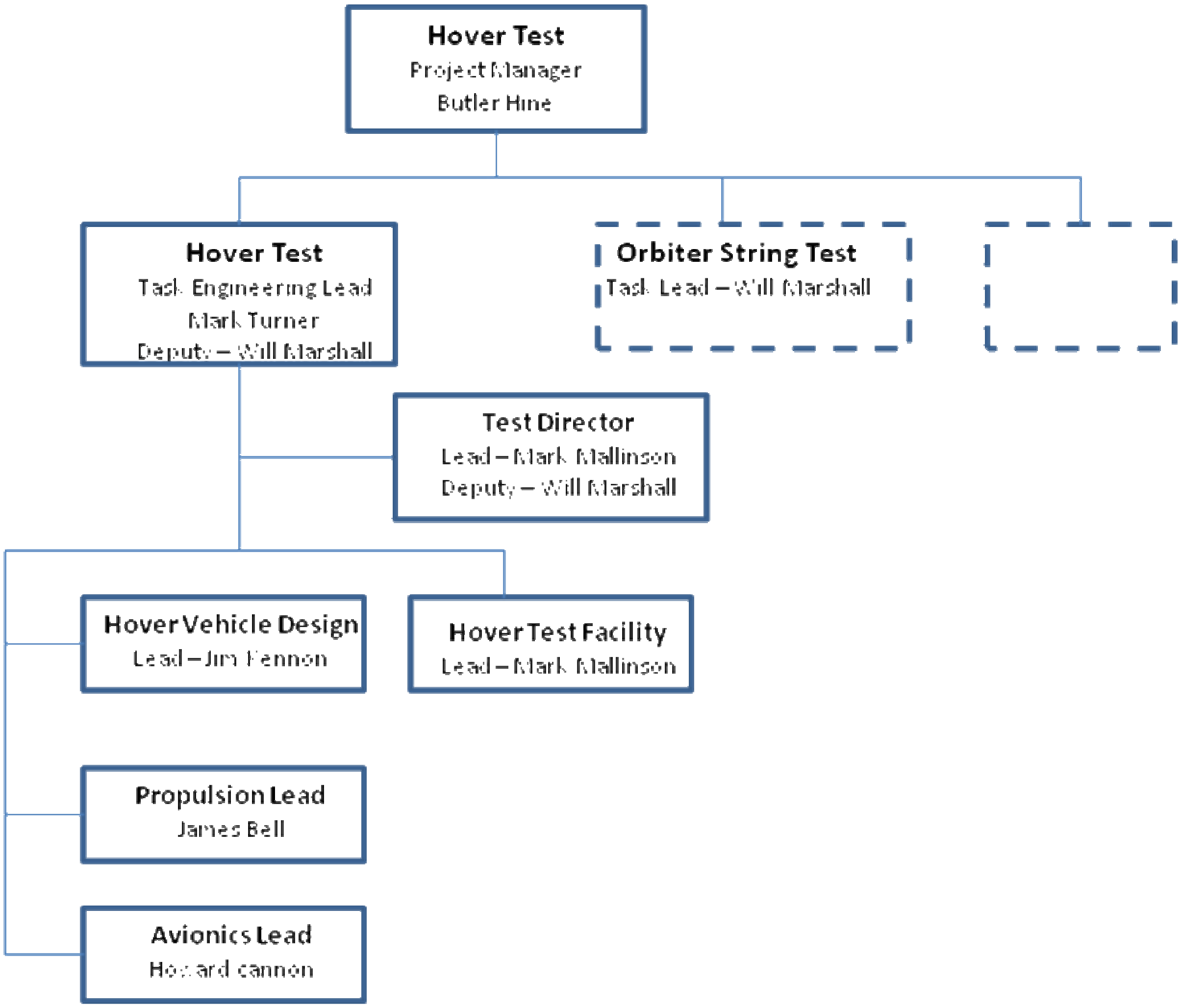

Figure 1: Roles & Responsibilities for Hover Test

3.3 System Test Plan and Overview

A series of integrated test flights were conducted. To mitigate potential damage to the vehicle, test and validation of control authority of the vehicle was conducted through a series of incremental tests.

The tests outlined herein followed a series of sub-system tests that included:

1. 'FlatSat' – a demonstration of the attitude control software in command of a generic test vehicle levitated on a 2D granite table top using real avionics hardware.
2. Mechanical structural tests – including
    a. Crush testing of honeycomb crushable legs
    b. Structure test with propulsion system

A9SP-0600-XR010, A9SP-0600-XR201, A9SP-0600-XR220, A9SP-0600-XR250, and A9SP-0600-XR251, Structural Testing of the HTV and components

The Hover test sequence in this report build on these sub-system tests, as well as a range of analyses, which are referenced above.

The following is a summary of the tests conducted.

1. Propulsion Test in Strapped Down Configuration

Description/Procedure

1. Assemble HTV propulsion system on a jig with a simple control system and mount upside down on load cells
2. Pressurize tanks to 6.9 MPa (1000 psi)
3. Run mock test firing sequence (based on simulation of typical firing sequence)
4. Read out thrust loads
   ---
5. Repeat Steps 1-4 for 13.8 MPa (2000 psi) tank pressure
6. Repeat Steps 1-4 for 20.7 MPa (3000 psi) tank pressure

Purpose

1. Test thrust loads of integrated propulsion system
2. Test structure can withstand loads associated with divert thruster
3. Check off-axis divert loads

Pass/Fail Criteria

1. Sufficient thrust to lift vehicle
2. Off-axis thrust less than control authority of the ACS
3. No structural faults

Cold Gas Thruster Test Results Summary Document

2. String test

Description/Procedure

1. Hang the HTV from a tether (fixed length, un-stretchable) such that it hangs approximately in the centre of the netting.
2. Pressurize tanks to 2.1 MPa (300 psi) (minimum pressure to run ACS is 1.0 MPa (150 psi))
3. Using just ACS nozzles (no divert), close IMU-ACS loop to stabilize in the presence of disturbances
   ---
4. Repeat Steps 1-3 for 13.8 MPa (2000 psi) tank pressure
5. Repeat Steps 1-3 for 20.7 MPa (3000 psi) tank pressure

Purpose

1. Close IMU-ACS loop and confirm stability (from attitude data in telemetry feed as well as visually)
2. Check coordinate systems are correct

Pass/Fail Criteria

1. Control authority works in accordance with simulation

3. Bungee Cord Pop Test

Description

1. Attach the HTV to a bungee cord (stretchable cord with k~1000N/m)
2. Pressurize tanks to 6.9 MPa (1000 psi) (minimum pressure to lift off is ~400psi and so for safety reasons need not go much higher than this on first pop up)
3. Raise HTV such that it hangs approximately in the centre of the netting
4. Supply one pulse of the divert engine to get the HTV to move a significant degree e.g. ~30cm height (which translates to ~64ms pulse width)
   ---
5. Repeat steps 1-6 at pressure of 13.8 MPa (2000 psi) (~50ms pulse length)
6. Repeat steps 1-6 at pressure of 20.7 MPa (3000 psi) (~44ms pulse length)
7. Repeat steps 1-8 with activated ACS control loop
8. Repeat step 7 with pop up height extended to 50cm (pulse lengths of 81ms, 64ms and 56ms for 6.9 MPa (1000 psi), 13.8 MPa (2000 psi) and 20.7 MPa (3000 psi) respectively)
9. Repeat step 7 with pop up height extended to 1m (pulse lengths of 116ms, 92ms and 80ms for 6.9 MPa (1000 psi), 13.8 MPa (2000 psi) and 20.7 MPa (3000 psi) respectively)

Purpose

1. Ensure that the ACS thrust is sufficient to compensate for off-axis thrust of the divert
2. Measure rotation of vehicle in flight to calculate the off-axis tilt of the divert thrust
3. Verify that vehicle position and rates are taken adequately while subjected to the large impulse.
4. Verify predictions that it is possible to sense and control while thrusting
5. Verify calculations of the height gained by divert pulse width are accurate

Pass/Fail Criteria

1. Divert thrust vector goes through Centre of Gravity (CG) of HTV within limits and that the vehicle lifts of vertically
2. Control authority works in accordance with simulation
3. Vehicle has sufficient ACS authority to compensate for off-axis thrust
4. Vehicle structure remains intact

4. Bungee Cord Multi Pop-Up Test

Description

1. Attach the HTV to a bungee cord (stretchable cord with k~1000N/m)
2. Pressurize tanks to 13.8 MPa (2000 psi) (minimum pressure to lift off is ~2.8 MPa (400 psi) and so for safety reasons need not go much higher than this on first pop up)
3. Raise HTV such that it hangs approximately in the centre of the netting
4. Activate ACS control loop
5. Supply initial pop pulses of the divert engine
6. Allow software to enable hovering mode until pressure drops below hovering capability
   ---
7. Repeat steps 1-6 at pressure of 20.7 MPa (3000 psi) (~44ms pulse length)
8. Repeat step 7 with HTV initially on collapsible table in the centre of the netting in the x-y plane and immediately after initial pulse, collapse the table

Purpose
1. Check that the hover test vehicle can maintain attitude control during a hover mode
2. This is the most complete verification that the HTV can hover prior to removing the bungee.[1]
3. Check that the table collapses sufficiently quickly

Pass/Fail Criteria

1. Verify that actual flight test matches simulation – principally that of hovering without a large deviation in attitude or position.
2. For tests operated from drop pedestal, verify that platform can be collapsed quick enough so as not to pose a hazard to the vehicle
3. Vehicle structure remains intact

5. Hover Test Free Flight

Description

1) Place the HTV on the collapsible table in the centre of the netting in the x-y plane
2) Pressurize tanks to 13.8 MPa (2000 psi) (minimum pressure to lift off and do some significant maneuvering)

[1] Note that in fact it is harder to hover with the bungee since it introduces external torques on the vehicle which would not be present in the free flight hover test (and are not therefore accounted for in the software control algorithm).

3) Carry out complete pulsing sequence of divert and ACS thrusters to (a) become air borne, (b) maneuver and (c) land onto the netting.
4) Collapse collapsible table as soon as HTV is airborne
5) Repeat steps 1-4 at full pressure (20.7 MPa (3000 psi))

Pass/Fail Criteria

1. Verify complete control authority of the HTV design: that all the subsystems work and that they all work together.
    a. Structure remains intact
    b. Avionics system performed as planned (wireless transponder worked, software correctly understood the IMU, software commanded the propulsion as planned etc)
    c. Trajectory: verify landing sequence.
    d. Principle Data Acquisition: verify that IMU, pressure transducers, and any other sensors read out appropriate information
    e. Propulsion: provided thrust as planned
    f. Diagnostics: external reference data of HTV position and orientation gained
    g. Facilities: collapsible table, netting, and so forth worked as planned
    h. Safety: no one was placed in any serious danger or was hurt

3.4 Equipment

3.4.1 Product Breakdown Structure & Master Equipment List (MEL)

The Master Equipment List enclosed in Appendix A serves as the baseline approved MEL for use with all analysis of this report unless measure values are available. For mass and C.G. measurements, actual measured values are listed in Section 3.6.1.1 and should be used for analysis unless otherwise noted.

Summary of Equipment List[2]
11-7-2007

	QTY	Unit Mass (kg.)	Total Mass (kg.)	Subsystem Mass (kg.)
Propulsion				**37.39728833**
CARLETON_6280-3-281	2	9.07788	18.15576	
MAC55	6	0.38024	2.281458	
MV524	1	0.83912	0.839121	
TANK_BRACKET	4	0.31688	1.267524	
TANK001001	1	0.77614	0.77614	
TANK002001	1	0.77669	0.776692	
TESCOM_26-1131-282	1	1.78953	1.78953	
THERMO5654	1	0.97882	0.978815	
Extension Module				**4.128139036**
Payload				**7.98806**
BATTERY1_COLD_GAS_TEST	1	0.18200	0.182	
ARC_SDU_AVIONICS			4.08106	
S050545-IMU_5_DL	1	0.95000	0.95	
Microhard Wireless Modem	1	0.30000	0.3	
Remote control Enable/Disable Box	1	0.15000	0.15	
Visualize System (2 boxes +LED's)	1	0.20000	0.2	
Octahedral Bus				**3.256286168**
Legs				**3.859284**
Fuel				**11.2**
CARLETON_6280-3-281_AIR	2	5.60000	11.2	

Table 1: Summary of Equipment List

3.4.2 Facility and Test Support Equipment

The following is a list of primary support equipment required to support the Hover Test Flight Operations:

- Test Containment Assembly, Drawing #A9SP-0600-M001
- Scissor Pedestal Assembly, Drawing #A9SP-0600-M060
- Control Room Window Assembly, Drawing #A9SP-0600-M050

[2] See Appendix A for full MEL.

- Air Compressor, Model Number CS9-7.5, www.northshorecompressor.com

3.5 Vehicle Requirements

3.5.1 Overall Performance Requirements

The overall vehicle performance requirements can be summed as follows:

Reqt. #	Requirement	Result
A.1	Demonstrate vehicle closed 6 dof loop attitude control during free flight. This includes: Propulsion divert sufficient to ensure that the following condition is met: vehicle flight duration > 10x control cycle duration (~100ms) Attitude Control System (ACS thrusters, valves, command electronics) with sufficient physical authority (thrust and response time) to maintain vehicle attitude both during free fall and under flight powered by the main engine Control software with sufficient efficiency to enable control given the physical ACS, the divert system and the vehicle inertial properties Vehicle structural integrity is maintained under the g-load of the divert thrust (~5g)	√
A.2	Demonstrate that all the COTS are functional in an integrated hover vehicle.	√

Table 2 Overall Performance Requirements

3.5.2 Avionics

Summary
The principle requirements for the ADCS, GN&C and software are to ensure that the vehicle maintains attitude control (within certain position and angle bounds) over the flight of the HTV – which is central to the purpose of the overall project.

Attitude Determination and Control

Reqt. #	Requirement	Feasibility Evidence	Result
CR.1	The control system shall provide angular control as specified by the guidance system to within 2 degrees within 1 second of command. [and remain there for the duration of the flight or commanded otherwise]	Test CR.1	?
CR.2	The control system shall provide position control within 1 meter of a commanded input value during powered flight	Test CR.2	√
CR.3	The control system shall met all control requirements with maximum system errors of +/- 1% of values specified in the Cold Gas Vehicle Specifications document	Test CR.3	√
CR.4	The control system shall provide for landing velocities no greater than 4 m/s	Test CR.4	√

CR.5	There shall be an open-loop individual thruster firing mode for strap-down tests.	Test CR.5	√
CR.6	The control system shall not command chatter such that thrusters cycle on/off at greater than 50 Hz.	Test CR.6	√
CR.7	The control system shall move the vehicle to achieve a commanded target position (to within 1 meter radius of the target) within 4 seconds, and remain there until the end of flight.	Test CR.7	√
CR.8	The control system shall provide modes for liftoff, translation and soft-landing.	Inspection	√
CR.9	The control system shall limit lateral velocities at landing to no greater than 1m/s.	Test CR.9	√

Table 3: Key ADCS and GN&C Requirements

Software Requirements
The Software requirements are under version control and stored in SRS.html

Reqt. #	Requirement	Feasibility Evidence	Result
S.1	The system shall use SI units.	Inspection	?
S.2	Most software will be autocoded from models. Hand-coded software shall not exceed 85% of the source lines of code (SLOCs)	Test S.2	?
UI.1	The operator station shall be located in the lab with the HoverSat.	inspection	?
UI.7	The system shall provide a capability to store all telemetry feedback to the operator.	inspection	?
HS.2	The system software shall check and prevent the system from executing commands that are out of limits.	Test HS.2	?
HS.3	There shall be a bounding box on all positions, velocities and accelerations. Violation shall result in shutoff of the thrusters. Specific bounding values are: X and Y position: -3.81 meters to 3.81 meters Z Position: 0 to 6.09 meters. . X, Y and positive Z: Velocities 5 meters/sec. Negative Z: 10 m/sec. X, Y and Z Accelerations: +/- 97 m/s^2 Pitch and Roll: +/- 15 degrees	Test HS.3	√ No limit exceeded
HS.4	There shall be a remote kill switch that disengages the thrusters.	Inspection	Partial: operation success in doubt.
HS.6	Failure of critical hardware systems shall result in the software shutting off all thrusters.	Test HS.6	√

Table 4: Key Software Requirements

The Full Software requirements are found in Appendix E.

3.5.3 Propulsion Requirements

The design goals for the propulsion system were as follows:

Reqt. #	Requirement	Result
P.1	Provide descent acceleration and attitude control moments that have the following specs: a. A descent engine thrust of 2000 N b. 6x ACS thrusters with a thrust of 30 N c. Capable of flying a vehicle of wet mass of 55 - 65 kg.[3] d. A propulsion system dry mass of ~7kg, capable of holding 26kg of fuel e. Has basic inertial specifications of Ixx Ixy Ixz 10 -1 -1 Iyx Iyy Iyz -1 10 -1 Izx Izy Izz -1 -1 10	√
P.2	The HTV shall have two sets of three ACS thrusters in a bow-tie configuration, placed at the bottom corners of the vehicle.	√
P.3	Fit within roughly the same volume as a bi-propellant propulsion system.	√
P.4	Not use exotic or extremely high pressure components. In practice this meant limiting pressures to 20 – 30 MPa (3000 – 4500 psi) and commercial pressure system components.	√
P.5	Provide throttling through Pulse Width Modulation. The main/divert thruster should be turned on and off within of order 10-50 ms; the ACS thrusters can be turned on and off within 10 ms.	√
P.6	Provide enough ACS mass flow to operate two ACS thrusters simultaneously throughout the flight	√
P.7	Be acceptable to the NASA Ames Pressure Systems Safety Office	√
P.8	Generate as high total impulse as possible subject to the constraints of goals 1 – 6 (in order to allow as long a flight duration as possible) and with a minimum time of 10x the attitude control timescale so as to allow demonstration of attitude stability	√

Table 5: Propulsion Requirements

3.5.4 Mechanical Requirements

Reqt. #	Requirement	Result
M.1	The HTV structure is to utilize fabrication methods and processes to provide path finding and lessons learned for the NASA Ames.	√
M.2	The structure should remain intact (without significant wear and without failure) through	√

[3] It is therefore capable of descent accelerations of 31 - 36 m/s^2 and ACS accelerations of 0.46 - 0.55 m/s^2

	hundreds of HTV flight operations	
M.3	The HTV and other NASA Ames vehicles have several major differences.	-
M.4	HTV total mass to be as low as possible with a target of 68 kg (wet), 57 kg (dry).	√
M.5	HTV thermal environment need not necessarily be considered when selection of materials or stress analysis is performed.	-
M.6	All HTV load cases are to be considered during vehicle design. For the z-axis load from the main thruster firing, a factor of 2 safety margin should be included.	√
M.7	The HTV is to withstand landing loads (structural damage the structure and legs) from maximum final velocities obtained from a theoretical free fall from the top of the Hover Test Cage, into the net.	√
M.8	Design components for ease of replacement as necessary. As an example, leg honeycomb cartridges fall into this category.	√
M.9	Structural analysis is to use a load factor of 1.4 times the limit load for all Margin of Safety calculations. Limit load is defined as the maximum expected load applied to the vehicle or component.	?
M/10	Landing Loads (these are initial design targets for the leg design. Considerable additional analysis and testing for various landing scenarios is required to approach completeness): a. 1 leg impact – 4g deceleration b. 2 leg impact – 8g deceleration c. 4 leg impact – 16g deceleration	√

Table 6: Mechanical Requirements

3.5.5 Electrical & Power Requirements

Reqt. #	Requirement	Result
E.1	The vehicle shall have an internal 28 V battery capable of supplying power for at least 60 minutes of operation without recharge	√
E.2	The vehicle shall provide a means for externally charging the battery and providing power for all systems when not in flight	√

Table 7: Electrical & Power Requirements

3.5.6 Test Data Requirements

Reqt. #	Requirement	Result
D.1	The Mission Operations software shall be capable of recording all vehicle telemetry at a rate of 10 Hz for a duration of 60 seconds minimum	√
D.2	The Mission Operations software shall be capable of archiving all telemetry data that is stored	√
D.3	Descriptions of tests and corresponding file names for data archive files shall be recorded in an Ascii human readable format	√
D.4	High speed cameras shall be provided that visually record the operation of the vehicle in flight	√

Table 8: Test Data Requirements

3.6 Facility Requirements

The Hover Test Facility (HTF) was designed to comply with all applicable building construction and welding requirements and was reviewed and approved by the Ames Building Review Board. The following itemized list contains the requirements by which the HTF was designed and analyzed:

1. California Building Code, Seismic Loading Analysis Requirements
2. ESR-1967, "HILTI HIT HY 150 Concrete Anchoring System Analysis Requirements", ICC Evaluation Services Inc., Dec 1, 2006
3. ANSI/AWS D1.1-84, "Structural Welding Code"
4. Mechanical and Structural Design Manual, Code EE, NASA/Ames Research Center, 1988
5. NSTS 08307, "Space Shuttle Specification: Criteria for Preloaded Bolts
6. Northrop Structural Design Manual, Section 201.6.1"Combined Shear and Tension in Bolted Joints"

3.7 Analysis

3.7.1 Vehicle Mass & Center of Gravity

The mass and centre of Gravity (CG) of the vehicle in the X-Y plane were determined using a balance table shown in Figure 2. The vehicle was placed upside down on a steel plate of mass 78.41 kg and whose C.G. is known. The vehicle and plate are on wheels and a roll bar in such a way a translation stage can be used to push them to a point where they tip over the roll bar and in so doing activate a small beep. The precision of measurement is estimated to be +/- 0.5 mm.

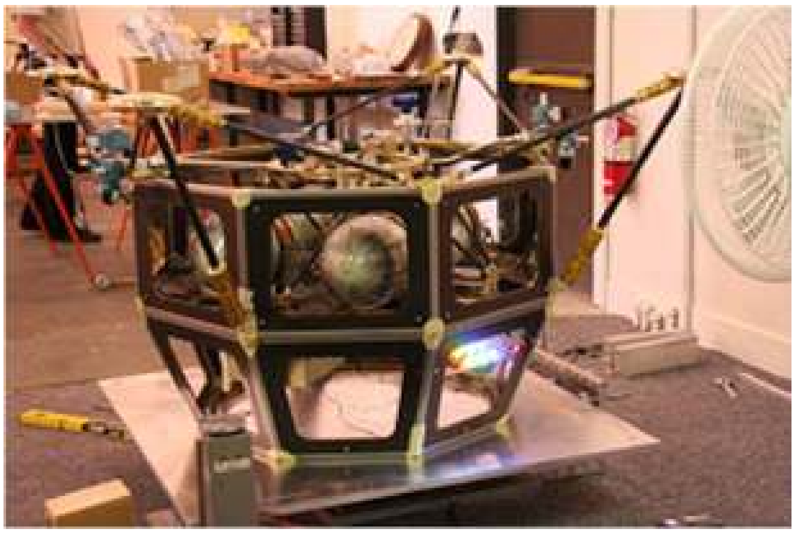

Figure 2: HTV mounted on balance table to measure CG in XY plane

The results of measured mass and C.G for the HTV are shown in Table 9. Actual measured values shall be used for all analysis unless stated otherwise.

Variable	CAD Model (Pro E)[4]		Measured Values for HTV				
			Pre-Testing (13.11.07)			Post-Testing (11.02.08)	
	Dry	Wet	Dry w/o Weights	Wet w/o Weights	Wet w/ Weights	Dry w/ Weights	Wet w/ Weights
Mass [kg]	59.245	70.990	58.82	67.32	68.49	58.82	68.49
Air Mass [kg]	0	11.745	0	-	9.67	0	9.67
Coord. System	CAD	CAD	HTV	HTV	HTV	HTV	HTV
CG X [mm]	-3.35	4.57	-0.48	3.5	-0.36	5.5	-0.16
CG Y [mm]	3.20	3.24	4.1	3.97	-0.18	-6.0	-0.55
CG Z [mm]	-2.96	4.89	-	-	-	-	-

Table 9: Actual and Calculated (CAD Model) Mass & C.G. Values (coordinates for Wet Vehicle)

Weights were added to obtain a maximum 0.6 mm displacement between the CG and the divert thruster position in the x and y-axes:

[4] See Appendix D for complete CAD Model specifications

1) 0.34 kg on the foot of leg 3
2) 0.83 kg on the foot of leg 2

The CG position was measured post the flight series reported herein since a number of minor movement of electronics had occurred (such as moving the aerial and adding further LEDs) during the flight series, and showed that the CG had changed insignificantly.

3.7.2 Structural

In order to verify the strength of the vehicle and lander legs and their attachment to the Hover Test Vehicle (HTV), the following stress analysis was performed.

1) Structural analysis used a load factor of 1.4 times the limit load for all Margin of Safety (MS) calculations. Limit load is defined as the maximum expected load applied to the vehicle or component.
2) Document number A9SP-0600-XR200 is the primary structural analysis document for the HTV. Other stress analysis reports referenced within –XR200 provide detailed analyses of specific components of the HTV.
3) Most of the load cases used for the design and analyses are derived from an assumed flight of the vehicle. Where necessary, load requirements are modified to include greater loads that may be encountered on a flight mission. The following is a summary of the load cases used for design and analysis:

Load requirement specific to the bungee test: the bungee attachment to the HTV is to withstand the maximum estimated force of 2044 N (459 lbf) based on a 68 kg HTV. This is equivalent to 3.07 g vertical acceleration of the HTV at maximum bungee stretch.

Main thruster load: 3560 N (800 lbf) on the HTV. The cold gas thruster firing produces a maximum acceleration of 5.3g on the HTV. This load should have a factor of 2 safety margin.

Landing Loads (these are initial design targets for the leg design. Considerable additional analysis and testing for various landing scenarios is required to approach completeness):

1 leg impact – 4g deceleration
2 leg impact – 8g deceleration
4 leg impact – 16g deceleration

Document Number	Revision	Document Type	Title
A9SP-0600-XR200	-	Stress Analysis Report	Hover Test Vehicle Stress Analysis
A9SP-0600-XR221	-	Stress Analysis Report	Upper Stiffener Panel Analysis
A9SP-0600-XR230	-	Stress Analysis Report	Stress Analysis of Hoist Ring Bracket for Bungee/String Tests
A9SP-0600-XR245	C	Stress Analysis Report	High Pressure Manifolds Stress Analysis
A9SP-0600-XR248	-	Stress Analysis Report	Primary Mount Reinforcement Bracket Analysis
A9SP-0600-XR249	-	Stress Analysis Report	Cold Gas Nozzle
A9SP-0600-XR252	-	Stress Analysis Report	Legs and Attachments to the Hover Test Vehicle
A9SP-0600-	-	Structural Test Report	Sandwich Panel Bushing Pullout Test

XR010			
A9SP-0600-XR201	-	Structural Test Report	Structural Test of the Propulsion Primary Mount Bracket Attachment to the Extension Module
A9SP-0600-XR220	-	Structural Test Report	Core-to-Core Bond Shear Test
A9SP-0600-XR250	-	Structural Test Report	Honeycomb Crush Test
A9SP-0600-XR251	-	Structural Test Report	Honeycomb Bushing Bearing Test
A9SP-0600-XR001	-	Process Specification	Carbon Tube Cutting Specification
A9SP-0600-XR002	-	Process Specification	Carbon Panel Cutting Specification
A9SP-0600-XR003	-	Process Specification	Bushing Installation Specification

Table 10: Document List, Structures, HTV

Summary of calculated Margins of Safety

1) Propulsion module struts
   - Tension, MS > 6.0
   - Compression, MS > 4.0
   - Buckling, MS > 0.03
   - Strut Attachment Fasteners, Shear, MS > 0.38
2) Propulsion Module Attachment to Bus, MS > 0.38
3) Propulsion system high pressure manifolds, MS = 0.28 (at 22.7 MPa (3300 psi))
4) Bus Panel stress, MS = 5.2
5) Extension Module top plate, MS = 0.78
6) Legs

   Primary strut
   - Compression, MS = 1.47
   - Buckling, MS = 0.12
   - End fittings, MS = 0.79
   - Clevis bolt, MS = 0.03
   - Bus Attach fitting bolts, MS = 0.66
   - Footpad screws, MS = 0.9

   Stabilizer Strut
   - Tension, MS = 0.4
   - Buckling, MS = 0.02
   - End fittings, MS = 0.13
   - Clevis bolt, MS = 0.11
   - Bus Attach fitting bolts, MS = 1.29

3.7.3 Avionics/Software

In developing the Avionics hardware and software, the team attempted to use as many flight-like processes and components as possible, while still meeting the challenging schedule requirements for the flight. The following describes the avionics, software processes, and simulation results that were utilized in order to prepare for the Hover test.

Avionics
An Engineering Development Unit from Broad Reach was in use for the avionics. The chassis contains 5 Command and Data Handling (C&DH) slots, and 3 power slots. The processor is a non-flight BRE Starter 440 (200 MHz/ 400 Mips), with 128 Mbytes of SDRAM and 8 Mbytes of Boot-Rom. Also included is a Broad Reach MOAB I/O board, with 47 AD590 temperature channels, 12 sun sensor channels, 24 analog channels, 40 RS422/LVDS transmitters and receivers, 48 discrete inputs and outputs, and MIL-STD-1553 bus support. The development unit also includes a Solar Array Control Integration (SACI) card, and a Power Switching and Pyro Integration (PAPI) board.

Figure 3: Broad Reach avionics non-flight, ground test engineering development unit.

Software Processes
Our approach to software development employs 3 primary stages in a spiral development process, continually increasing the fidelity and complexity of the software and simulations over time in order to meet all of the software requirements: (1) algorithm development using Workstation Simulations (WSIM) of the vehicle and software; (2) automatic software generation; and (3) software downloaded to a flight-like avionics box for Hardware-in-the-Loop (HIL) simulations. Unfortunately, this phase of the development had to be bypassed due to schedule constraints.

Command and Control Software

For the hover test, we utilized command and control software. The software we are currently utilizing is commercially available software from Octant Technologies.[5]

Verification and Validation
In the beginning of the project, we used html documents to capture the software requirements and test plans. As software development progressed, selected unit tests were created for the lowest level functional blocks in the models to ensure that the input and output assumptions were correct, parameterization correctly applied, and the units function as intended. Integrated testing was conducted in the WSIM and PIL. The scripts are set up such that the results of the tests can be automatically logged, and links were provided in the HTML based requirements document that the supporting test evidence that the requirements were met.

Software Design
Figure 4 shows a description of key top level module functionality of the flight software design that is encoded in the SystemBuild model.

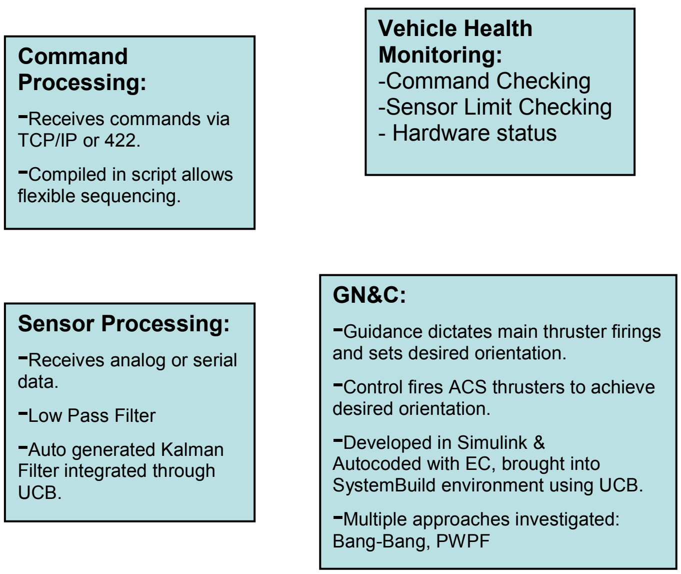

Figure 4: Flight Software Module Functionality

Simulation Results
During the course of development, many simulations were run with both the low fidelity Simulink model and the high fidelity WSIM. Figure 5 shows the output of one of the WSIM runs, in the format that is typically used to analyze the results. In the first column, the x, y, and z positions are plotted. The black lines labeled RBD correspond to the truth model results. The red lines are the positions estimated by the Kalman filter (this is what the GN&C software uses for feedback) and the Green line shows the positions as sensed by the external Visualeyez system. Also shown are the main thruster pulses in blue. Note that the x and y positions are all staying within 1 meter of the desired position (0,0) and therefore meets the requirement. The second column shows the Euler rotation angles. Again RBD corresponds to the truth, KFL is the estimated, and Cmd corresponds to the commands as generated by the Guidance system. Note that the angles are staying within 3 degrees of the commanded angle, which actually violates the requirement slightly. Finally, the last column shows

[5] More information about these tools can be found at: (http://www.octanttech.com/pdf/Octant%20Technologies%20Ground-Segment-White-Paper.pdf)

the velocities, truth and estimated. The negative z velocity is less than 2 m/s, and the horizontal velocities are all less than 1 m/s. So this simulation shows that all of the velocity requirements were met.

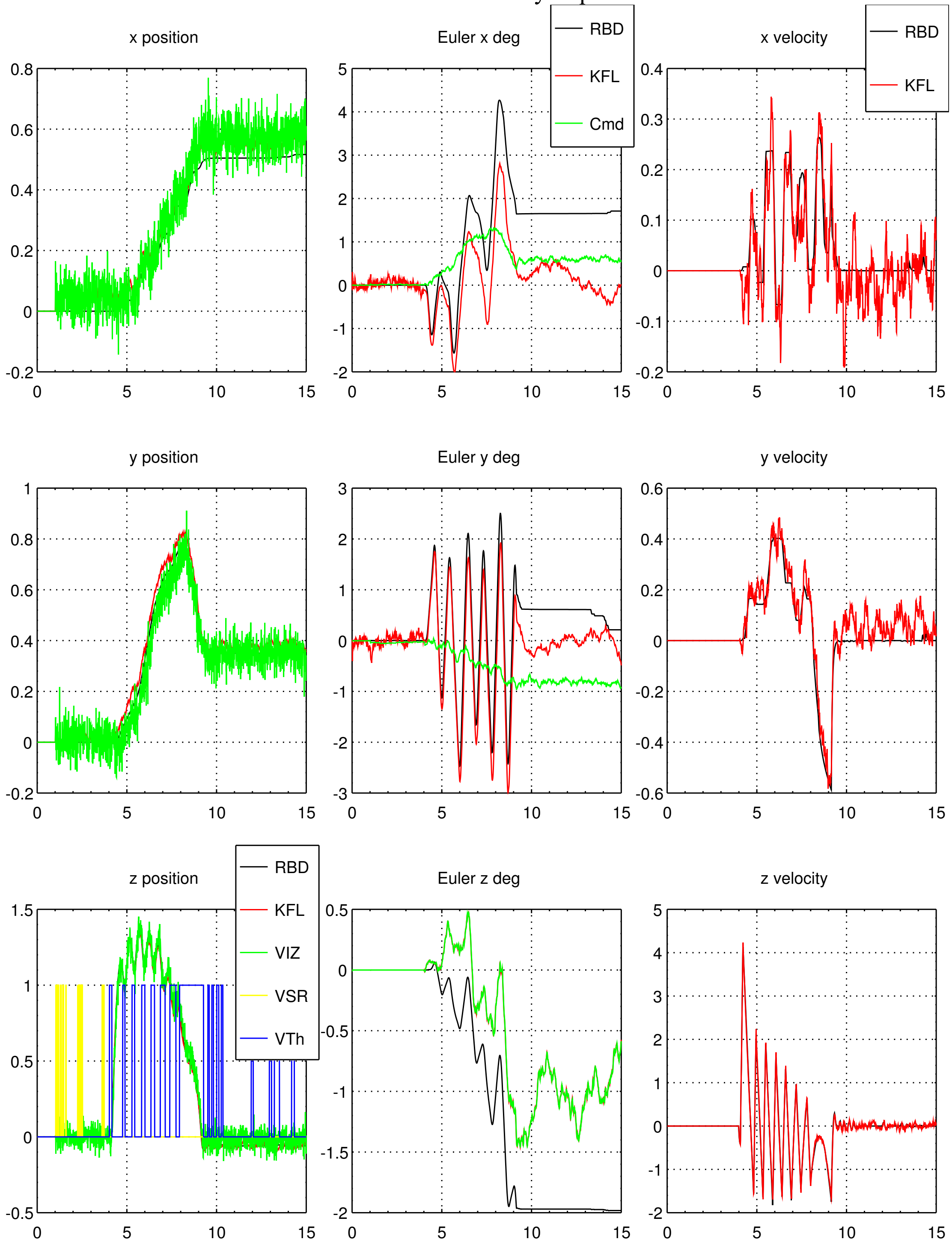

Figure 5: WSIM Simulation Results

Monte Carlo Analysis
In preparation for un-tethered flight, a Monte Carlo analysis was performed on the 6DoF HTV simulation model.

This analysis was intended to determine if it was likely that the flight of the model would still meet the performance requirements on its flight given a range of likely variances in initial mass, center of gravity, moments of inertia, tank pressure and orientation. An additional goal was to estimate the margin from the assumed operating point to the failure front in each of the dispersion ranges.

The resulting data was analyzed for sensitivities to input parameter ranges. A "clustering" analysis was performed in order to identify common and anomalous behaviors of the vehicle. A "Treatment Learner" was then used to identify the parameter sets associated with each cluster. Scatter plots of the results were used to visualize the sensitivities among the parameter sets.

Parametric Sensitivities

The mean values used were derived from the Cold Gas Vehicle Specifications document. The mass, wet and dry CG values were estimated by weighing and balancing the vehicle itself, while the moments of Inertia were estimated using a CAD model.

The dispersions applied to these mean values were:

- CG was allowed to independently vary +/-3 mm
- Wet and Dry masses were allowed to independently vary +/- 1 kg
- Moments of Inertia were allowed to independently vary +/-.2 kg*m^2

In addition, during tethered tests, it was observed that initial ACS pressure and initial orientation also varied. For this calculation, their dispersions were:

- ACS pressure variation = +/- 14kPa (20 psi)
- Maximum rotation angle around each axis = +/- 3 degrees.

These dispersions were in excess of the 1% specified in CR.3 in order to ensure compliance within the 1% variation zone, and to estimate margins to the failure front. Independent linear distributions were utilized for each of these parameters. In total, 1000 cases were performed.

Analysis Description

For a description of the general analysis techniques see Gundy-Burlet et al.[6] A "penalty function" is used in these analyses in order to rank the resulting clusters and identify compliant and failure cases. For the Hover Test, the penalty function is directly derived from the requirements set. It is formed by taking the sum of the squares of any position or velocity in excess of the requirements.

Results

Overall statistics for compliance with the requirements are:

- Max Position Excursion no greater than 3 m (258 cases failed)
- Vertical Velocity on Landing no greater than 4.0 m/s (167 failed)
- Horizontal Velocity on Landing no greater than 1.0 m/s (49 failed)

Some cases failed more than one of the requirements, so the total number of cases without failure was 656.

[6] "Parametric Analysis of Antares Re-Entry Guidance Algorithms using Advanced Test Generation and Data Analysis" by Gundy-Burlet, Schumann, Menzies and Barrett.

A normalized trajectory plot is shown in Figure 6 identifying the characteristics of the clusters. Blue identifies the “best trajectory cluster” ranging to the red for the “worst trajectory clusters”. 10 classes identified by the clustering analysis.

As seen in Figure 7, the clusters are highly correlated with wet Mass (Horizontal Axis) and Vertical Landing Velocity (Vertical Axis).

The treatment learner was applied in order to identify the parameters causing the poor performing runs. The performance was relatively immune to variations in a single parameter. However, there was strong correlation between failure and the following sets of parameter ranges:

Worth=3.118381
Treatment:
MAS cgy location wet=[0.005951..0.007885]
INI roty=[-2.993240..-1.011870)
MASS Iyz wet=[-1.235420..-1.092510)
INI rotx=[0.928976..2.996930]]

Worth=2.763458
Treatment:
MAS cgy location wet=[0.005951..0.007885]
INI roty=[-2.993240..-1.011870)
MASS Ixy dry=[-0.968851..-0.835307)
INI rotx=[0.928976..2.996930]]

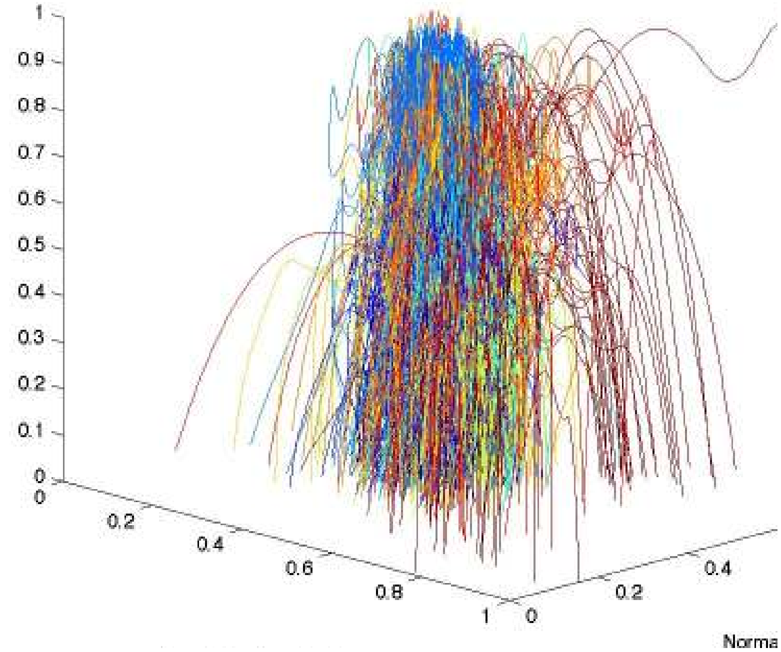

Figure 6: X-Y-Z axis normalized trajectory ploy identifying 10 classes of the clustering analysis (by color)

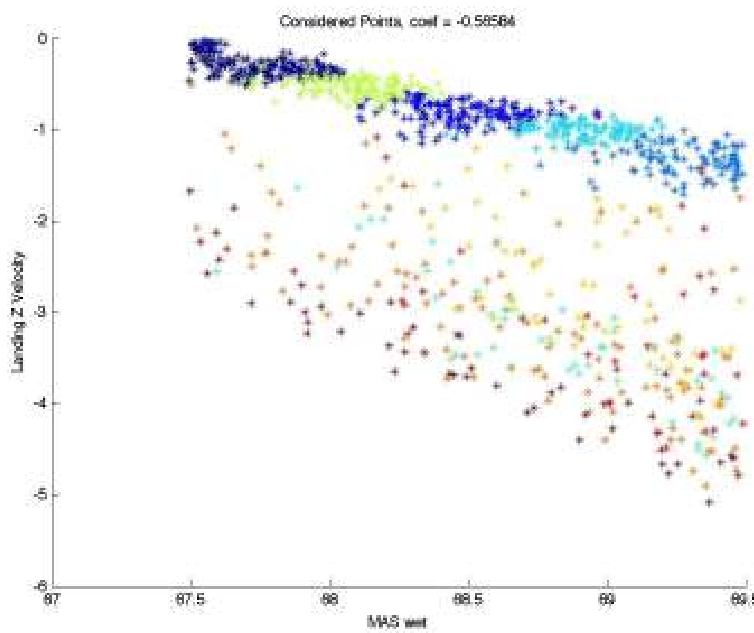

Figure 7: Landing Velocity vs. Wet Mass of the vehicle showing the 10 classes of the clustering analysis (by color

“Likelihood of success” plots were formed among these parameters to visualize best and worst performance ranges among the parameters. One such plot is provided below:

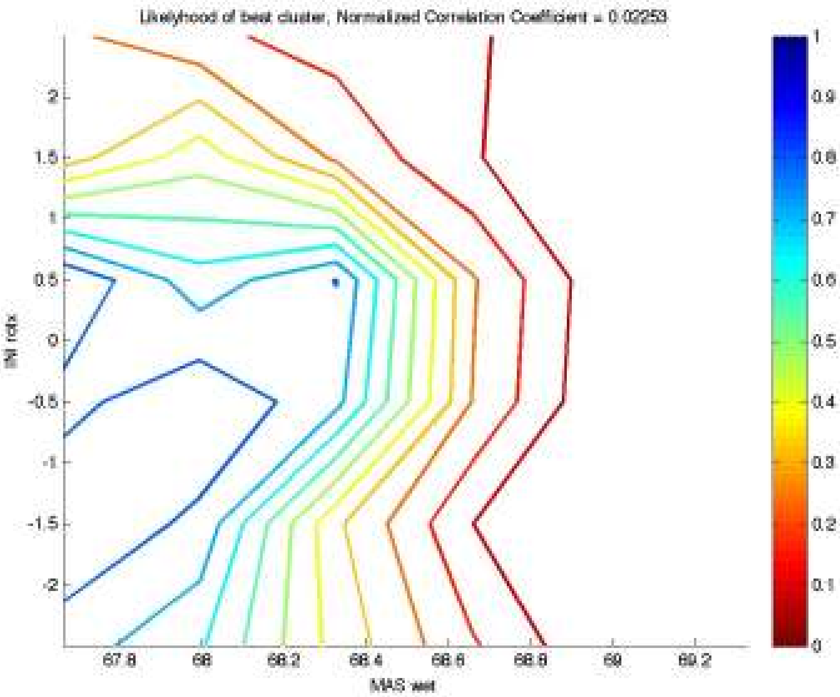

Figure 8 Likelihood of success plots as a function of initial rotations about x (degrees) and wet mass (kg).

Overall, the vehicle performance significantly degrades when Cgy >6 mm and the initial vehicle orientation is Rot_X > 1 degrees and Rot_Y < -1 degrees. Off-axis moment of inertias also contribute to the failure modes. It was felt that these ranges were sufficiently outside of the normal operating parameters that the vehicle would perform within the requirements for the un-tethered flight test.

3.7.4 Propulsion

The propulsion system is designed to provide thrust and control moments similar to those, which could be available for a small (40-120 kg) lunar lander. The propulsion system consists of two cold gas storage tanks, a single high thrust, high pressure nozzle driven directly from the storage tanks, and six low thrust, low pressure nozzles fed via a regulator. The propellant is dry air stored at 22.7 MPa. The main nozzle, fed directly from the storage tanks, operates at a variable pressure from 17 MPa to 3 MPa, and generates a peak thrust of 3600 N. The smaller nozzles are fed regulated air at 1.0 MPa and generate thrusts of 30 N. The system is fabricated from commercially available parts.

The propulsion system design was constrained by the limited selection available of low cost, low mass, high pressure tanks, and of fast-acting valves. The following design decisions were made based on component availability:

1) Carleton 6280-3 tanks were chosen based on cost, delivery time, and size considerations. The pressure rating of the tanks determined the maximum propulsion system pressure of 22.7 MPa (3295 psi).
2) No ACS valves, which met the requirements, were found, primarily because valves with sufficiently high pressure and mass flow ratings were not sufficiently fast-acting. MAC Series 55 valves were selected

because their open/close times, at 10-20 ms, were considered acceptable, and because their mass flow rate was sufficient to generate 30 N thrust. The MAC valves operate at 1 MPa (150 psi) nominal pressure, and so a regulator is required to provide 1 MPa flow to the valves as the tank pressure varies.

3) No valves or regulators were identified which were light enough to operate the descent thruster at a regulated 1 MPa while maintaining anything like an acceptable vehicle mass. It was therefore decided to operate the descent thruster in an unregulated mode, with variable pressure delivered directly from the tanks. The only valve identified with an acceptable pressure rating and mass flow rate was the Marotta MV524. This valve has an on/off time of 50 – 100 ms, which was judged to be acceptable, and sufficient flow rate to generate the desired thrust.

These decisions resulted in a propulsion system, which operates at two pressures. A (variable) high pressure side operates the descent thruster, while a (regulated) low pressure side is fed by the high pressure side to operate the ACS system. This design further constrained the choice of components, and tubing size and layout. Once these decisions had been made, an initial mass estimate was made for the Hover Test Vehicle. This estimate was made by totaling the masses of notional propulsion system components, assuming the current structure mass of the HTV, and estimating a GN&C mass at 5 kg. It was decided to use two tanks because this was the maximum number that would fit within the envelope of the HTV prototype propulsion system. These decisions defined the dry (55 kg) and wet (65 kg) masses of the Hover Test vehicle.

Simple analysis with 1D gas dynamics showed that, with two tanks, the vehicle has enough total impulse to hover for approximately 5 s. This was judged to be acceptable.

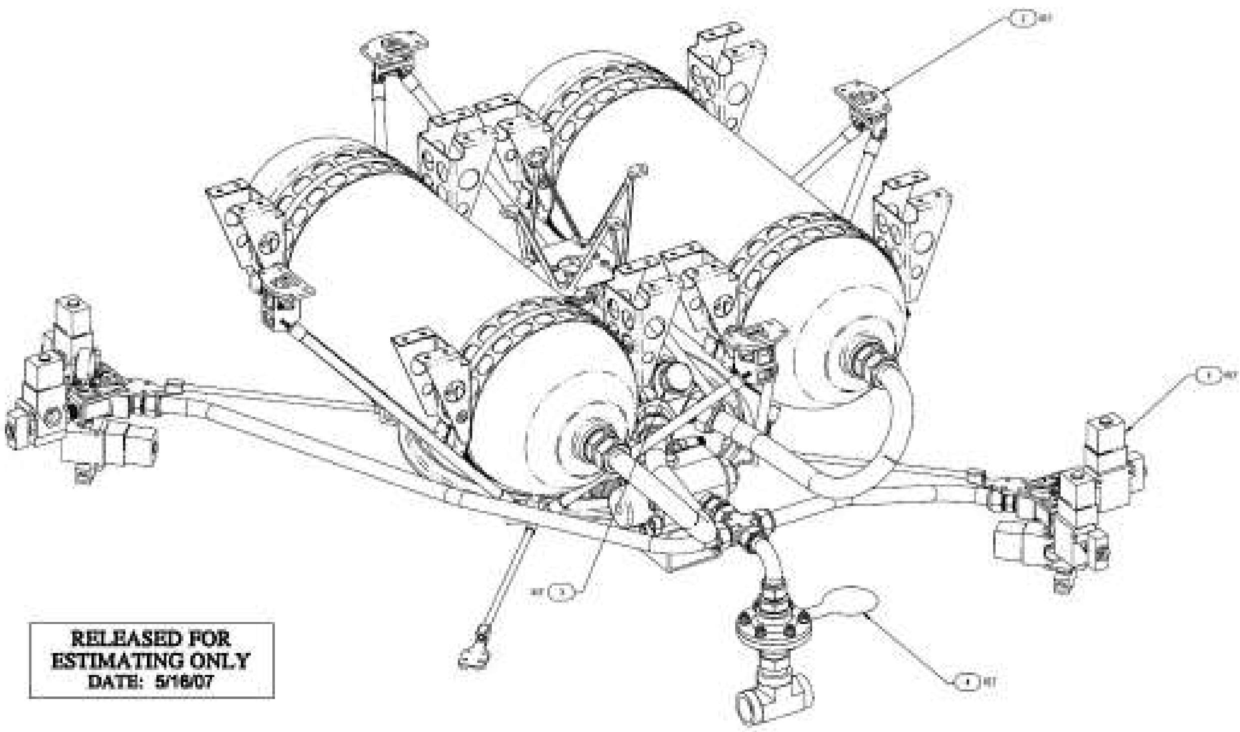

Figure 9: Cold Gas Propulsion System

Design Tradeoffs

The main design tradeoffs were whether to develop a tethered or free-flying system, the choice of propellant gas, choice of pressure level, and the decision to use a partially pressure-regulated system. Decisions about propellant gas, initial pressure level, and component sizing were made using a simple one-dimensional gasdynamic simulation which was coded first as a spreadsheet and later as a C program. The simulation modeled flow from a storage reservoir through a valve and hence through an ideal nozzle, from which it exhausted to the atmosphere. The reservoir thermodynamic conditions, valve flow coefficient, and nozzle sizes were input as initial conditions. The flow rate through the system was determined by matching the flow rate through the valve (which is a function of the pressure drop through the valve) with the flow rate through the nozzle choaked throat (which is a function of the pressure downstream of the valve). Knowing the flow rate and nozzle upstream pressure, it is possible to calculate the thrust and mass flow rate. The mass flow rate integrated over one time step is subtracted from the propellant reservoir, and the reservoir conditions are updated assuming isentropic expansion. New instantaneous thrust and mass flow rate values are calculated, and the time step is advanced. The process is repeated until the reservoir reaches atmospheric pressure.

While this procedure is useful for predicting peak thrust and thrust decay characteristics, the correct stopping point for simulation of a hover test vehicle is not when thrust goes to zero, but when thrust drops below that needed for 1 G acceleration. This condition was simulated by also tracking the weight of a notional hover test vehicle, which decreased as the propellant tanks emptied. The simulation then determined the duty cycle of the main valve which would, within a given time step, produce 1G acceleration. The mass flow rate adjusted for duty cycle was then subtracted from the propellant load at each time step. As time steps were incremented, the tank pressure fell and the instantaneous thrust decreased, requiring longer duty cycles to maintain hover. The simulation ended when the duty cycle reached 100%, and the amount of 1-g hover time obtained was the figure to be maximized.

The simulation was run with several different propellant gases; the hover times obtained with the different gases are shown in Table 11.

Gas	Ratio of Specific Heats	Propellant Load (kg)	Hover Time (sec)
Helium	1.667	1.57	2.6
Air	1.40	11.4	8.0
Argon	1.667	15.7	7.0
Krypton	1.667	32.8	8.5

Table 11: Simulated hover time obtained for different gases with the same 55 kg dry mass vehicle and tank conditions of V=0.0430 m3 (2621 in3), P0 = 22.7 MPa (3300 psi), T0=300K.
Nozzle throat and exit area optimized for each case.

The 1D gas dynamic analysis also showed that, for a given valve flow coefficient, there was a nozzle size that optimized total impulse. Three main and three ACS nozzles were fabricated, with a range of sizes that spanned the expected optimum. The actual nozzle to be used was chosen after benchtop comparison testing of the candidate nozzles. The nozzle size that optimizes total impulse results in a peak thrust of 3800 N, which gives a peak acceleration of 58 m/s^2. However, this acceleration is sustained for only about 50 ms, after which acceleration decays as gas pressure decreases. This peak acceleration was also judged to be acceptable.

3.7.5 Facility Analysis

3.7.5.1 Hover Test Facility System Description

The Hover Test Facility (HTF) is a completely enclosed containment volume for levitating and testing the guidance, navigation and control software of a cold gas powered vehicle. The HTF structure is made up of four 25cm (10 inch) diameter thick walled steel pipes that are 6m (20 feet) tall. The A-36 steel pipes are welded to gussets and a 2.5cm (1 inch) thick mounting flange with 0.63 mm (.25”) fillet welds. Each post assembly is bolted to a 91 x 91 x 2.5 cm (36 x 36 x 1 inch) A-36 steel floor mounting plate with eight (8) ¾-10 UNC grade 5 bolts. The four-floor mounting plates are bolted to the 6 inch thick cement floor with twelve (12) 1.3cm (½-inch) diameter HILTI HIT HY-150 bonded anchor bolts.

The containment portion of the HTF is made from lightly tensioned 0.63 cm (¼-inch) diameter steel wire ropes and sections of nylon sport netting. The top and sides of the HTF "box" are made from 15.2 cm (6-inch) square mesh nylon netting while the floor sections are made from 1.9 cm (0.75-inch) square mesh nylon netting. There are four additional 1.52 x 4.57 m (5 x 15-foot) Corner Nets that keep the vehicle from colliding with the Corner Posts. All of the nets are hung from the wire ropes with spring clips and nylon pull ties.

In order to maintain the verticality of the four Corner Posts under net weight and cable preload tension, each Corner Post will have the same 0.63 cm (0.25-inch) wire rope tied to the externally facing heavy duty.

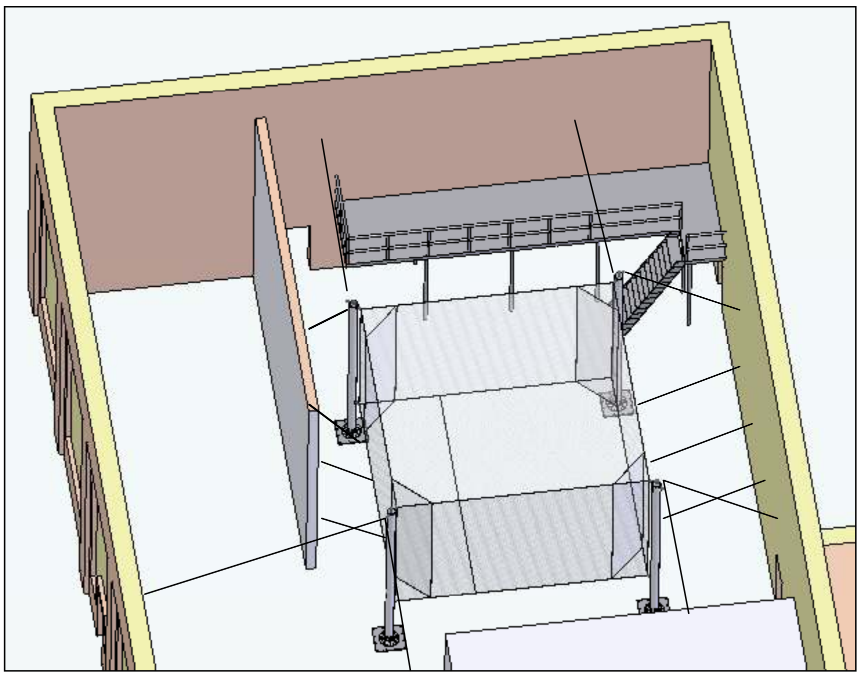

Figure 10: Hover Test Facility in Building NRP 045

The cables were attached to the concrete walls with the same swivel eyebolts that will be bonded into the walls.[7]

3.7.2.2 Operational and Zone-4 Seismic Loads

The HTF will be subjected to light operational loads due to the limit on thrust from its cold gas powered main thruster. With an estimated vehicle mass of ~68kg (~150 lb) and a maximum thrust of ~890N (~200lbf) from its main levitation thrust nozzle, the vehicle will not impart loads to the structure or netting greater than 890N. As such, it was found through analysis that the greatest loads on the HTF structure come from the California Building Code's Zone-4 seismic load requirement. For Zone-4 loading, the structure must be able to react ½-g equivalent lateral acceleration at the center of mass (See Figure 10). For conservatism, the analysis used 1-g lateral acceleration at the CG. See Appendix G.

[7] See drawing A9SP-0600-M001 HTF assembly, Appendix G, for detailed installation procedures that minimize bending loads and moments on the Corner Posts and HILTI floor rods.

In the case of pre-loaded bolted joints, the fasteners will be analyzed with given Factors of Safety and Margins of Safety derived. The definition of Margins of Safety (MS) are given as:

$$\mathbf{MS_y = ((S_y / (FS_y * Applied\ Stress)) - 1.0 \geq 0.0,}$$

$$\mathbf{MS_u = ((S_u / (FS_u * Applied\ Stress)) - 1.0 \geq 0.0.}$$

Where Sy and Su are the material's yield and ultimate strengths and Fsy and Fsu are the given yield and ultimate factors of safety. In the case of all other structural members, Factors of Safety on yield will be calculated with respect to the material's yield strength. In the case of welds, the section properties will be calculated based on the effective throat area and the estimated shear yield strength (S_{shy} = 0.577Sy) of the material. Weld penetration into the parent members will not be considered for conservatism.

Analysis Report Section	Subassembly /Component Description	Load / Stress Type	Factor of Safety FS_y	Analysis Page No.
4.2	Corner Post - Pipe	Bending/Shear	9.0	4.2.1
4.3	Gusset to Flange Welds	Bending/Shear	10.5	4.3.1
4.4	Post Flange to Floor Plate Bolts	Tension/Shear	2.44[8]*	4.4.1
4.4	Post Flange to Floor Plate Bolts	Shear Pull-Out	14.7	4.4.1
4.5	HILTI HIT HY 150 Bonded Anchors	Tension/Shear	Pass[9]	4.5.1
4.5	HILTI ½-13 UNC Rod	Tension/Shear	+0.05*	4.5.12
4.6	Cover Plate Swivel ¾-10 UNC Bolt	Thread Pull-Out	16.8	4.6.1
4.6	¾-10 UNC Bolt, Grade 5	Shear	12.0*	4.6.5
4.6	¾ Swivel Ring	Rated Load	7.17	4.6.5
4.6	Post Side ½-13 UNC Bolt	Thread Pull-Out	18.4	4.6.6
4.6	½-13 UNC Bolt, Grade 5	Tension/Shear	3.52*	4.6.7
4.6	½ Swivel Ring	Rated Load	3.17	4.6.7
4.7	Post Cover Plate Fillet Welds	Shear	High	4.7.1
4.7	Swivel Bolt Mounting Block Welds	Shear/Bending	13.9	4.7.2
4.8	Gross Soil Pressure	Compression	6.6	4.8.1
4.8	Concrete Sear – Two Way	Compression	9.9	4.8.2
4.8	Concrete Bearing	Compression	High	4.8.2

Table 12: Factor of Safety Summary from Hover Test Facility Analysis

3.7.6 Risk Analysis

A preliminary risk analysis has been performed for both the Hover Test Vehicle and the Hover Test Facility, Building 45, in accordance with NPR 7123.1A. As part of the Continuous Risk Management process, Candidate

[8] * Margins of Safety on yield based on Northrop Design Manual methodology w/ FSy = 3.0.
[9] ICC methodology for the HILTI Floor Anchors does not give a FS or MS, but result shows safe margin

Risks are addressed and reviewed periodically to identify, analyze, plan and track new and existing risks. Candidate Risks are captured on a "Candidate Risk Information list" and on a Risk Summary Card enclosed in the Appendix. The objective is to ensure that identified risks are mitigated to an acceptable level prior to Hover Test Operations. Currently, per the Risk Summary Card[10], all identified risks have been mitigated to an acceptable level.

[10] See Appendix B

3.8 Operations

3.8.1 Preflight Operations

3.8.1.1 Safety

Prior to stating hover test operations, the Test Director shall ensure that the NRP 45 Building Emergency Action Plan is posted in appropriate locations, such as exits of Building 45, and that all personnel have reviewed and are familiar with is document in the event of an emergency. The Test Director shall ensure that all personnel have eye hearing protection prior to initiating filling operations of high pressure gas into the vehicle.

3.8.1.2 Test Operations Procedures

Step by step operations for preparing the vehicle for flight are conducted through a Test Operations Procedure that contains over 80 specific steps under the following sections:

1) Test Conditions and Details
    i) Critical Personnel List
    ii) Accident Plan
2) Pre-fill Procedure
3) Avionics Initialization Procedure
4) Tank Fill Procedure
5) Pre-Flight Procedure
6) Flight Procedure
7) Safing Procedure

The Test Director is responsible for implementing the Test Operations Plan and that all safety precautions are followed. The latest version of the full procedure is maintained in the document database.[11]

The operational flow for staging the HTV for the flight tests are covered in Appendix H.

3.8.2 Flight Operations

3.8.2.1 Data Acquisition

As per the TOP[12]:

1. 10 to 20 seconds prior to running the test, the test director will tell the Data Collection Officer (DCO) to start recording data.
2. The DCO will start the Mission Operations software data logging and ensure that the cameras are rolling.
3. DCO shall respond “Data is Recording for Test Number X”. In this way, the test number is announced for the cameras.

3.8.3 Post flight Operations

3.8.3.1 Vehicle Safing

A procedure is carried out post flight to ensure that it is safe before people approach.[13]

[11] TOPv8-2008-01-15-1.doc, Test Operation Procedure, dated 15.1.2008
[12] TOPv8-2008-01-15-1.doc, Test Operation Procedure, dated 15.1.2008
[13] TOPv8-2008-01-15-1.doc, Test Operation Procedure, dated 15.1.2008

3.8.3.2 Data Reduction and Analysis

1. After the test is complete, the DCO will stop the data logging in the Mission Operations software, and stop the cameras.
2. DCO will respond “Data Recording Stopped for test number X”
3. DCO will record the test number, test conditions, and observational notes into test log.
4. DCO will archive test log, data, and derived data products onto NX.
5. Matlab and System Build shall be used for correlating data to model results.

4. Test Results

4.1 Summary of Results from Pre-Testing

Prior to undertaking the full tests, and in addition to the analysis summarized above, a number of subsystem tests were undertaken. These were primarily to test each of the subsystems prior to the integrated tests. The results from some of these tests are written up in separate documents, which are linked, but prior to moving on to the integrated testing results, they are summarized below.

4.1.1. FlatSat

FlatSat was a demonstration of preliminary avionics and control software in command of a generic test vehicle levitated on a 2D granite table top. This was used as a first step in testing and troubleshooting issues related to the model based development process, avionics hardware, and sensors. Figure 11 shows the FlatSat testbed with the onboard avionics. The Avionics/Sensors included a Broad Reach Software Development Unit (SDU), a Microhard Wireless Modem capable of supporting wireless RS422 and TCP/IP communications, a Crossbow IMU400, and a BEI MotionPak IMU. The difference between the SDU and the EDU used on the hover was primarily the processor (Gespace PPC750 versus BRE 440), and the fact that there was no built in power control boards. Instead, the SDU digital output was connected to an external driver board, which allowed control of the eight thrusters. These thrusters used compressed Nitrogen gas, with a total thrust of approximately 1 Newton per thruster.

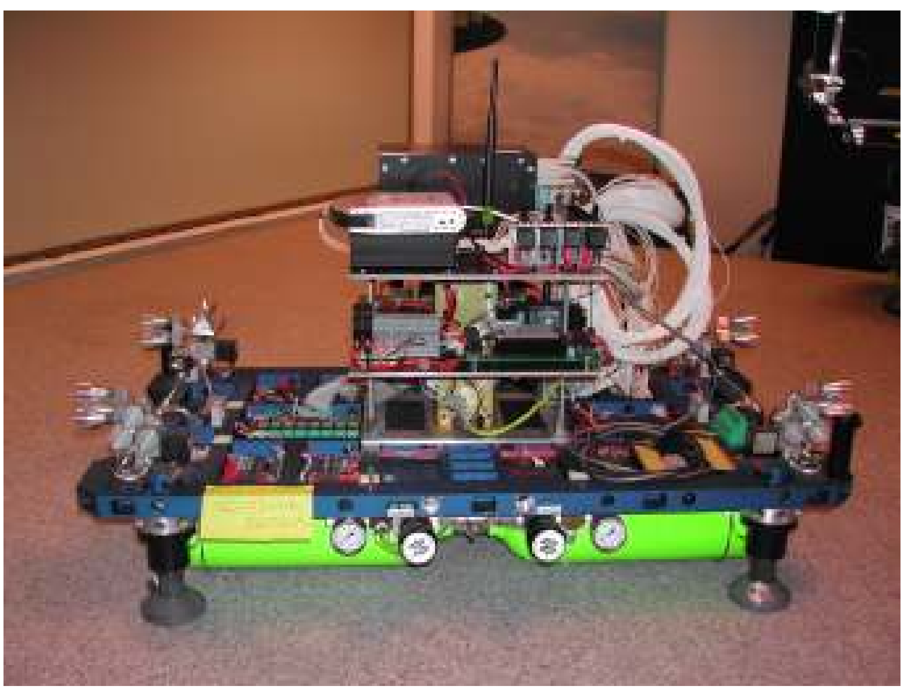

Figure 11: FlatSat testbed.

The FlatSat testbed provided an excellent first step in understanding the hardware and software development tools. Table 13 shows a summary of the lessons learned. In general, the team was able to successfully use these tools to demonstrate two axis closed loop control of this vehicle. It also demonstrated the value of the model based approach to software development and the value of doing the three tiered approach to software integration and test: WSIM, PIL, and HWIL. Each of these steps was utilized prior to development on the testbed. Utilization of these tools allowed the system to be developed within only a short four month period. The tests themselves pointed out the weakness of trying to utilize the IMU accelerometers for position control. Although rotational control was robust with the use of the IMU gyros, the thrusters were so weak that the motions of the vehicle were swamped by the noise in the accelerometers. This insight spurred our development of a Kalman Filter for integrating multiple sensors and for utilization of an internal model of the system to augment the sensors. Later, the Visualeyez subsystem was incorporated into the test and used for position feedback. This provided our first experience with using this subsystem, which turned out to be an indispensable component for the Hover test. However, the coordinate transformation algorithms at that time were not worked out sufficiently in order to demonstrate control beyond a single position axis and rotation. In order to meet the schedule requirements for hover flight, this work was terminated before full 3 DOF control was achieved.

Problems Encountered	**Resolution**
Needed to get up to speed with SystemBuild and model based software development practices.	Utilized WSIM to develop FlatSat vehicle dynamics model and control models, utilizing CSCI/CSC/CSU framework.
GN&C control system development difficult, in System build, primarily because of lack of familiarity with the software. Viewed this as a development risk for the future in that there are far fewer people familiar with SystemBuild than Simulink.	Developed an interface between Simulink derived GN&C components and SystemBuild tools.
Familiarity with SystemBuild Autocode process for software generation.	Became familiar with SystemBuild/Autocode and ran first real time tests using PIL.
Integration and familiarity with Octant Mission Ops tools.	Developed TCP/IP based command and telemetry interface using PIL.
Integration of Hardware and Software	Became familiar with low level MOAB software through the use of the PIL tests. Also developed analog and serial communications algorithms for the two onboard IMU’s.

Table 13: FlatSat Lessons Learned

4.1.2. Mechanical structural tests

Two major tests were performed on the structural integrity of the vehicle prior to the integrated flights:

Component testing:

Crush testing of honeycomb crushable legs cartridges

Hardpoint bushing tests, shear and pullout

Attachment of propulsion module bracket

Structure test with propulsion system

Component testing
Several structural tests were performed to validate various design details of the HTV structural design. Hard point bushings were tested in both pull-through[14] and shear/bearing[15] directions. The honeycomb panel core-to-core bond was tested to verify the shear strength of the adhesive[16]. The structural design feature tests indicate that those features are sufficiently strong and the resulting limits are referenced in the various stress analyses to calculate margins of safety as applicable. A structural test of the attachment of the Propulsion Module Primary Bracket was performed. Initial analysis indicated the need for structural reinforcement of this joint. The reinforcing bracket was also tested to verify sufficient margins (see A9SP-0600-XR201). Structural tests were performed on the aluminum honeycomb crushable cartridges that are designed to absorb energy in the leg system upon landing impact. Both quasi-static and dynamic load tests were performed to verify the cartridge designs. The results indicated somewhat lower than expected crush forces and slightly reduced stroke than assumed during the design phase[17]. The current design is adequate for all HTV activities planned to date. Minor re-design will be required to the leg system to meet the landing load requirements for the 108 kg landed mass defined in Section 3.6.1.2.3.iv above.

Structural testing with propulsion system
During the Hover/Bungee/String Tests, the HTV has been tested with maximum thrust force of 3100-3600 N (tank pressure of 23000 kPa) approximately 25x to date with no apparent damage to the structure. Up to this point only visual inspections have been performed. No hard landings have been experienced, only soft landings in the netting, so the leg system has not been fully exercised. However, minor damage occurred to one of the legs at landing. Details can be found in the full Structural Testing documents.[18]

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[14] See A9SP-0600-XR010
[15] See A9SP-0600-XR251
[16] See A9SP-0600-XR220
[17] See A9SP-0600-XR250 for a more complete discussion
[18] The following documents detail the Structural Testing of the HTV and components: A9SP-0600-XR010, A9SP-0600-XR201, A9SP-0600-XR220, A9SP-0600-XR250, and A9SP-0600-XR251.

4.2 Results from Propulsion Strap-down Tests

Three simple thrust test stands were built to verify the predicted performance of the propulsion system, as well as to discover any unexpected aspects of the propulsion system behavior. The first and second stands were used to test the Descent Thruster and Attitude Control System (ACS) thrusters independently. The main valve integrated test stand is shown in Figure 12. It consists of a single storage tank which exhausts through a flexible U-shaped hose into the main valve and out the main nozzle. The main valve/nozzle assembly is mounted on flexures. Together with the U-shaped gas supply hose, this ensures that there is little resistance to motion in the direction of the nozzle thrust. Instead the thrust is reacted against by a 4500N (1000 lb) capacity load cell restrained by a steel block. Measurements of load cell output, valve inlet and outlet pressures and temperatures, and valve voltage and current were all recorded at 1 KHz. After testing with the main nozzle was complete, the test stand was converted, to allow testing of the ACS nozzles.

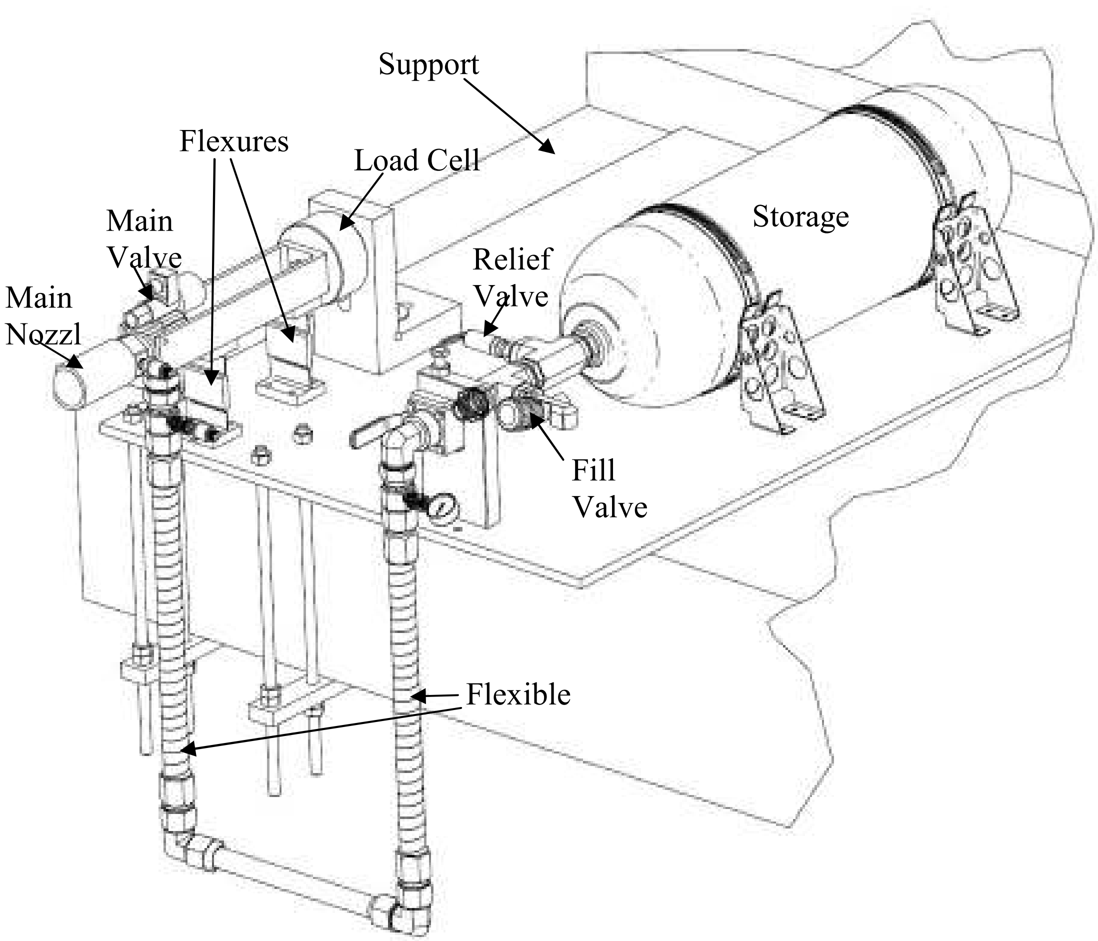


Figure 12:Diagram showing thrust test stand for main nozzle

In the ACS test configuration, the flight regulator was used to supply gas at constant pressure from the storage tank. A burst disk was also added to the pressure system because the test stand was under the same safety requirement as the flight vehicle to withstand a complete regulator failure. The final round of qualification involved the entire propulsion system, which was assembled upside-down on a jig, then mounted on a set of three load cells with the main nozzle firing downward. In this way the entire propulsion system could be pressurized, leak-checked, and test-fired to detect any anomalies, and to get final thrust measurements.

Testing of the main nozzle on the first test rig was intended to verify the accuracy of the simulations, study the transient characteristic of the combined valve/nozzle, and determine which of the three candidate main nozzles gave the best performance. Figure 13 shows the decay of thrust *vs.* time for a test where the main valve is opened and the system is allowed to blow down. The nozzle initially develops 3100-3600 N (700-800 lb) thrust, considerably more than necessary to support the HTV. But thrust decays rapidly as the storage tank pressure drops. Figure 13 also shows the simulation results for this operating condition. Initially the simulation overpredicts thrust. This is to be expected. The simulation does not take into account several factors, including the the finite flow rate downstream of the valve, boundary layer effects, and cosine losses in the nozzle. In addition, the simulation underpredicts the pressure loss across the main valve. Later in the blowdown, the simulation underpredicts thrust. One possible reason for this is that the simulation does not take heat transfer from the structure into account. This adds heat, and thus thrust, in the real case. Since the simulation was used mainly as a parametric tool, these results were seen as validating the simulation, despite its observed inaccuracies. Further runs with the three different main nozzles showed that the highest total impulse was obtained with the mediu-sized nozzle, and this nozzle was used for all flight tests.

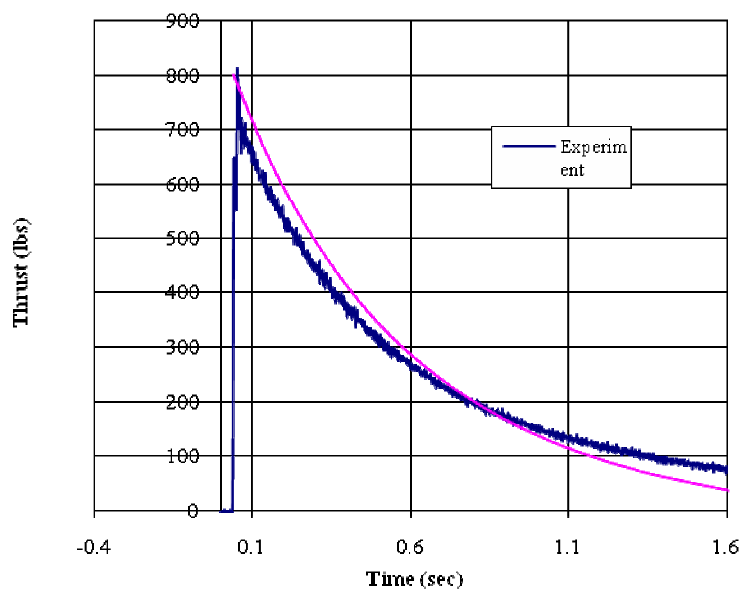


Figure 13: Comparison of measured main nozzle thrust *vs.* simulation.

The startup transient behavior of the main valve and nozzle were also examined in this test phase. Figure 14 shows how the nozzle thrust and valve inlet pressure vary immediately after the valve is commanded open. There is about a 37 millisecond delay between the time the main valve voltage is increased and the time thrust begins to build up. This is attributed to the mechanical delay required for valve components to open. Once the valve opens, thrust rises to 75% of its peak value within 4 milliseconds. Thrust remains approximately constant for 10 milliseconds before increasing to its peak value of about 3600 N (810 lbs). When the valve opens there is a rapid drop in valve inlet pressure, followed by a partial recovery within roughly 18 milliseconds, before the pressure begins a secular drop characteristic of blowdown of the tank. The sudden pressure drop at the start of the blowdown is attributed to the time required for the mass of air in the supply tubing to begin moving. The tubing length from the valve head to the back of the storage tank is about 2m. Thus the “out and back” travel time for a pressure wave generated by the valve opening would be about 14 milliseconds, which is relatively close to the length of the initial pressure drop. (While the initial pressure drop was a subject of some interest, it was believed that this phenomenon would not occur in the HTV itself, which has a much shorter flow path with a greater flow capacity. In fact the initial pressure drop was not seen in testing of the full propulsion system.) The thrust data also show some high frequency content which is not seen in the inlet pressure. The load cell, flexures, and valve/nozzle form a mass-spring system which would be expected to oscillate somewhat after thrust was suddenly applied. This is believed to be the cause of the high frequency variation in the thrust data.

Following testing of the main nozzle the thrust test stand was converted to testing of the ACS nozzles. The primary aim of these qualification tests were to determine the ACS thrust for a given inlet pressure. The thrust values were used by the HTV control system to estimate the amount of ACS firing needed to apply a given moment to the vehicle. In addition, this allowed the regulator reference pressure to be chosen to given acceptable ACS control authority while minimizing the parasitic propellant usage of the ACS system. In addition, testing was used to determine the optimum size and area ratio for the ACS nozzles, out of a set of three nozzle sizes determined by the simulation. Qualification testing of the ACS also provided useful experience in operating the system. It was found that to obtain a desired regulator outlet pressure, the regulator reference pressure had to be set to a value about 15% higher. It was also found that the regulator's opening and closing times were considerably longer than those of the ACS valves. This meant that there could be significant pressure droops and spikes in the ACS system, depending on the rate at which the ACS valves were driven. This was not seen primarily as a controls problem, since it was expected that the ACS valves would be opened for a longer or shorter time, as needed, to compensate for pressure variation in the ACS system. However, there was considerable concern that pressure spikes to rupture the burst disk, or damage the ACS valves. As a result, tests were undertaken to operate the ACS valves at higher than their nominal pressure of 1000 kPa (150 psi), and the ACS system was qualified to higher pressure than originally planned (2800 kPa (400 psi) *vs.* 1000 kPa (150 psi)). This allowed the installation of a 3100 kPa (450 psi) burst disk, which provided significant headroom compared to the 1000 kPa (150 psi) standard operating pressure.

In total there were 32 strapdown propulsion tests, all but one of which were successful. The one failure was a premature firing of the thruster. Of these 26 for the divert and 6 for the ACS. A complete list of these can be found in Appendix F.

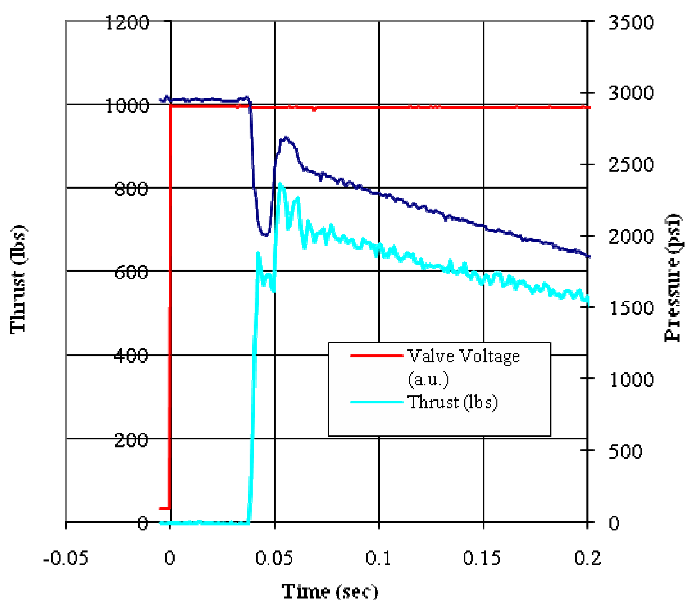


Figure 14: Startup transients in main nozzle thrust and inlet pressure. Thrust startup is delayed 40 milliseconds after valve open command.

Key Results

A cold gas propulsion system has been designed and built to provide thrust and attitude control for a planetary lander simulator. The system provides a peak thrust of 3600 N, and can support the vehicle in 1G hover for roughly six seconds. The propulsion system operated successfully in 32 strapdown tests, 27 tethered tests and six untethered tests to date.[19]

All the requirements for the test were met:

1. There was sufficient thrust to lift the vehicle mass in a 1 g environment
2. The off-axis thrust was measured to be less than the control authority of the ACS thrust
3. There were no structural faults of the vehicle

[19] A complete list of the completed tests can be found in Appendix F.

4.3 Results from String Test

The purpose of the string tests was to work out the coordinate transformations, and to verify that when the control system commanded an attitude, the system actually tried to achieve that attitude. Through simulations, it was realized that the attitude control system was not powerful enough to maintain a rotation angle greater than 5 degrees, because it rotates about the pivot point of the tether instead of rotating about the cg. In addition the simulations showed that the system would eventually go unstable because of interactions with the swinging motion of the tether. However, as long as the system demonstrated that it fired the correct thusters, and tried to control about the correct axis, the tests would be deemed a success.

Table 14 shows the lessons learned from the string tests. Perhaps the most time consuming part of this phase of development was getting the coordinate transformations correct. Note that there are multiple coordinate transformations that need to take place – IMU to Vehicle, Vehicle to ECI, LED's to Vehicle in VIZ Camera frame, VIZ Camera frame to ECI. Mixed up in this was the VIZ system was highly unreliable at first because of infrared interference with the lights, and problems with calibration. Eventually these problems were solved by updating the camera software, changing the lighting, and removing sources of infrared such as cameras. This allowed the coordinate systems transform work to progress and finally were deemed correct because the Vizualeyez, IMU, and Kalman filter outputs all provided similar results when translating and rotating the vehicle by hand about all three axes.

Once the coordinate transformations were corrected, the control system was tested. One of the first problems encountered was that the relief valve blew, causing the vehicle to spin out of control. Within a few hours, the problem was diagnosed. The problem was solved by moving the relief valve to the pressurization system, and removing it from the vehicle.

Problem Encountered	**Resolution**
VIZ system had many ghost points	Many of the problems were caused by IR cameras and lights.
Lack of network access caused excessive delays in development and testing	Network antennas added. Added ability to tunnel to license servers for model development in facility.
Radio network to vehicle had periodic dropouts	Upload of new firmware for radios. Solved printer IP issues.
Coordinate Systems not matching	Verified similar results from VIZ, IMU, KF, and Visual Inspection. All Euler Angles were expressed in ZYX. VIZ system used post multiplication of transformation matrix. Fixed onboard bias calculations for VIZ.
Lights confusing in terms of functionality causing potential safety issue.	Rewired to simplify and ensure it is consistent for all modes. Red light – power on. Blue Light – Slow blink is nominal, fast blink is problem. Yellow Light – Mostly off, software disabled thrusters. Green Light – Double redundancy on thrusters firing (key and remote).
VIZ system had dropouts	Kalman Filter protects against dropouts for short tests. This capability was demonstrated during one of the free flight hover tests.
Kalman filter too slow and causing task overruns	Several optimizations in the filter now have it running 3-5X faster. Could have been detected & debugged in PIL.
System unstable and appears to move the wrong way.	Thruster numbering was wrong. Fixed this in the low level software. All tether tests now indicate we are moving in the correct direction initially.

Table 14: String Tests Lessons Learned

Further testing indicated that the control system fired thrusters that caused to rotate the vehicle in the opposite direction to which it was commanded. After further investigation, this was found to be caused by an incorrect mapping of thruster numbers to locations. In fact, the thruster numbers were exactly reversed about the vehicle's pitch axis. This occurred because the numbering was done when the vehicle was upside down for the pressure tests. After correcting the problem in software, the proper control was demonstrated about all three axes. Figure 15 shows the behavior of a command to a 45 degree step input about yaw. Note that the roll and pitch axes are oscillating but staying under control.

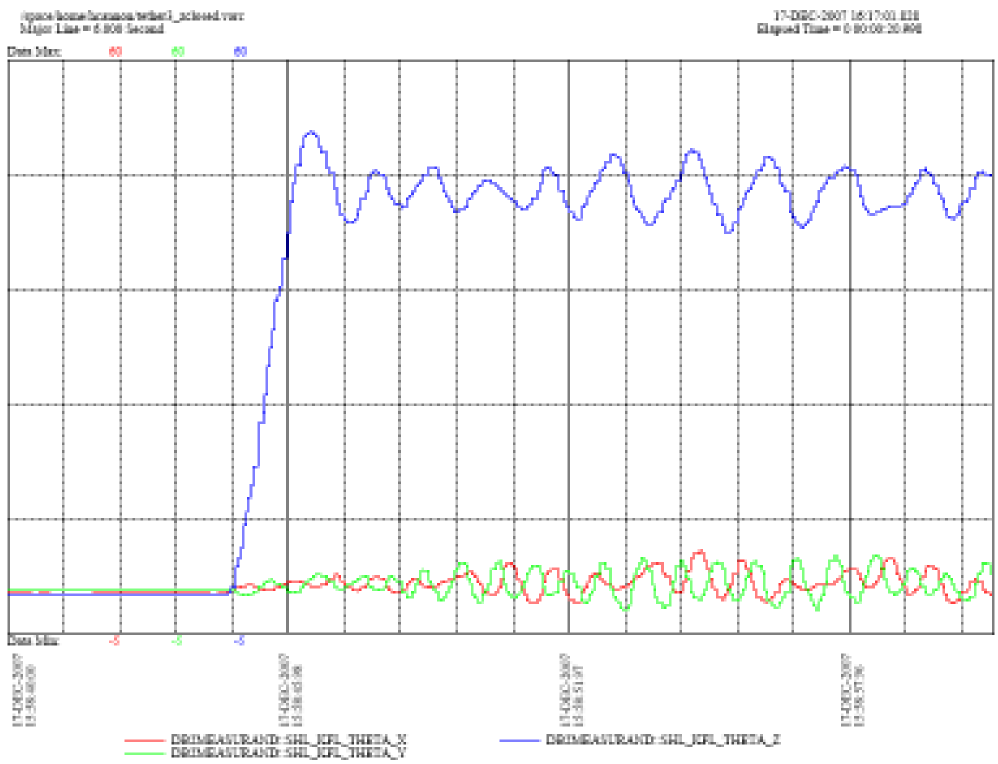


Figure 15: Vehicle response to a 45 degree step input about the yaw (z) axis.

Summary

The HTV met the overall requirement for this test:

1. The control authority worked in accordance with the simulation

In total there were 9 string tests, all of which were successful. A complete list of these can be found in Appendix F.

4.4 Results from Integrated Pop-Up Tests

The purpose of the pop up test was to test the firing of the main nozzle as well as to test the control of the ACS while the vehicle was falling. The test was accomplished by suspending the vehicle from a bungee cord, and then, firing a single pulse on the main nozzle. During the entire test, the vehicles' attitude control system was on and trying to maintain zero degrees in roll, pitch, and yaw.

Table 15 shows the lessons learned from the pop up tests. The main problem encountered had to do with the system firing the ACS prematurely prior to firing the main thruster. This problem was mostly caused by the fact that the system entered closed loop control mode long before the main thruster command was injected. During this time, the vehicle rotated slowly about the bungee. Since the ACS was trying to control yaw, it would fire the ACS thrusters to compensate. This problem was solved by removing the yaw angle control. It was realized during the testing that the only yaw rate control was needed (ie. if the vehicle rotated about the yaw axis in a hover flight it was not a problem). Another solution was to decrease the time between when the vehicle entered closed loop mode, and when the main thruster command was injected. To do this, the onboard sequencer was fixed, and both commands were issued within a single sequence. This also helped to simplify test procedures, resulting in fewer mistakes and a faster set up time.

After these problems were solved, the successful pop up tests provided sufficient confidence for attempting multiple pops.

Problem Encountered	**Resolution**
System fires ACS prematurely when entering closed loop mode.	Sequencer implemented so that thrusters enabled at the same time we enter closed loop mode. Removed yaw orientation control, now only controls yaw rates.
Overly complicated software procedure causes pressure to drop and leads to mistakes.	Incorporated much of the procedure into the onboard sequencer
In one test, a relief valve, installed to prevent over-pressurization during filling, instead opened immediately after the first pop.	Analysis suggested that the relief valve had opened due to a pressure spike that occurred when the main valve was closed. It was determined that the relief valve could be relocated off the vehicle without compromising system safety. The relief valve was removed from the vehicle.

Table 15: Lessons Learned from Pop-Up Tests

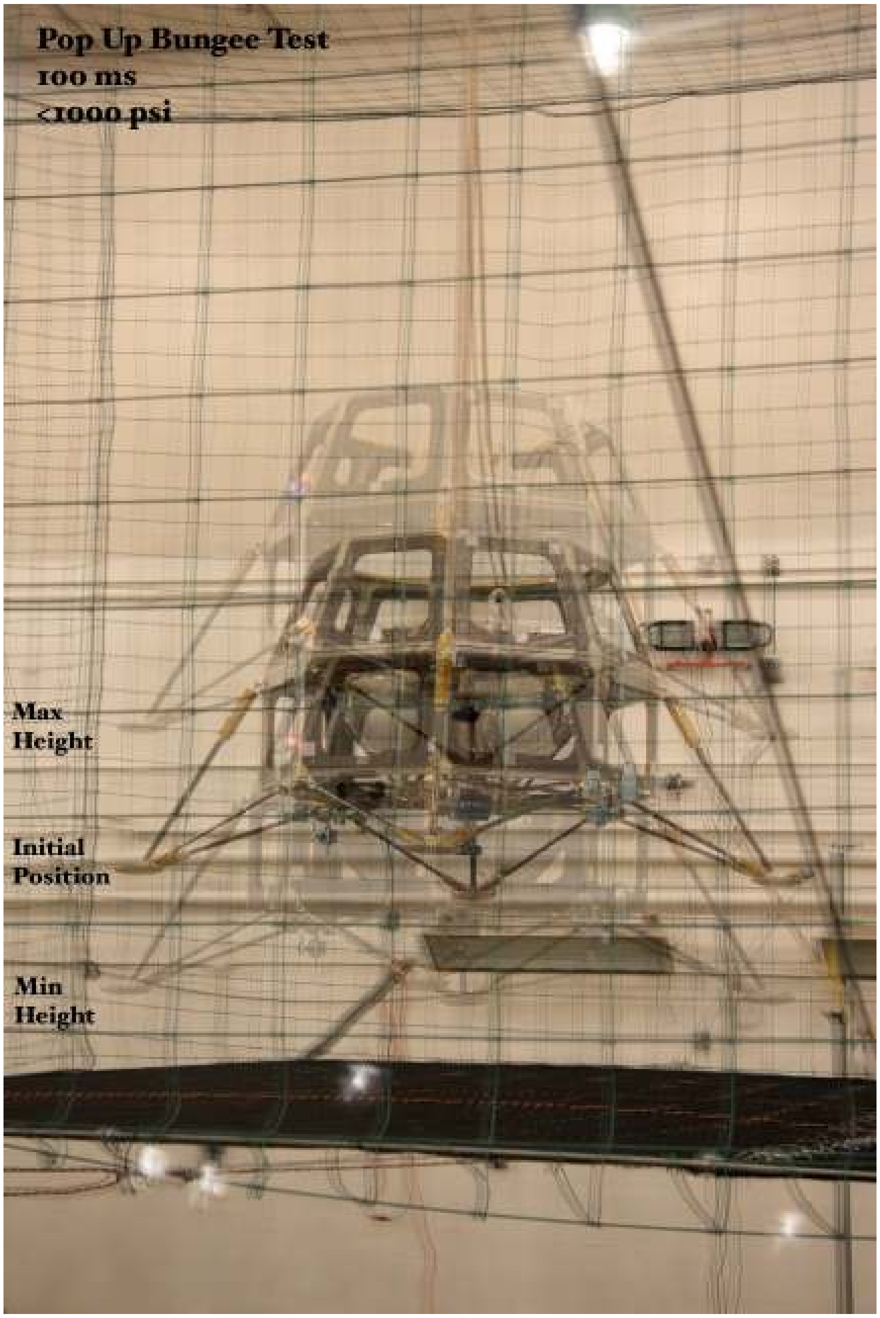


Figure 16: Overlap of three images of the pop up test showing the initial position and minimum and maximum height following a 100ms Pulse of the main engine with ~6.89 MPa (~1000 psi) pressure.

By overlapping high speed still camera images of the bungee pop up test it was possible to put an upper bound on the angle of the thrust vector relative to the nozzle-CG axis of 1 degree.

In total there were 13 pop up tests, 11 of which were successful. The two failures were due to the pressure relief valve blowing and a premature firing. A complete list of these can be found in Appendix F.

4.5 Results from Integrated Multi-Pop Up Tests

The purpose of the Multi-Pop Up test was to provide confidence that the system would behave properly before going to a full free flight hover test. This was essentially a Hover test, with a bungee cord attached. The belief was that the bungee would provide a degree of protection, if the vehicle were to try and fly off into the net or rotate too far. In addition, the multi-pop provided a chance to test the ability of the platform to get out of the way in time, in case the vehicle popped up into the air and immediately came down. Therefore the first multi-pop was conducted with the vehicle suspended above the platform, then sitting on the platform while still primarily supported by the bungee, and finally fully sitting on the platform with only minimum tension on the bungee.

Table 14 shows the lessons learned from the multi-pop up test. The primary problem encountered had to with the system seeming to tilt a large amount (15 + degrees) near the end of the run. This effect was simulated as well, although until the test was conducted, there wasn't enough confidence in the bungee model to determine whether this effect was real. Upon further investigation, it was determined that the reason was that the control system was sending large angle commands near the end of the run in order to compensate for the lack of thrust from the main thruster. That is, the guidance system changes the desired angle based on position error, and the amount of thrust available to accelerate to compensate. When the thrust goes low, then the guidance system commands a large angle to make up for it. To prevent this situation from occurring, a temporary fix was added to fool the guidance system into thinking that more thrust was available at the end of the test. This was deemed acceptable, because the lack of thrust is an artifact of running out of air in a short amount of time, and wouldn't be encountered in a real flight.

Further simulations showed that the system still oscillated more than was desirable near the end of the test. Therefore, just prior to running the final multi-pop up test, the control system was tuned. Reducing the derivative in the PD control of the guidance system (which dictates desired pitch and roll) proved to be the key to getting the entire flight under stable control.

Problem Encountered	**Resolution**
System appears to go unstable as the run progresses.	Guidance system trying to compensate for lack of thrust available sent large angle commands. Work around tricks guidance system into thinking more thrust available. Further tuning also required in guidance system PD control (reduced derivative component by a factor of 10).
In one test, the system fired first pop, but failed to fire subsequent pops.	Unresolved. A subsequent command was sent from the flight software, but the system did not respond. Not sure where error occurred – serial communication to SACI? Wiring?

Below are 3 graphs displaying the angle, position and velocities measured for each axis for the vehicle during a single multi-pop flight. On Figure 17 it can be seen how the vehicle angle around the x and y-axes remain under 3 degrees for longer than an anticipated free-flight duration (<10s). The rotation around the z-axis remained unconstrained during the multi-pop flight.

Similarly, on Figure 18 one can see the target (commanded) and real positions throughout the flight and afterwards. These again are well within the 1m range requirement during the flight. The oscillatory motion in the x and y-positions is due to harmonic motion induction on the bungee cord. Note that the z position command is not actually a closed loop control command. We were not closing the loop on z position. Instead, the z command was utilized as a trigger to initiate the main thruster pops, while closing the loop on z velocity.

On Figure 19 one can see the velocities throughout the flight and afterwards. These are also well within the 1 m/s lateral velocity requirement during the flight – although in this case the bungee cord may be aiding this.

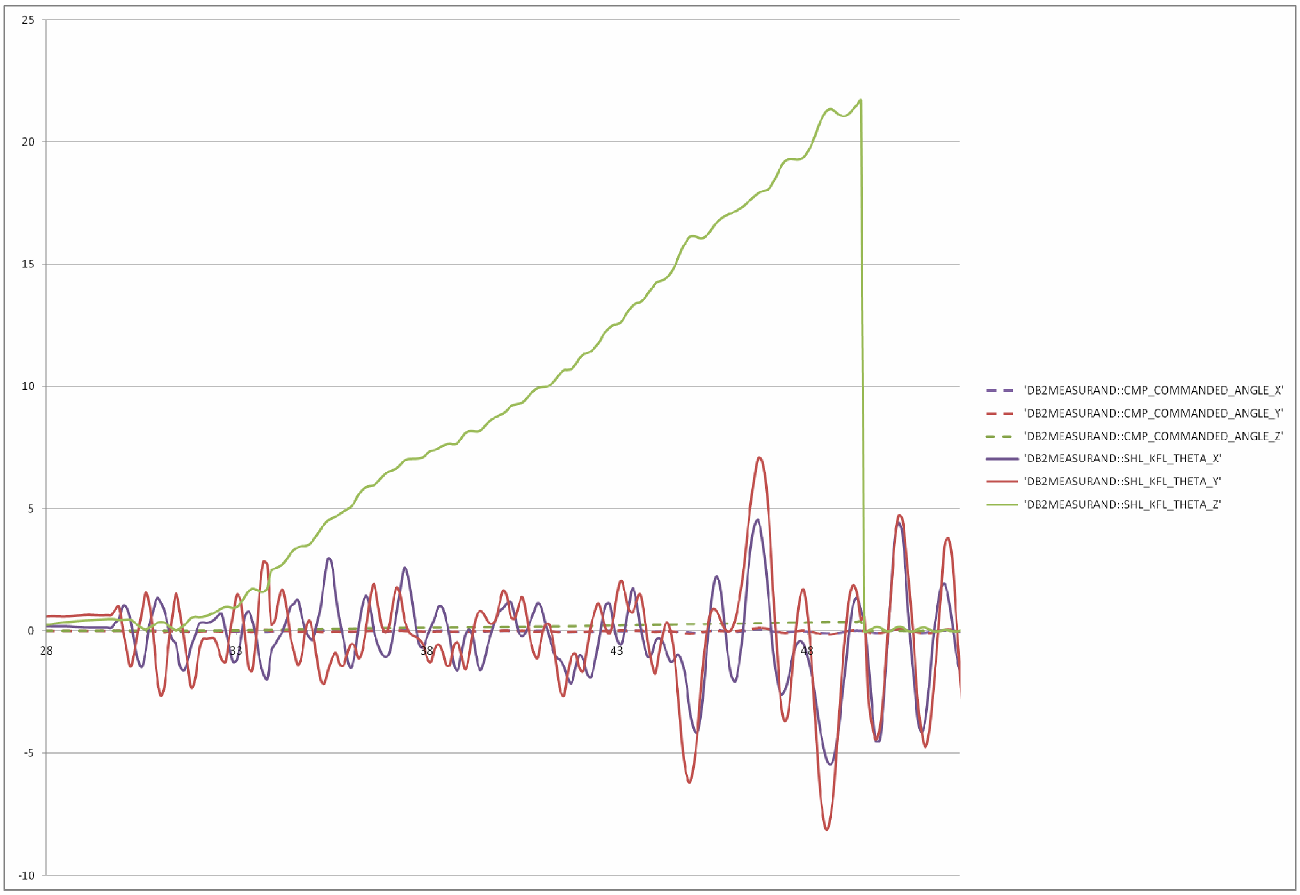


Figure 17: Angles X, Y and Z during multi-pop up flight test

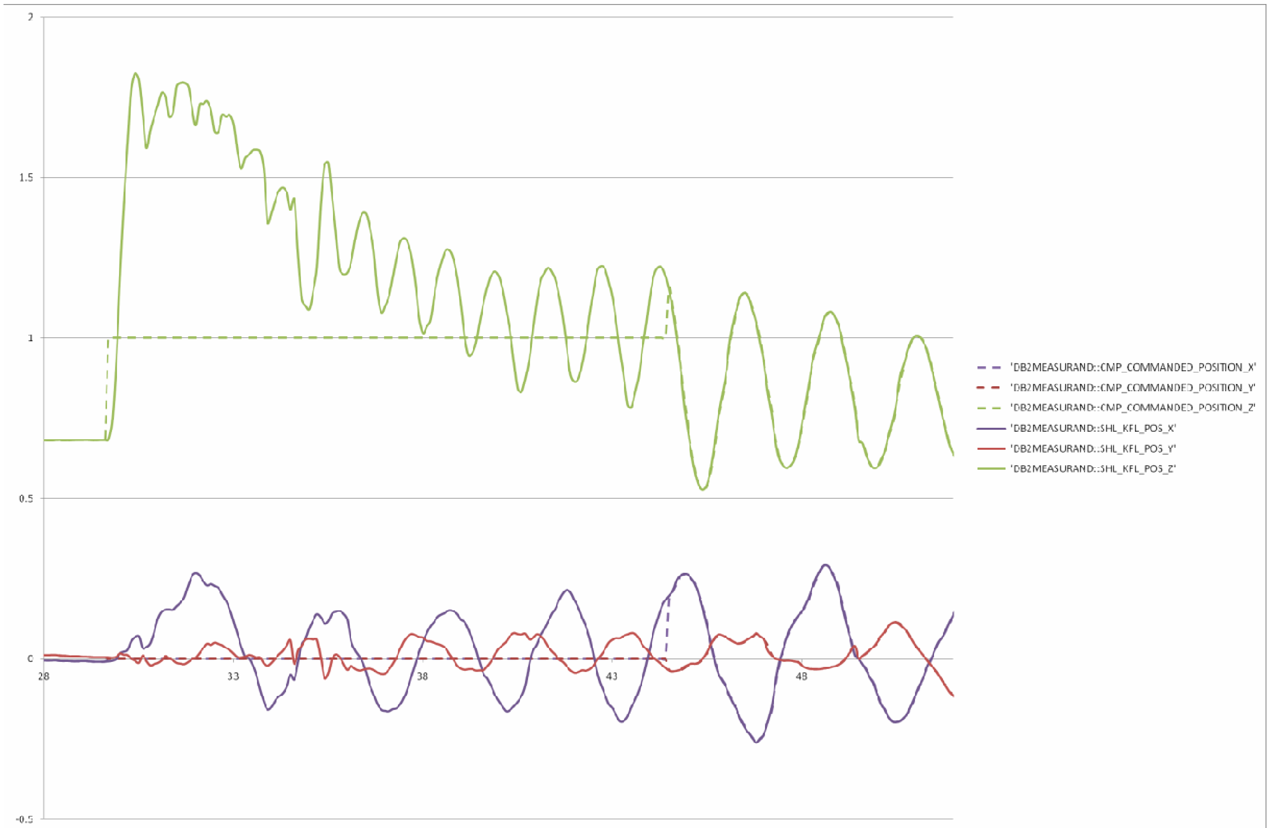


Figure 18: Commanded (dashed lines) and Measured (solid lines) Positions (X, Y and Z axes) during multi-pop up flight test

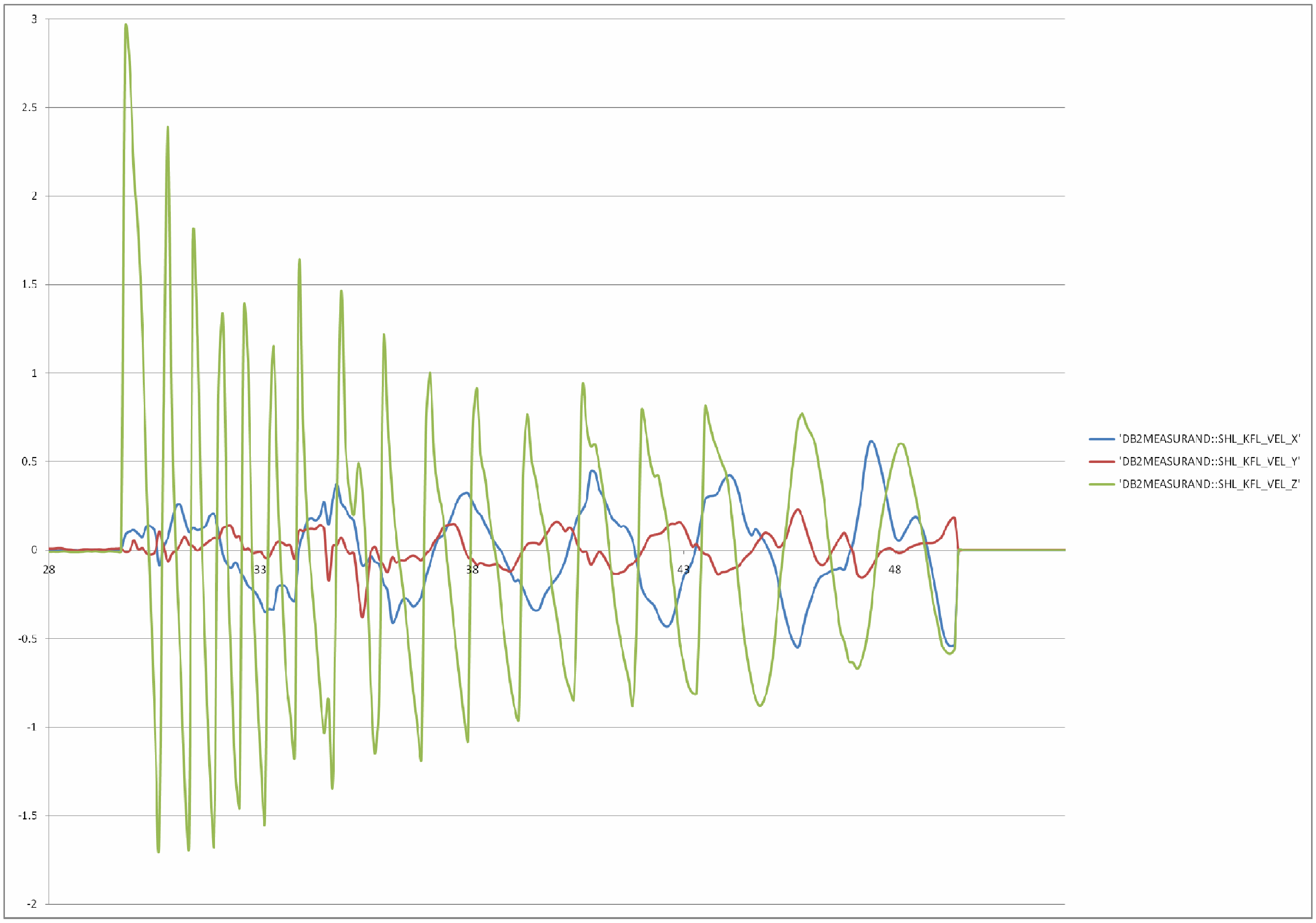


Figure 19: Measured Velocities (X, Y and Z axes) during multi-pop up flight test

Summary
The HTV met each of the overall requirements for this test:

1. The control authority worked in accordance with the simulation
2. The vehicle demonstrated sufficient ACS authority to compensate for off-axis thrust
3. The vehicle structure remained intact

In total there were 5 multi-pop up tests, all of which were successful. Three of these were hung purely from the bungee cord, and two were from the stand. A complete list of these can be found in Appendix F.

4.6 Results from Integrated Free-flight Hover Tests

Results of the string, pop-up, and multi-pop up tests were deemed successful enough in a delta TRR to allow the system to be tested in free-flight. A total of six free flight tests were run successfully with only minor incidents occurring. The tests demonstrated that the HTV met each of these overall requirements:

1) The vehicle demonstrated closed loop control during free flight.
   The propulsion had sufficient thrust to lift the vehicle into free flight in a 1g environment.
2) The duration of flight of 6-7s enabled >50 control cycles.
   The attitude control had sufficient physical authority to enable attitude control during free flight
   The control software was sufficiently efficient to enable attitude control during free flight.
   The vehicle remained structurally in tack during the free flight (no loosening of any plumbing, nuts, no major structural damage).
3) The vehicle successfully demonstrated the use of COTS hardware.

Figure 20: Image of free flight hover test shortly after liftoff. The main engine gas stream (and associated mach diamonds) are visible.

Assessment with respect to key GN&C Requirements

Reqt. #	**Requirement**	**Results (HoverSat)**
CR.1	The control system shall provide angular control as specified by the guidance system to within 2 degrees 1 second after commanded and remain there for the duration of the flight or commanded otherwise	YX angles stayed within +/-6 degrees during all flights (and stayed mainly within +/- 2 degrees).
CR.2	The control system shall provide position control within 1 meter of a commanded input value during powered flight	Yes. (Generally stayed within +/-0.5m). See Figure 18
CR.4	The control system shall provide for landing velocities no greater than 4 M/S	Yes. (Generally stayed <1.5m/s). See Figure 19
CR.5	There shall be an open-loop individual thruster firing mode for strap-down tests.	Yes.
CR.6	The control system shall not command chatter such that thrusters cycle on/off at greater than 50 Hz.	Yes. This limit was reached but not exceeded.
CR.7	The control system shall move the vehicle to achieve a commanded target position (to within 1 meter radius of the target) within 4 seconds, and remain there until the end of flight.	Yes. In fact it moved within a 1m radius of the target within 2 s and generally to within 0.5m within 4 s. See Figure 18
CR.9	The control system shall limit lateral velocities at landing to no greater than 1M/S.	Yes. In fact these were always <0.5 m/s. See Figure 19.

Table 16: Key ADCS and GN&C Results

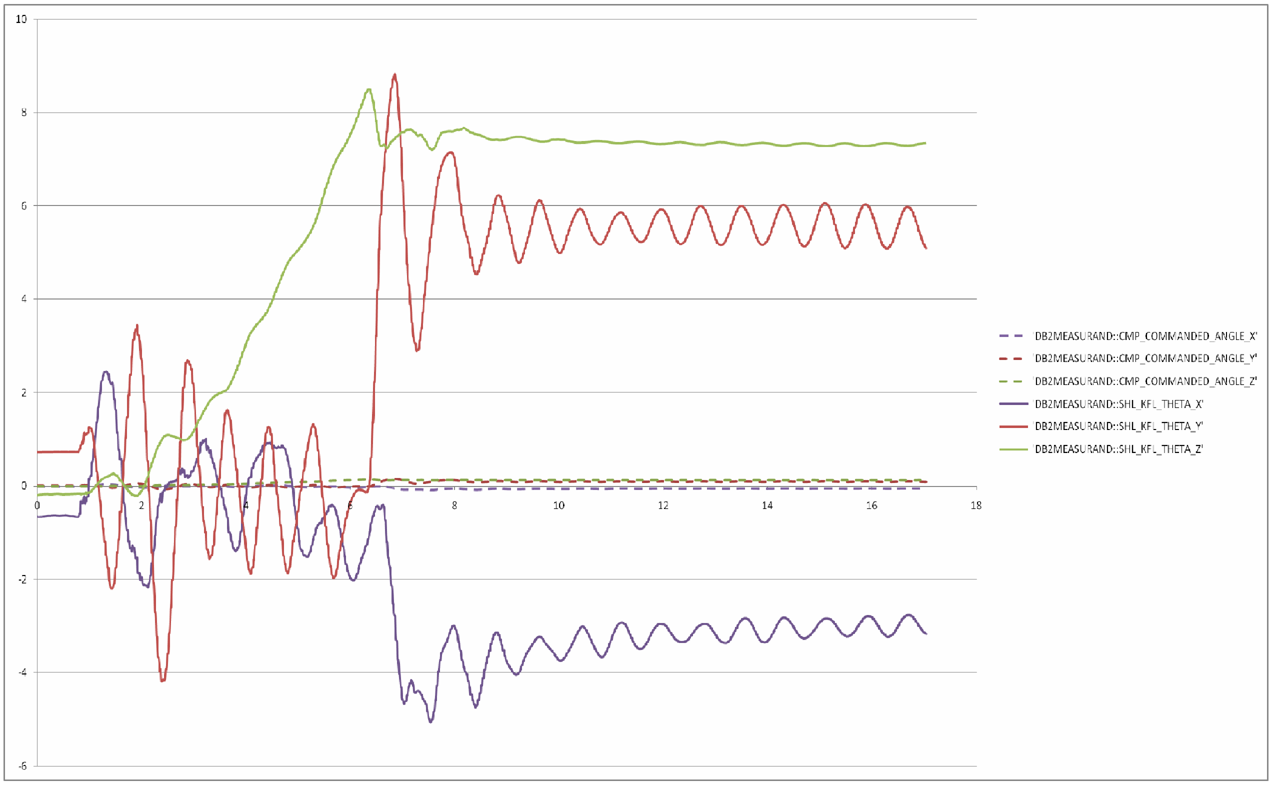


Figure 21: Angles X, Y and Z during free flight test

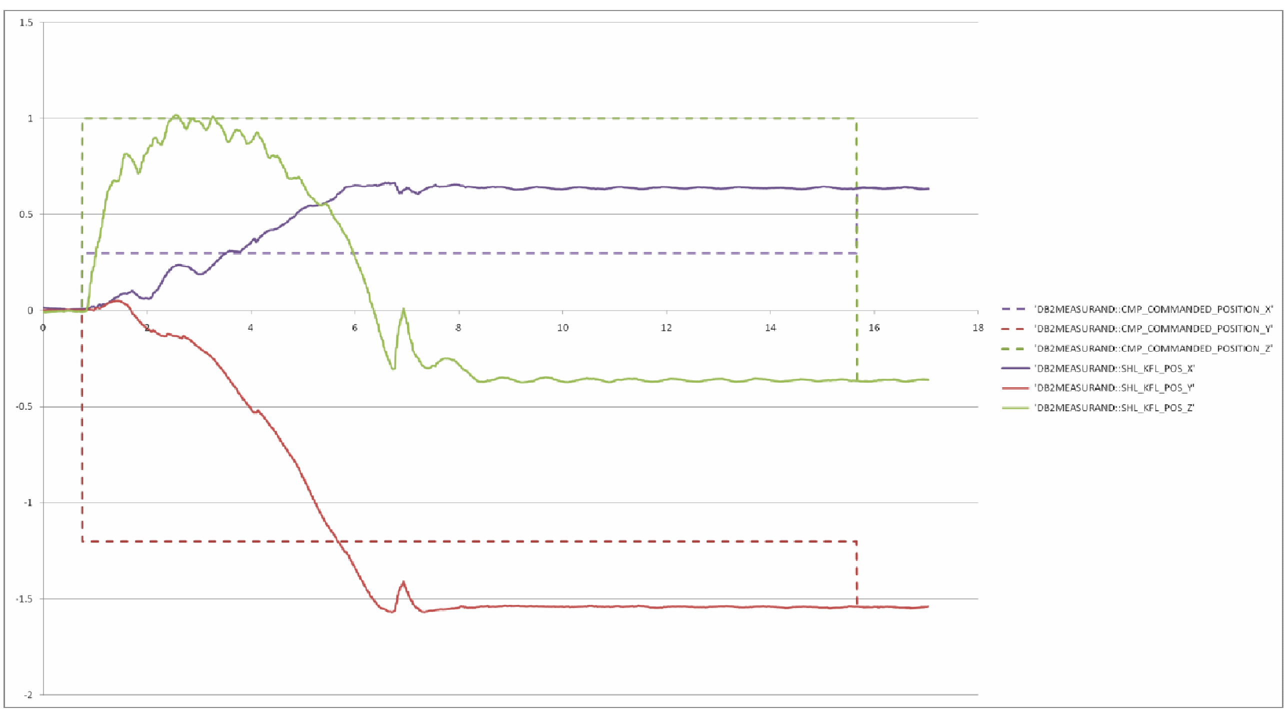


Figure 22: Commanded (dashed lines) and Measured (solid lines) Positions (X, Y and Z axes) during free flight test

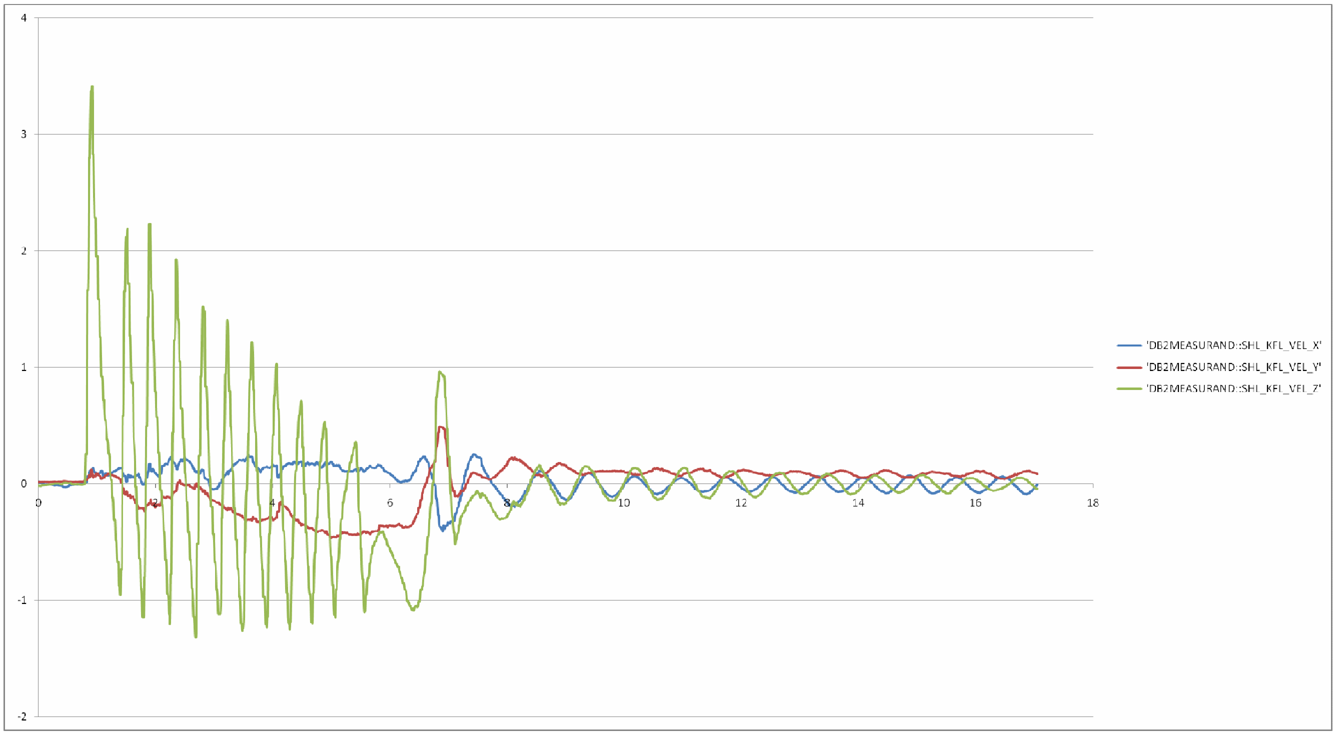


Figure 23: Measured Velocities (X, Y and Z axes) during free flight test

Above are 3 graphs displaying the angle, position and velocities measured for each axis for the vehicle during a single flight. On Figure 21 it can be seen how the vehicle angle around the x and y-axes remain under 5 degrees for the flight duration (although are greater when landing on the flexible net). The rotation around the z-axis, which remained unconstrained during the flight, stayed within 10 degrees.

Similarly, on Figure 22 one can see the target (commanded) and real positions throughout the flight and afterwards. These again are well within the 1m range requirement during the flight.

On Figure 23 one can see the target (commanded) and real velocities throughout the flight and afterwards. These are also well within the 1 m/s lateral velocity requirement during the flight.

Repeatability
The repeatability of the results was analyzed. Figures 24 and 25 show that over 4 separate tests, the x-axis positions remained repeatable to within 0.5 m from flight to flight. The result was very similar for the y-axes and so no graphs are shown. This extends to 1m for the z-axis. Similarly, over 4 separate tests, the x-axis velocities remained repeatable to within 0.5 m/s from flight to flight, with a similar result for the y-axis and raising to 1 m/s for the z-axis.

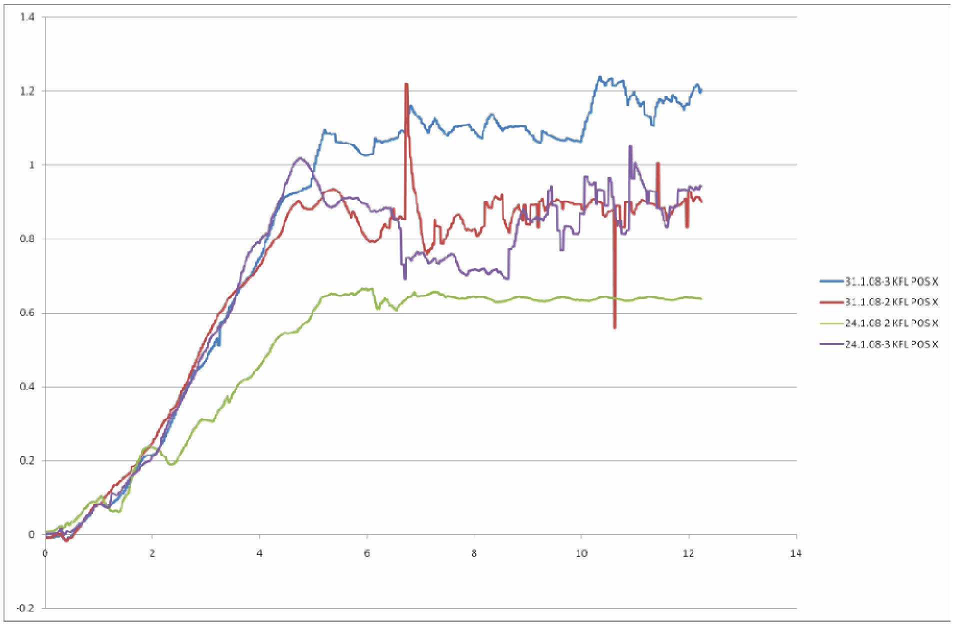


Figure 24: Repeatability of the x-axis position during 4 separate flight tests

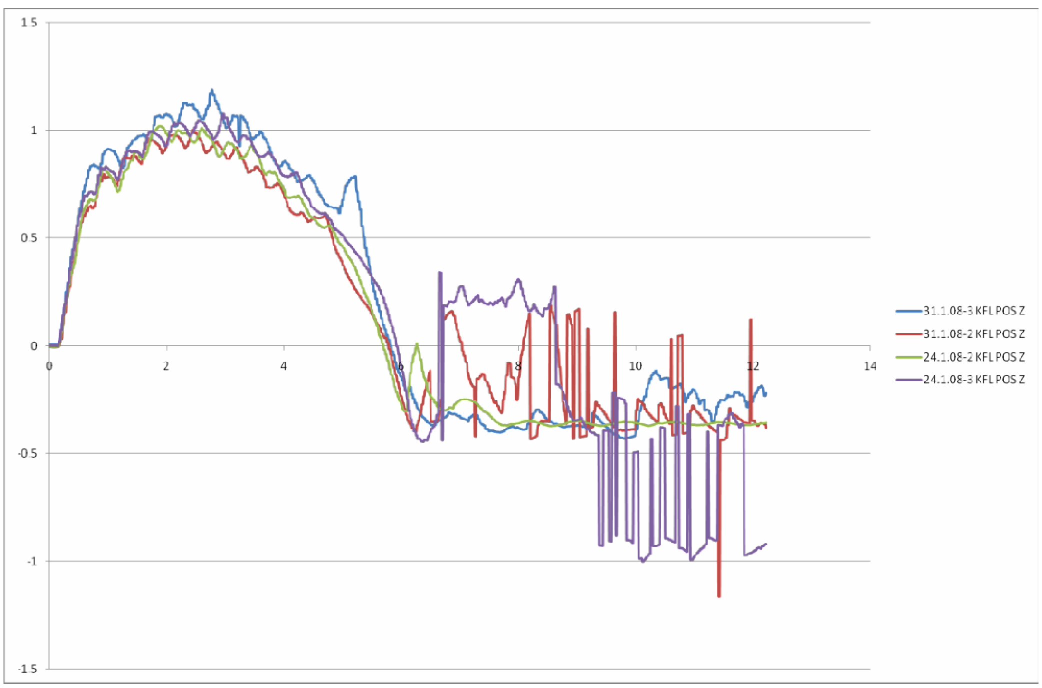


Figure 25: Repeatability of the z-axis position during 4 separate flight tests

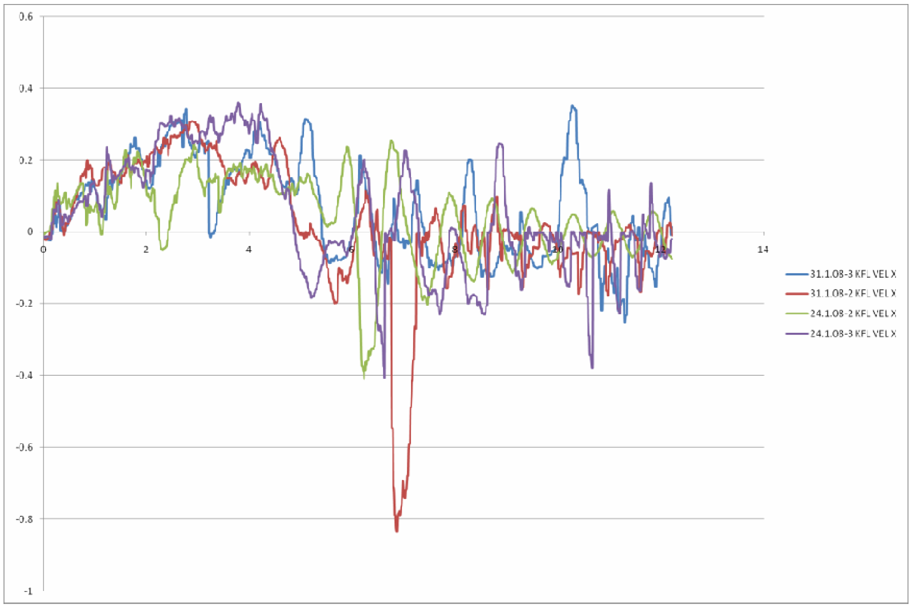


Figure 26: Repeatability of the x-axis velocity during 4 separate flight tests

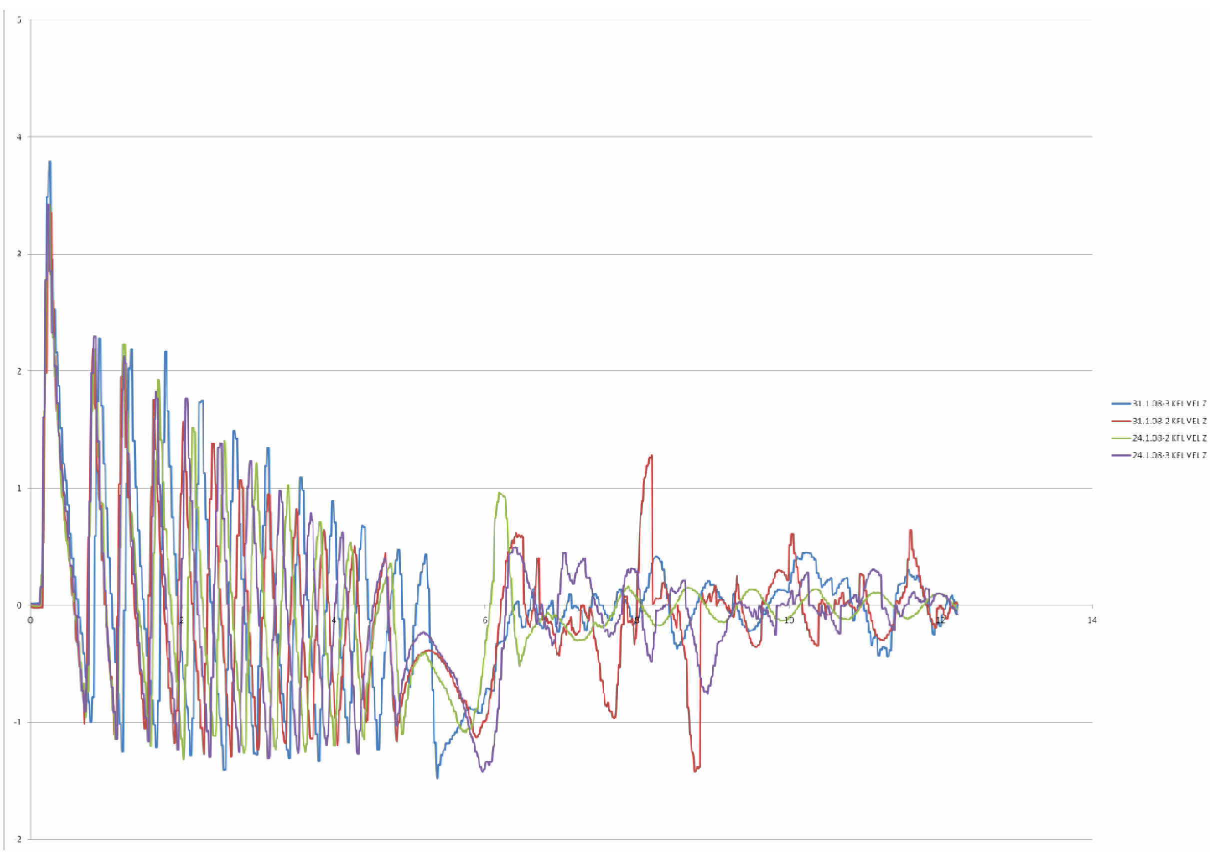


Figure 27: Repeatability of the z-axis velocity during 4 separate flight tests

Assessment with Respect to Model Correlation
One of the goals in conducting the hover test was to verify that the modeling was sufficiently accurate to allow closed loop control development prior to testing. Figures 28 through 30 show the correlation between the model results and the vehicle tests. Note that the comparisons are between simulated Kalman filter outputs, and measured Kalman filter outputs that were recorded during the test. This comparison is necessary because there is no "ground truth" measurement, so we have to rely on a comparison of the estimates.

Although the simulation results shown appear to be fairly accurate, it should be mentioned that the simulation results are highly sensitive to several of the estimated parameters. In the Monte Carlo analysis previously conducted, our predictions showed that within a range of vehicle parameter estimates, the control system should behave well, and the requirements can be met. The correlation results shown here were conducted after the fact. That is, the model was tuned to values within the range of our parameter estimates to give similar results to the test.

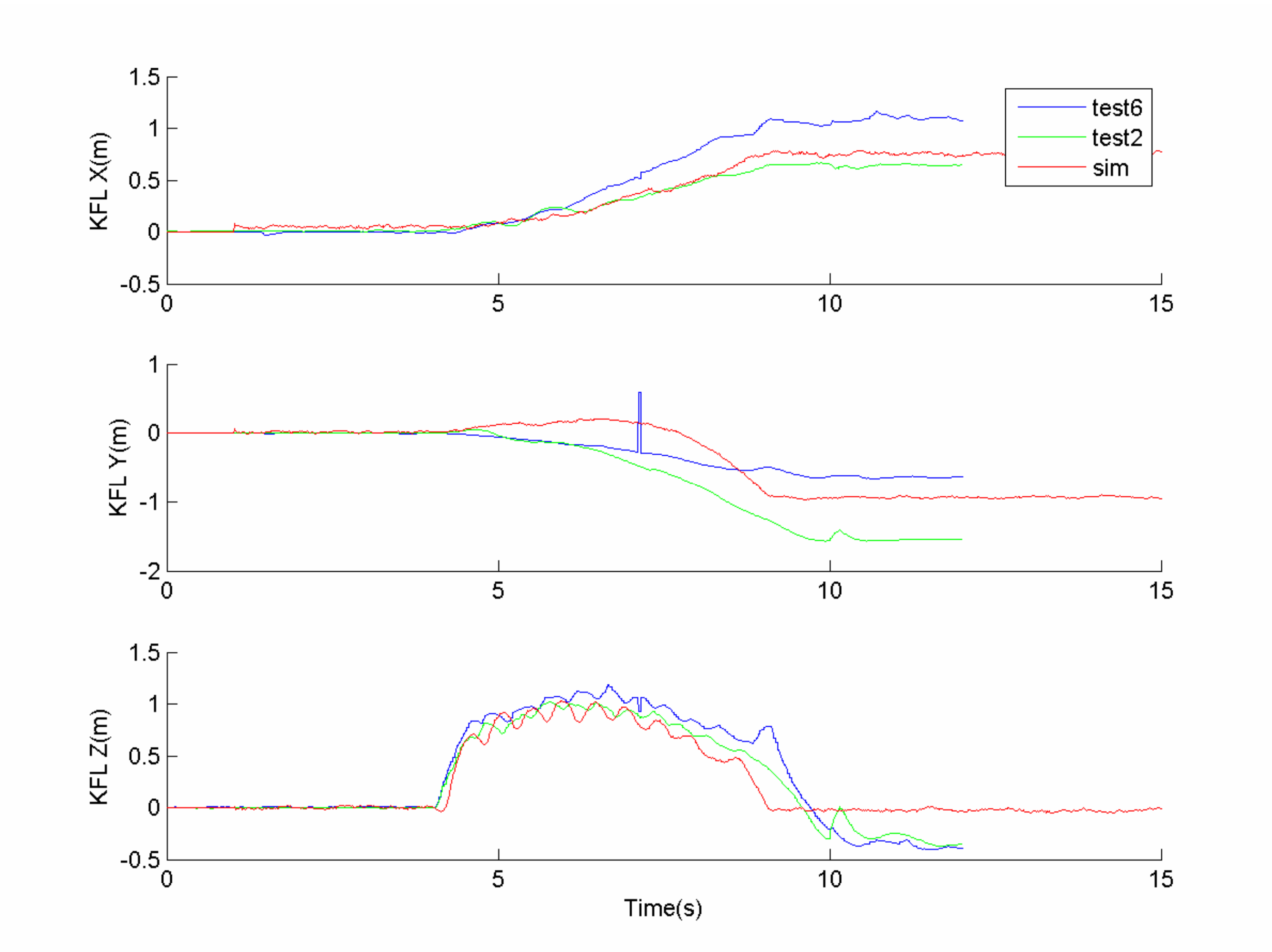


Figure 28: Comparison of simulation results for estimate positions to free flight test 2 and 6.

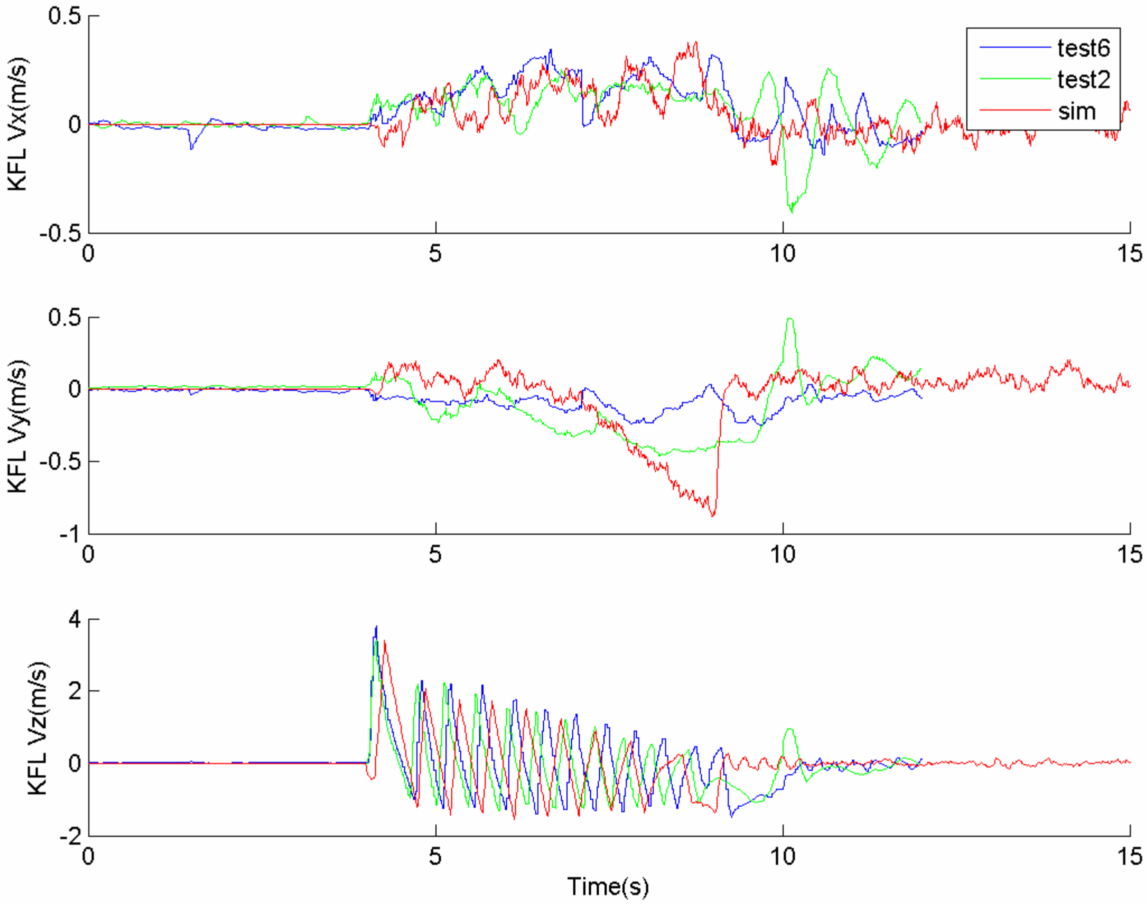


Figure 29: Comparison of simulation results for estimated velocities to free flight test 2 and 6.

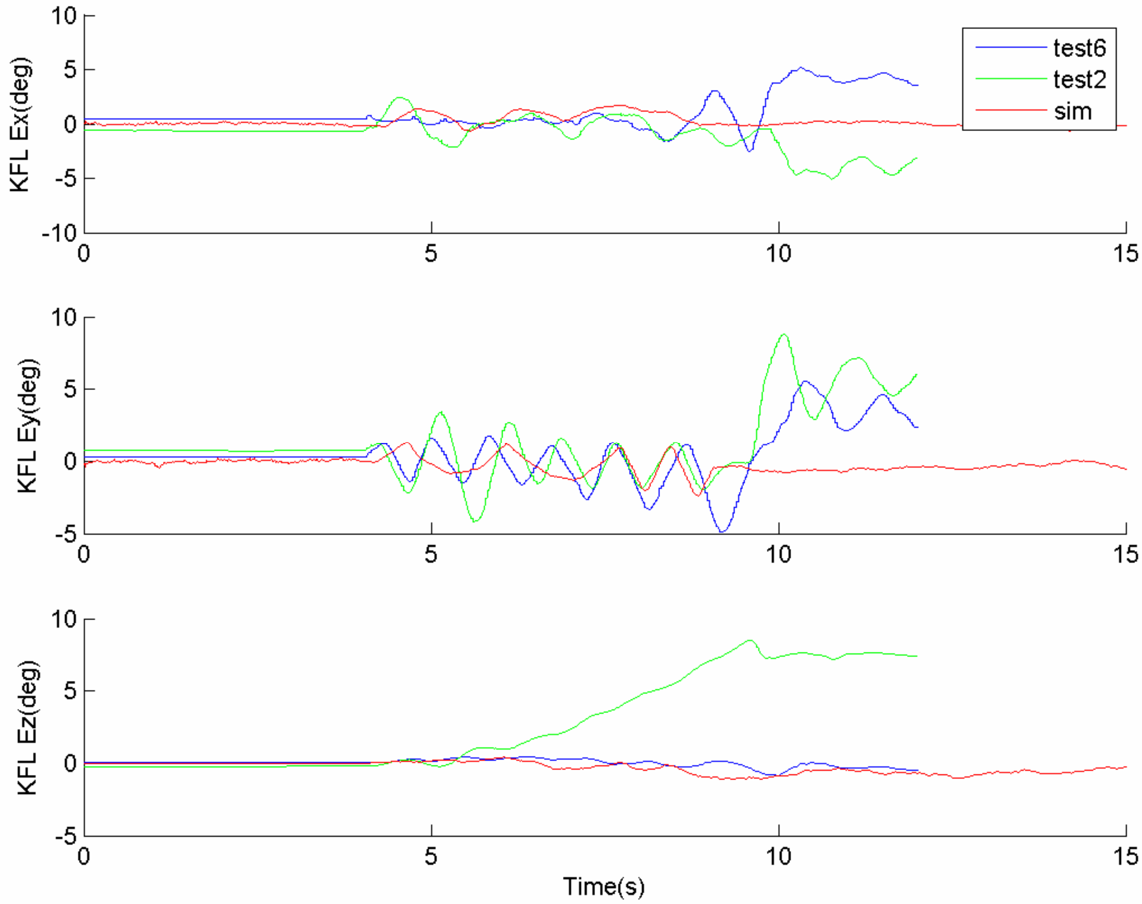


Figure 30: Comparison of simulation results for estimated Euler angles to free flight test 2 and 6.

Other Results & Anomalies

During 3 tests analyzed, there was 1 data point where the software estimated a Y-axis position that was 0.8m from the trend line for a duration of 0.04s. A smaller change is evident at the same time on the X- and Z-axis positions. This is likely due to an erroneous reading or data drop out from the VIZ system.

In total there were 6 integrated free flight tests, all of which were successful. One had only partial success since data was not logged and the HTV flew near to the edge of the net, which also caused minor damage to one of the legs upon landing on the net. A complete list of these can be found in Appendix F.

5. Conclusions

The central aim of the hover test was to demonstrate stable 6 dof attitude control during a hover flight. This has been successfully demonstrated. The Hover Test Vehicle used a Cold Gas propulsion system which simulated the performance of bipropellant systems but for smaller timescales. The flight time was 6-7s, which was considerably more than the control timescale of the vehicle, and thus more than adequate time to determine stable attitude control (including visually). The key point is that the software, attitude determination and control system and attitude control systems were able to command the propulsion system fast enough and in the correct manner to maintain attitude control. Further, each major subsystem was successful:

1) Avionics – enabled 6 dof attitude determination and control.
2) Propulsion – adequate thrust to achieve lift off and hover for >> attitude control timescale and ACS thrust sufficient to maintain attitude control over deviations in the divert alignment.
3) Structure – remained intact through >10 free flights and 50 flights that included a >3000 N thrust impulse.
4) Facility – the netting facility and bungee cord arrangements allowed the progression towards free flight with much reduced risk to the test vehicle and components.

These tests allow us to develop the capability to test low cost flight vehicle technologies and concepts – to iterate the design as well as collect data that can help the design to proceed to a spaceflight mission. Finally, the project built a team capable of implementing a spaceflight mission.

These tests allow us to develop the design further – to iterate the design as well as collect data that can help the design to proceed to a spaceflight mission. Finally, the project built a team capable of implementing a spaceflight mission.

Appendices

Appendix A: Master Equipment List

Master Equipment List
11-7-2007

Propulsion	**Description**	**QTY**	**Mass (kg.)**	**Verified Mass (kg.)**	**Total Mass (kg.)**	37.39728833	**kg**	
1_MMO-S	Burst Disk T-Fitting		0.12869	0.14500	0.128687		36.98178731	kg
1FF-S	Burst Disk Coupling		0.04036		0.0403642			
ACS_MANIFOLD		2	0.17925		0.358494			
ACS_CLAMP3		2	0.07241	0.07240	0.144828			
ACS1001003		1	0.32150	0.30050	0.3215			
ACS1002002		1	0.67682	0.66990	0.67682			
ACS1004	SS-6-HN	1	0.01978	0.03970	0.0197825			
ACS1005	SS-6-HN	1	0.03614	0.03970	0.0361403			
ACS1006	SS-6-HN	1	0.01978	0.03970	0.0197837			
ACS2004	SS-6-HN	1	0.03620	0.03970	0.0361987			
ACS2005	SS-6-HN	1	0.03620	0.03970	0.0361982			
ACS2006	SS-6-HN	1	0.03620	0.03970	0.0361996			
BOLT_HEX-3-019		4	0.00576	0.00460	0.02305892			
BOLT_HEX-4-014		2	0.00779		0.01557864			
BOLT_HEX-4-018		6	0.00935		0.0560877			
BOLT_HEX-4-044		2	0.01948	0.01870	0.038958			
BOLT_HEX-6-012		2	0.01656		0.0331108			
BURST_DISK	1.0 MPa burst disk		0.00754	0.02800	0.00753636			
BURST_DISK_HOLDER_LEFT		1	0.13533		0.135326			
BURST_DISK_HOLDER_RIGHT		1	0.11954		0.119542			
BURST_DISK001		1	0.11414	0.11030	0.114138			
CARLETON_6280-3-281		2	9.07788	9.07790	18.15576			
CUSTOM_WASHER		2	0.00568		0.01136154			
HP_MANIFOLD2		1	0.58878		0.588779			
HP_MANIFOLD3		1	0.25794		0.257942			
INTERMANIFOLD001	SS-8-HLN-3.00		0.12385	0.15240	0.123849			
J515-295X0234H		1	0.00079		0.000785147			
KUNKLE_30-A01-KM	20.7 MPa relief valve		0.17961	0.17000	0.179614			
MAC55		6	0.38024	0.36480	2.281458			
MAIN001001		1	0.23689	0.22990	0.236891			
MANIFOLD2REGULATOR001		1	0.05773		0.0577317			
MAROTTA_BRACKET3		1	0.17673	0.17770	0.176725			
MATING_RING		1	0.90800		0.908			
MV524		1	0.83912	0.87000	0.839121			
NAS1149_D_0363		4	0.00034		0.001352328			
NAS1149_D_0463		18	0.00040		0.007262694			
NAS1149_D_0663		2	0.00054		0.00107068			
NAS1149_D_N432		8	0.00009		0.000745278			
NON-ACS_CLAMP3		2	0.02058	0.02030	0.0411618			

NUT_HEXLOC-04		40	0.00072	0.00060	0.02875404
NUT_HEXLOC-3		4	0.00252	0.00210	0.0100684
NUT_HEXLOC-4		10	0.00408	0.00350	0.0407659
PRESSUREGAUGE3850K2	Pressure indicator		0.04467	0.01590	0.089341
PRIMARY_MOUNT		4	0.05797	0.05760	0.2318748
PRIMARY2LB	Primary to Lightband Strut		0.04960		0.3968048
THRUSTPLATE2		1	0.36965	0.37340	0.369645
REGULATOR_BRACKET		1	0.20286		0.202862
SETRA3100		2	0.07950	0.15000	0.1589992
SHCS-04-08		40	0.00092	0.00070	0.03696988
SHCS-04-22		8	0.00202	0.00180	0.0161528
SHCS-3-12		8	0.00419	0.00320	0.03353664
SS_1210_1_12		2	0.14859	0.12850	0.297172
SS_1210_1_8		1	0.13583	0.11680	0.135831
SS_1210_4		1	0.37479	0.34930	0.374789
SS_1211_PC		1	0.03715	0.03910	0.037152
SS_16_P		1	0.28722	0.26320	0.287217
SS_1610_1_12ST		1	0.23501	0.21650	0.235011
SS_1610_1_16		4	0.27763	0.24820	1.110504
SS_1610_1_16ST		2	0.26667	0.24890	0.53333
SS_BVM4_SH	Low Pressure Bleed Valve		0.05645	0.05140	0.0564533
TANK_BRACKET		4	0.31688	0.34800	1.267524
TANK001001		1	0.77614	0.75180	0.77614
TANK002001		1	0.77669	0.74740	0.776692
TESCOM_26-1131-282	Tescom Regulator		1.78953	1.82000	1.78953
THERMO5654		1	0.97882	0.68700	0.978815
THRUSTER_10E10	ACS Thruster (w/o p taps)		0.01100		0.066
THRUSTER_200E10	Main Nozzle	1	0.55577		0.555772
THRUSTER_SUPPORT	Thruster Support Strut		0.01922		0.0768652
THRUSTER2LB	Thruster to Lightband Strut		0.03889		0.1555496
WASH_FL-04-16R		72	0.00004	0.00005	0.00322398

Extension Module	**Description**	**Quantity**	**Mass**	**Total Mass**	4.128139036
172_HOLE_FLANGED_BUSHING		42	0.00080	0.033689754	
250_OD_X_172_ID_BUSHING		80	0.00050	0.04007568	
250_OD_X_196_SHORT_BUSHING		16	0.00032	0.005136272	
HALFINCH_PANEL_ALIGN_BUSHING			0.00180	0.00538974	
OCT_EXT_MODULE_BOTTOM_PLATE			0.25974	0.259744	
OCT_EXT_PANEL_COLD_GAS		8	0.15726	1.25808	
OCT_EXTNSN_MODULE_TOP_PLATE			0.00539	0.00538975	
OCT_EXTNSN_MODULE_TOP_PLATE_COL			1.38321	1.38321	
PANEL_DBLR_90_OCT_PNL_INNR_BENT			0.01604	0.2567088	
PANEL_DOUBLER_135_OCT_PNL_BENT			0.01017	0.040666	
PANEL_DOUBLER_90_OCT_PNL_BENT			0.01667	0.2667776	

PANEL_FITTING_90_DBLR_SP_IN		12	0.00169	0.02027868
PANEL_FITTING_90_DBLR2_SP_OUT			0.00203	0.0244038
PANEL_FITTING_CORNER_90_DBLR_IN			0.01083	0.0433392
PANEL_FITTING_CORNER_90_DOUBLER			0.01118	0.0447384
PANEL_FITTING_CORNER_90_SP_BENT			0.02014	0.080574
PANEL_FITTING3_CORNER_90_SP		8	0.00556	0.04445128
PANEL_FITTING4_CNR_90_SP_BENT			0.00571	0.09137648
PANEL_FITTING5_CNR_90_SP_BENT			0.01840	0.0735972
PNL_DBLR_135_OCT_PNL_IN_LG_BENT			0.01344	0.0537696
PNL_DBLR_135_OCT_PNL_INNER_BENT			0.01272	0.0508744
PNL_DBLR_135_OCT_PNL_NO_LG_BENT			0.01147	0.0458684

Payload	**Description**	**Quantity**	**Mass**	**Total Mass**	7.98806	**kg**
BATTERY1_COLD_GAS_TEST		1	0.18200	0.182		
ARC_SDU_AVIONICS		1	4.08106	4.08106		
LN 200 (S050545-IMU_5_DL)		1	0.95000	0.95		
Microhard Wireless Modem	guess	1	0.30000	0.3		
Remote control Enable/Disable Box	guess	1	0.15000	0.15		
Visualize System (2 boxes +LED's)	guess	1	0.20000	0.2		
Terminal Block, Small	guess	1	0.10000	0.1		
Terminal Block, Large	guess	1	0.10000	0.1		
Electronics Mount Plate		2	0.21000	0.42		
Thermocouples	guess	1	0.00500	0.005		
Cable Harnesses		1	1.50000	1.5		

Octahedral Bus	**Description**	**Quantity**	**Mass**	**Total Mass**	3.256286168	**kg**
250_OD_X_172_ID_BUSHING		56	0.00050	0.028052976		
SHIM_CORNER_LOWER-IB		8	0.00092	0.007340392		
SHIM_CORNER_LOWER-OB		8	0.00140	0.01121808		
SHIM_CORNER_UPPER-OB		4	0.00154	0.0061788		
SHIM_CORNER_UPPER-IB		4	0.00179	0.00714776		
HALFINCH_PANEL_ALIGN_BUSHING			0.00180	0.00359316		
PANEL_FITTING_CORNER_70_SP_2		4	0.00451	0.01803144		
PANEL_FTNG_CRNR_70_SP_ACUTE2			0.00499	0.03991672		
PANEL_FITTING_CORNER_70_SP_3		4	0.00592	0.02366688		
PANEL_FTNG_CRNR_70_SP_ACUTE			0.00729	0.05831296		
PANEL_FITTING_CORNER_70_SP		4	0.01214	0.0485696		
9SP-0600-M213-08		4	0.01321	0.0528592		
PANEL_DBLR_70_OCT_SP_INNER2		4	0.01345	0.0537896		
PANEL_DBLR_70_OCT_SP_ACUTE_IB			0.01372	0.1097824		
PANEL_DOUBLER_70_OCT_SP		4	0.01459	0.05836		
PANEL_DBLR_70_OCT_SP_ACUTE_OB			0.01480	0.1183752		
PANEL_DBLR_70_OCT_SP_ACUTE_OB			0.01496	0.1196568		
PANEL_FITTING_CORNER_70_SP_4		4	0.01519	0.0607668		

PANEL_DOUBLER_70_OCT_SP_TOP			0.01522	0.1217816		
PANEL_DBLR_70_OCT_SP_INNER		4	0.01548	0.0619008		
TRAP_PNL_COLD_GAS		8	0.13388	1.071024		
OCT_STRUC_UPPER_STIFFNER		1	0.32335	0.323345		
OCT_BUS_MODULE_BOTTOM_PLATE			0.35262	0.352616		
Fasteners		1	0.50000	0.5		

Legs	**Description**	**Quantity**	**Mass**	**Total Mass**	3.859284	**kg**
FEATHERWEIGHT_LEGS		4.00	0.96	3.859284		

Fuel	**Description**	**Quantity**	**Mass**	**Total Mass**	11.2	**kg**
CARLETON_6280-3-281_AIR		2	5.60000	11.2		

Appendix B: Structural Testing and Analysis of the HTV and Components – data-package

Structural Testing and Analysis of the HTV and Components data-package is a complete database of structural analysis of the Hover Test Vehicle and the Hover Test Facility. The complete package can be found on the document website under the Hover Test Vehicle folder. This includes:

1. Test Analysis and Results/Structural Testing and Analysis:
    a. A9SP-0600-XD1
    b. A9SP-0600-XR010
    c. A9SP-0600-XR200
    d. A9SP-0600-XR201
    e. A9SP-0600-XR220
    f. A9SP-0600-XR221
    g. A9SP-0600-XR230
    h. A9SP-0600-XR245
    i. A9SP-0600-XR248
    j. A9SP-0600-XR249
    k. A9SP-0600-XR250
    l. A9SP-0600-XR251
    m. A9SP-0600-XR252

Appendix C: Test Operations Procedure of the HTV – instruction list

Test Operations Procedure of the HTV is a step-by-step instruction list of operating the Hover Test Vehicle in flight mode in the Hover Test Facility. Its purpose is to ensure the safe operation of the HTV. The complete procedure can be found on the document website under the Hover Test Vehicle folder. This includes:

1. HT-TOPv8-2008-01-15-2, Hover Test Vehicle, Test Operating Procedure

Appendix D: HTV structural and electrical drawing package – database

The HTV structural and electrical drawing package database is a complete engineering drawing package for the HTV, the wiring diagrams and of the hover test facility as needed for the construction of said vehicle. The complete drawing package database can be found on the document website under the Hover Test Vehicle folder. This includes:

1. Drawings:
    a. Facilities Drawings [Package]
    b. HTV _Drawings_OneFile.pdf
    c. Hover test Vehicle Wiring Diagram.pdf
    d. Hover Vehicle MASTER e-Drawings file
    e. Hover Vehicle Main Assembly.exe
    f. Propulsion Assembly.exe

Appendix E: Archived Test Videos and Photos – database

The HTV Archived Test Videos and Photos database includes a sampling of pictures and videos from the construction and test phases of the Hover Test Vehicle. The complete Video and Photo database can be found on the document website under the Hover Test Vehicle folder. This includes:

1. Test Videos and Photos:
    a. Facilities Pictures and Videos
    b. HoverTestVideos
    c. HoverVehicle 20080201

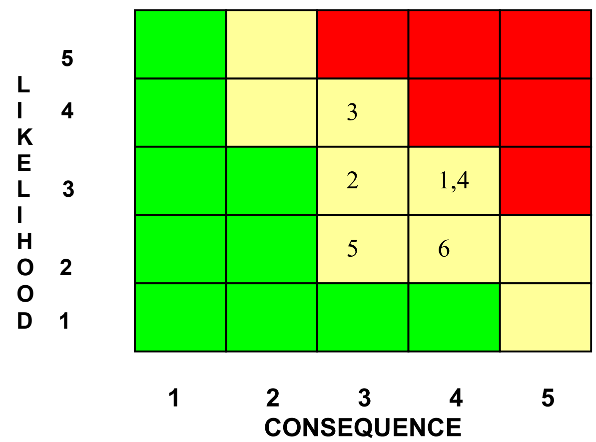
Appendix F: Risk Summary Card

RISK SUMMARY CARD
PAGE 1 OF 1

	L x C Trend	Approach
↓	Decreasing (Improving)	M – Mitigate
↑	Increasing (Worsening)	W – Watch
→	Unchanged	A – Accept
*	New since Last month	R – Research

LIKELIHOOD

What is the likelihood of occurrence?		
Level	Probability	Description
5	Very High	Occurrence is almost certain, and may not be controlled by following existing processes, procedures, and plans.
4	High	Occurrence is very likely, and may not be entirely controllable by existing processes, procedures, and plans.
3	Moderate	Occurrence is possible, and may not be controllable by existing processes, procedures, and plans.
2	Low	Occurrence is unlikely, and may not be entirely controllable by existing processes, procedures, and plans.
1	Very Low	Occurrence is very unlikely, and is generally controllable by existing processes, procedures, and plans.



- RAC-1 –high priority
- RAC-2 – medium priority
- RAC-3 –low priority

CONSEQUENCE

What is the consequence (cost, schedule, technical, safety) of this risk?					
Level	1	2	3	4	5
Cost	Minimal Budget Effect, <1%	Budget increase of 1% - 5%	Budget increase of 5% - 10%	Budget increase of 10% - 15%	Budget increase over 15%
Schedule	0 – 1% Overrun	1 – 5% Overrun	5 – 10% Overrun	10% - 25% Overrun or Critical Path Impact	Over 25% Overrun or Failure to achieve RLEP milestone
Technical, Safety	Nuisance, No loss of Mission Goals	Goals Subject to Minor Impact,	Goals Achievable Subject to Corrective Actions, nominal injury	Project Goal Achievable at Cost of Other Objective, serious injury	Inability to Meet Project Goals, possible fatality

Risk Consequence Scoring Terms

1. Cost is defined as the dollar amount of the risk if it occurs.
2. Schedule definitions: Overrun to the schedule for the effected activities of (given)% of the schedule.
3. Technical definitions includes everything that is not cost and schedule; i.e. safety, operations.
4. Cost, Schedule, Technical and Safety consequences may exist concurrently and may not be mutually exclusive.
5. Risk scoring is accomplished by rating likelihood and consequence, determining matrix location, and using the 1-25 rating in that matrix location.

Appendix G: Preliminary Risk List

No.	Candidate Risk Information
1	**Risk Title:** Filling of high pressure air **Condition & Consequence**: Given that there is a possibility that the nozzle solenoid valve and/or ACS valves are not closed at the start of charging the tanks with compressed air, there is the possibility of injury to personal or damage to the vehicle by ejecting gas directly out of the nozzles. **Risk Source: Operations** **Risk Owner:** Mark Mallinson **Risk Status:** Mitigate through use of Hover Test procedures **Plan:** All operations shall be conducted under the supervision of a Test Director with a representative from safety present during the operations. A detailed test procedure has been developed highlighting this operation as a potential safety operation and all personnel shall be cleared of the immediate area during filling operations. **Related Impacts:** Injury to personnel and hardware could prevent future testing **Likelihood:** 3 **Consequence:** Cost (3), Schedule (3), Performance (1), Safety (4)
2	**Risk Title:** Flying debris from rocket exhaust **Condition & Consequence**: Given that the vehicle is capable of producing 900 lbs of thrust, there is the possibility that someone could get injured from debris kicked up from the exhaust of the primary nozzle. **Risk Owner:** Mark Mallinson **Risk Status:** Mitigate through use of Hover Test procedures & blast shield is being installed for viewing. Eye protection required & provided for everyone during testing **Related Impacts:** Injury to personnel and hardware could prevent future testing **Likelihood: 3** **Consequence:** Cost (1), Schedule (1), Performance (1), Safety (3)
3	**Risk Title:** Personnel exposed to Excessive noise form vehicle during flight **Condition & Consequence**: Given that the vehicle produces excessive noise during flight, it is possible that personnel could develop loss of hearing **Risk Owner:** Mark Mallinson **Risk Status:** Mitigated by providing ear protection and limiting number of people for each test **Related Impacts:** **Likelihood: 4** **Consequence:** Cost (1), Schedule (1), Performance (1), Safety (3)
4	**Risk Title:** Components of the vehicles high pressure system may break free if the vehicle crashes **Condition & Consequence**: Given that components of the vehicles high pressure system may break free if the vehicle crashes, there is the possibility that the vehicle could get damaged **Risk Owner:** Jim Kennon **Risk Status:** Mitigated, stress analysis was performed on the entire vehicle to ensure the vehicle was designed to survive operational loads. Also the vehicle will go through a series of incremental test flights on bungee cords, string tests and limited pop tests. **Related Impacts:** Injury to personnel and hardware could prevent future testing **Likelihood: 3** **Consequence:** Cost (4), Schedule (4), Performance (1), Safety (4)

5	**Risk Title:** Vehicle could lose control and crash into the net **Condition & Consequence**: If the ACS fails to maintain control authority, there is the possibility the vehicle could crash into the net and get one or legs snagged causing the legs to get damaged. **Risk Owner:** Howard Cannon, Craig Pires **Risk Status:** Mitigated – ACS control authority validated incrementally through a series of incremental test flights on bungee cords, string tests and limited pop tests. **Likelihood: 3** **Consequence:** Cost (2), Schedule (2), Performance (1), Safety (1)
6	**Risk Title:** Scissor Drop Stand may fail to retract after take-off **Condition & Consequence**: Given that the Scissor Drop Stand may not retract after take-off the possibility exist the vehicle could crash land on the stand causing damage to the vehicle **Risk Owner:** Mark Mallinson **Risk Status:** Risk will be mitigated by testing the Scissor Drop Stand multiple times before actual use to verify that it works. **Related Impacts:** similar to Risk 4 **Likelihood: 2** **Consequence:** Cost (4), Schedule (4), Performance (1), Safety (2)
7	**Risk Title:** Vehicle feet may grab or cut into the net upon impact if the vehicle lands unevenly or with horizontal velocity **Condition & Consequence**: Given that the vehicles legs may get stuck or grab the net on impact, the possibility exists that the vehicle could roll over on impact and damage the vehicle **Risk Owner:** Mark Mallinson- Cage Facility, Jim Kennon vehicle dynamics **Risk Status:** Currently under review. Risk will be mitigated by limiting the height of travel and by minimizing horizontal translation of the vehicle until a full assessment has been completed. Stronger netting has been ordered to prevent penetration of the vehicles legs through the net. **Related Impacts**: damage to vehicle legs and possibly the structure of the vehicle, also damage to the net structure **Likelihood: 4** **Consequence:** Cost (3), Schedule (3), Performance (1), Safety (1)
8	**Risk Title:** Unexpected thruster firings **Condition & Consequence**: Given that on two test flights, (1st and 4th on Jan 18th) the vehicle failed to fire in primary thruster for unknown reasons, the possibility exists that the vehicles main thruster could fail unexpectedly **Risk Owner:** Howard Cannon **Risk Status:** Under review –risk will be mitigated by limiting the flight altitude such that it is not too high to free fall or not too low to not give enough time for proper pedestal collapse **Related Impacts:** If the vehicle lost it's main thruster while hovering towards the top of the net, damage to the vehicle or the net could result **Likelihood:** 4 **Consequence:** Cost (3), Schedule ()3, Performance (1), Safety (1)
9	**Risk Title:** Tescom Failure **Condition & Consequence**: Given that there is currently a leak in the Tescom regulator there is the possibility the ACS pressure could drop well below it's operating pressure of 1.0 MPa (150 psi) thus limiting control authority. **Risk Owner:** Jim Kennon

	Risk Status: Risk is noted and a repair kit for the regulator will be installed after the next set of testing. Until the regulator is repaired, the pressure will be monitored prior to flight and adjusted accordingly using procedures. Also the vehicle will be limited to flying a safe altitude until the regulator is rebuilt. **Related Impacts:** Vehicle could potentially have insufficient control authority and crash land potentially damaging the vehicle. **Likelihood: 4** **Consequence:** Cost (3), Schedule (3), Performance (2), Safety (1)
10	**Risk Title:** ACS Regulator Pressure Gets too High **Condition & Consequence**: Given that there is currently a leak in the Tescom regulator there is the possibility the ACS pressure could increase well above it's operating pressure of 1.0 MPa (150 psi) thus rupturing the burst disc. **Risk Owner:** Howard Cannon **Risk Status:** Same as item 9 **Related Impacts:** Vehicle could potentially lose control authority and crash land potentially damaging the vehicle. **Likelihood: 4** **Consequence:** Cost (3), Schedule (3), Performance (2), Safety (1)
11	**Risk Title:** Incorrect axes or input software **Condition & Consequence**: Given that it is possible to have a wrong axis or software command, the exists the possibility that the vehicle can loose control and crash when not on the tether **Risk Owner:** Howard Cannon **Risk Status:** To mitigate potential damage to the vehicle, any software change will require a tethered flight to verify operation before performing an untethered free flight **Related Impacts:** Vehicle could potentially lose control authority and crash land potentially damaging the vehicle. **Likelihood: 3** **Consequence:** Cost (3), Schedule (3), Performance (2), Safety (1)

Appendix H: Cold Gas Hover Test Specification & CG/Mass/Inertia Properties Wet and Dry

Cold Gas Hover Test Specification
Last Update: 9/4/07

Purpose:

The purpose of this document is to describe the essential parameters needed to model the dynamics of the Cold Gas Hover vehicle.

Coordinate Frames:

The Master Coordinate frame is located .127 m above the ground. The x axis points towards an ACS thrusters 1, 2, and 6. The Y axis points vertically upwards. The Master Coordinate frame is also 0.127 m directly below the vehicle-mating ring.

The coordinate system that will be used for controlling the vehicle (hereafter called the "Vehicle Coordinate frame") will be coincident with the center of the mounting location for the IMU. The origin of this coordinate frame is located at (0.0, 0.477 m, 0.0) with respect to the Master Coordinate frame. The x axis is aligned with the x axis of the Master coordinate frame, and the z axis points vertically upwards.

The Inertial Reference frame will correspond to the initial location and orientation of the Vehicle coordinate frame. This is accomplished by zeroing the IMU position and orientation just before flight.

ACS Thruster Forces, Locations and Numbering:

The direction of the thrust vectors for each of the nozzles is shown below. Thruster 7 is the Main Thruster. The force of the main thruster varies with pressure according to Figure 1. The pressure for the ACS system is pressure regulated. Therefore it puts out a constant thrust of approximately 34 N. The Main thruster has a response time of approximately 40 mS. The ACS thrusters respond in approximately 10 mS.

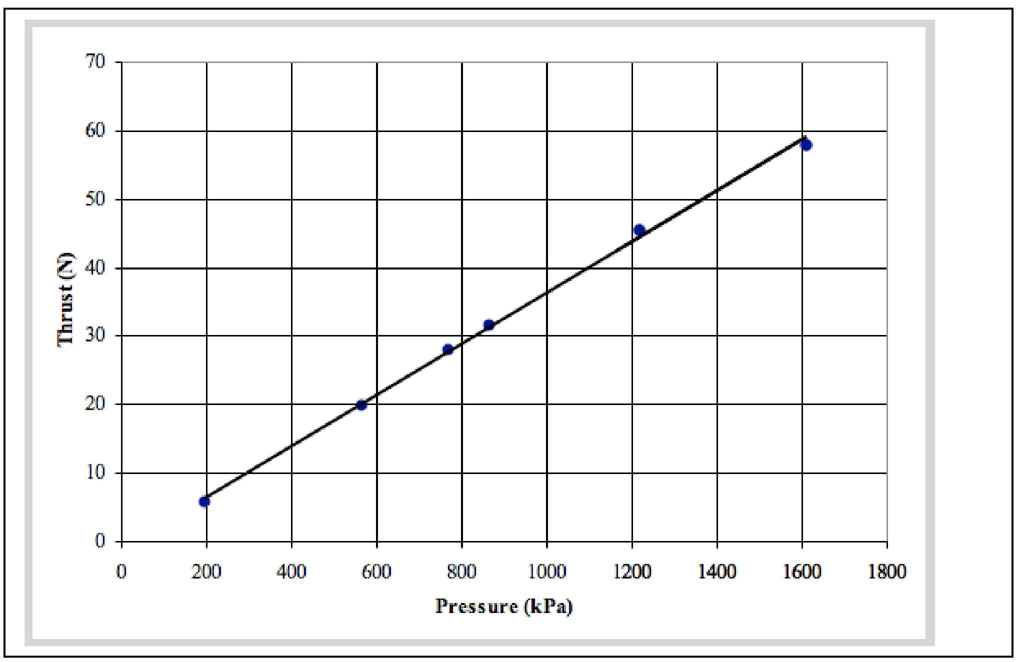


Figure 1

The numbering for the thrusters is shown in Figure 2. Note that thrusters 2,3,5, and 6 are 45 degrees from the x axis. Thrusters 1,2, and 6 all intersect at a common point: (0.569428,0.100254,0). Similarly thrusters 3,4, and 5 all intersect at: (-0.569428,0.100254,0). Thruster 7 acts through its mounting bracket located at: (0, 0.2531, 0). (All with respect to Master Coordinate frame).

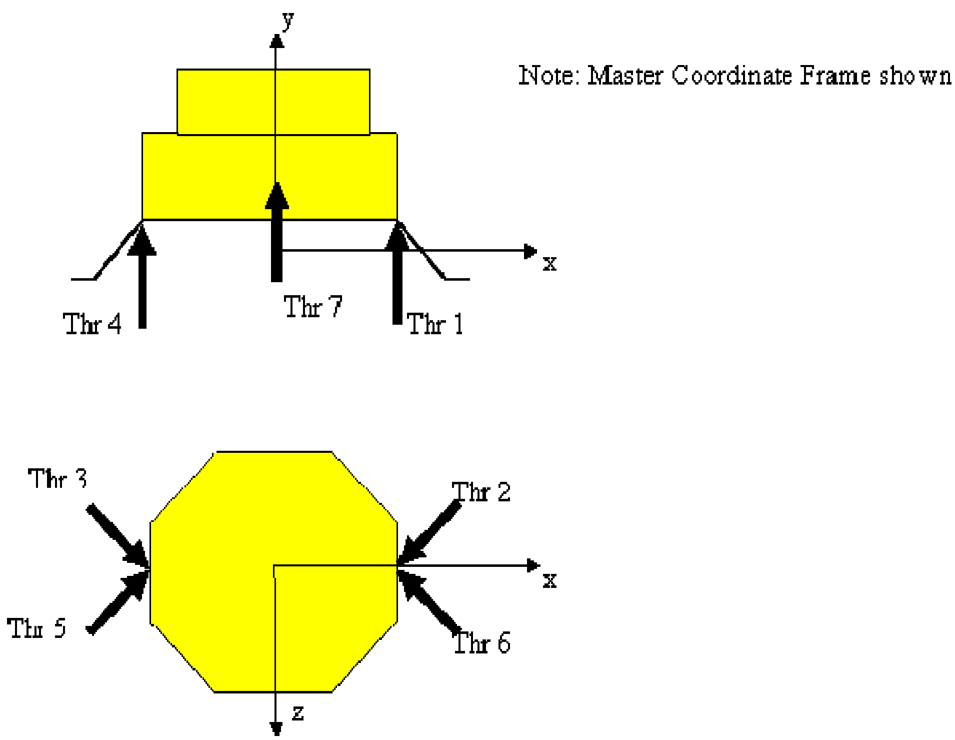


Figure 2

CG/Mass/Inertia Properties - WET
VOLUME = 8.5420080e-02 M^3
SURFACE AREA = 1.7136782e+01 M^2
AVERAGE DENSITY = 7.7149626e+02 KILOGRAM / M^3
MASS = 6.5901272e+01 KILOGRAM

CENTER OF GRAVITY with respect to _MASTER coordinate frame:
X Y Z 5.9089091e-03 3.2107055e-01 2.7415315e-03 M

INERTIA with respect to _MASTER coordinate frame: (KILOGRAM * M^2)

INERTIA TENSOR:
Ixx Ixy Ixz 1.2684762e+01 -6.5451464e-01 -7.8824333e-01
Iyx Iyy Iyz -6.5451464e-01 9.6726298e+00 -6.2848304e-01
Izx Izy Izz -7.8824333e-01 -6.2848304e-01 1.4008441e+01

INERTIA at CENTER OF GRAVITY with respect to _MASTER coordinate frame: (KILOGRAM * M^2)

INERTIA TENSOR:

Ixx Ixy Ixz 5.8907488e+00 -5.2948828e-01 -7.8717576e-01
Iyx Iyy Iyz -5.2948828e-01 9.6698335e+00 -5.7047509e-01
Izx Izy Izz -7.8717576e-01 -5.7047509e-01 7.2126215e+00

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * M^2)
I1 I2 I3 5.4009449e+00 7.5434340e+00 9.8288249e+00

ROTATION MATRIX from _MASTER orientation to PRINCIPAL AXES:

0.88370	-0.45840	0.09457
0.16799	0.12203	-0.97821
0.43687	0.88033	0.18485

ROTATION ANGLES from _MASTER orientation to PRINCIPAL AXES (degrees):
angles about x y z 79.299 5.427 27.417

RADII OF GYRATION with respect to PRINCIPAL AXES:
R1 R2 R3 2.8627800e-01 3.3832777e-01 3.8619256e-01 M

MASS PROPERTIES OF COMPONENTS OF THE ASSEMBLY
(in assembly units and the _MASTER coordinate frame)

DENSITY MASS C.G.: X Y Z

STRUCTURE5 MATERIAL: UNKNOWN
8.60255e+02 4.89225e+01 -2.00131e-02 2.87679e-01 -2.45089e-02
OCT_LNDR_EXTENSION_ASSY_11-8-06 MATERIAL: UNKNOWN
4.96965e+02 1.03759e+01 1.31891e-01 4.70849e-01 1.32972e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 5.39507e-01 1.07371e-01 -4.74544e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 4.74544e-01 1.07371e-01 5.39507e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 -5.39507e-01 1.07371e-01 4.74544e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 -4.74544e-01 1.07371e-01 -5.39507e-01
OCTAGONAL_MICRO_BUS MATERIAL: UNKNOWN
4.11269e+02 2.74353e+00 0.00000e+00 6.50658e-01 0.00000e+00

CG/Mass/Inertia Properties – Dry

VOLUME = 4.2726185e-02 M^3
SURFACE AREA = 1.6216972e+01 M^2
AVERAGE DENSITY = 1.2675248e+03 KILOGRAM / M^3
MASS = 5.4156498e+01 KILOGRAM

CENTER OF GRAVITY with respect to _MASTER coordinate frame:
X Y Z 1.7307016e-04 3.1624673e-01 -3.6812082e-03 M

INERTIA with respect to _MASTER coordinate frame: (KILOGRAM * M^2)

INERTIA TENSOR:
Ixx Ixy Ixz 1.0829912e+01 -5.2404461e-01 -8.0174769e-01
Iyx Iyy Iyz -5.2404461e-01 8.7915874e+00 -4.9801284e-01
Izx Izy Izz -8.0174769e-01 -4.9801284e-01 1.2153591e+01

INERTIA at CENTER OF GRAVITY with respect to _MASTER coordinate frame: (KILOGRAM * M^2)

INERTIA TENSOR:
Ixx Ixy Ixz 5.4128789e+00 -5.2108047e-01 -8.0178220e-01
Iyx Iyy Iyz -5.2108047e-01 8.7908519e+00 -5.6106022e-01
Izx Izy Izz -8.0178220e-01 -5.6106022e-01 6.7372896e+00

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * M^2)
I1 I2 I3 4.9040753e+00 7.0734900e+00 8.9634551e+00

ROTATION MATRIX from _MASTER orientation to PRINCIPAL AXES:

0.87940	-0.46647	0.09515
0.18143	0.14361	-0.97286
0.44015	0.87280	0.21092

ROTATION ANGLES from _MASTER orientation to PRINCIPAL AXES (degrees):
angles about x y z 77.767 5.460 27.943

RADII OF GYRATION with respect to PRINCIPAL AXES:
R1 R2 R3 3.0092154e-01 3.6140286e-01 4.0682950e-01 M

MASS PROPERTIES OF COMPONENTS OF THE ASSEMBLY
(in assembly units and the _MASTER coordinate frame)

DENSITY MASS C.G.: X Y Z

STRUCTURE5 MATERIAL: UNKNOWN
2.62261e+03 3.71777e+01 -3.65575e-02 2.70104e-01 -4.24735e-02
OCT_LNDR_EXTENSION_ASSY_11-8-06 MATERIAL: UNKNOWN
4.96965e+02 1.03759e+01 1.31891e-01 4.70849e-01 1.32972e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 5.39507e-01 1.07371e-01 -4.74544e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 4.74544e-01 1.07371e-01 5.39507e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 -5.39507e-01 1.07371e-01 4.74544e-01
FEATHERWEIGHT_LEGS MATERIAL: UNKNOWN
3.85625e+03 9.64821e-01 -4.74544e-01 1.07371e-01 -5.39507e-01
OCTAGONAL_MICRO_BUS MATERIAL: UNKNOWN
4.11269e+02 2.74353e+00 0.00000e+00 6.50658e-01 0.00000e+00

Appendix I: Software Requirements Specification

Software Requirements Specification
Release Information

Project:	HoverSat
Internal Release Number:	1.0.1
Related Documents:	NPR 7150.2 NASA-STD-8719.13A

Introduction

The HoverSat project is intended to be a training ground for the Ames team to learn rapid prototyping of space flight hardware and software. In this experiment, a platform hovers on a cold-gas thrust system. Limited maneuvers will be accomplished as flights proceed. Commands are telemetered from an operator command station. The speed and orientation of the platform are determined through the use of an IMU, and a real-time control algorithm provides stable progress to the commanded point. Current position, system health and other parameters are telemetered back to the command station.

Assumptions inherent in this plan are that there is a containment structure to control the HoverSat in case of out of control behavior. The Mass Properties will be within a controllable range as specified. It is assumed that there is a master hardware shutoff for all thrusters that can be enabled during all operations.

These requirements are high-level specifications of needed system behavior. They are not specifying the design or implementation: that is done in the system models.

General Software Requirements

Reqt. #	Requirement	Feasibility Evidence (WSIM/MSIM/PIL)
S.1	The system shall use SI units.	Inspection
S.2	Most Software will be autocoded from models. Hand-coded software shall not exceed 85% of the source lines of code (SLOCs)	Test S.2
S.3	The Software documentation shall be automatically generated.	Inspection
S.4	Software test shall be in compliance with QA test plan.	Inspection

Mission Operations Requirements

Reqt. #	Requirement	Feasibility Evidence (WSIM/MSIM/PIL)
MO.1	The system shall communicate to a remote operators station wirelessly.	Inspection
MO.2	The remote operator shall be able to send position commands to the control system.	Inspection
MO.3	The system shall immediately execute a position command when an "Inject Position Command" is received.	Inspection

MO.4	The software system shall synchronize the IMU and high speed camera data for post test analysis.	Inspection

Control Requirements

Reqt. #	**Requirement**	**Feasibility Evidence (WSIM/MSIM/PIL)**
CR.1	For the tether test, the control system shall provide angular control as specified by the guidance system to within 2 degrees 1 second after commanded.	Test CR.1
CR.2	The control system shall provide position control within 1 meter of a commanded input value during powered flight.	Test CR.2
CR.3	The control system shall met all control requirements with maximum system errors of +/- 1% of values specified in the Cold Gas Vehicle Specifications document	Test CR.3
CR.4	The control system shall provide for landing velocities no greater than 4 M/S	Test CR.4
CR.5	There shall be an open-loop individual thruster firing mode for strap-down tests.	Test CR.5
CR.6	The control system shall not command chatter such that thrusters cycle on/off at greater than 50 Hz.	Test CR.6
CR.7	The control system shall move the vehicle to achieve a commanded target position (to within 1 meter radius of the target) within 4 seconds, and remain there until the end of flight.	Test CR.7
CR.8	The control system shall provide modes for liftoff, translation and soft-landing.	Inspection
CR.9	The control system shall limit lateral velocities at landing to no greater than 1M/S.	Test CR.9

User Interface Requirements

Reqt. #	**Requirement**	**Feasibility Evidence (WSIM/MSIM/PIL)**
UI.1	The operator station shall be located in the lab with the HoverSat.	Inspection
UI.2	All position commands and telemetry feedback shall be provided in meters.	Inspection
UI.3	Angular telemetry feedback shall be provided in degrees as Euler angles with rotation sequence ZYX.	Inspection
UI.4	The software shall provide the capability to zero the position at any time. All subsequent positions shall be relative to the last calibrated position.	Inspection

UI.6	The system shall provide real time feedback to the operator regarding position, orientation, thruster state, thruster on-time, current command.	Inspection
UI.7	The system shall provide a capability to store all telemetry feedback to the operator.	Inspection
UI.8	For simulation runs, the system shall have a visualization system that allows the operator to view the action of the HoverSat in real time.	Inspection
UI.9	The system software shall provide feedback to the operator when a command is out of limits.	Inspection

Health and Safety Requirements

Reqt. #	**Requirement**	**Feasibility Evidence (WSIM/MSIM/PIL)**
HS.1	The system shall have a software state of health module that ensures that all subsystems are functional upon startup and during runtime.	Inspection
HS.2	The system software shall check and prevent the system from executing commands that are out of limits.	Test HS.2
HS.3	There shall be a bounding box on all positions, velocities and accelerations. Violation shall result in shutoff of the thrusters. Specific bounding values are: X and Y position: -3.81 meters to 3.81 meters Z Position: 0 to 6.09 meters. . X, Y and positive Z: Velocities 5 meters/sec. Negative Z: 10 m/sec. X, Y and Z Accelerations: +/- 97 m/s^2 Pitch and Roll: +/- 15 degrees	Test HS.3
HS.4	There shall be a remote kill switch that disengages the thrusters.	Inspection
HS.5	The System software shall provide an onboard visual indication of all safety-critical modes. Status lights shall indicate current state of Flight Software as well as well as Software current state of thrusters. Specific requirements are: a) Status light for System software shall be mostly on for normal operational mode (3 seconds, 37.5% duty cycle), and rapidly flashing for other error conditions. b) An Amber Software Thruster Status light shall indicate current state. When thrusters are not intended to be fired, disarmed, status light will be mostly off (1 Second, 75% duty cycle). When thrusters are enabled, armed, status light will be mostly on (3 Second, 5% duty cycle). Rationale: The lights need to be flashing so that we can be sure of a changing state and not hung software or broken connection. The flash also differentiates them from the HW Status Lights.	Inspection

HS.6	Failure of critical hardware systems shall result in the software shutting off all thrusters.	Test HS.6
HS.7	There shall an onboard disable switch that completely turns off the HoverSat.	Inspection
HS.8	There shall be an onboard enable thruster switch.	Inspection
HS.9	Thruster enable/disable state shall be fed back to the operator.	

Interface (Software/Hardware) Requirements

Reqt. #	**Requirement**	**Feasibility Evidence (WSIM/MSIM/PIL)**
IR.1	The software shall monitor the state of the master kill switch.	Inspection
IR.2	The software shall monitor the state of the solenoids in the system.	Inspection
IR.3	The software shall monitor main tank and regulated temperatures and pressures.	Inspection
IR.4	The software shall monitor system voltages.	Inspection

Appendix J: List of Tests Completed

# / Type	Date	Pressure, MPa (psi)	Result	Notes/Comments/Purpose
1. Strapdown Divert	2007/06/20	11.0 (1600)	Success	Largest Nozzle. Blow Down.
2. Strapdown Divert	2007/06/20	14.5 (2100)	Success	Largest Nozzle. Blow Down. Valve is 1.38 MPa (200 psi) high
3. Strapdown Divert	2007/06/20	17.9 (2600)	Success	Largest Nozzle. Blow Down. Valve is 1.38 MPa (200 psi) high
4. Strapdown Divert	2007/06/20	21.0 (3050)	Success	Largest Nozzle. Blow Down.
5. Strapdown Divert	2007/06/21	21.4 (3100)	Success	Largest Nozzle
6. Strapdown Divert	2007/06/21	21.4 (3100)	Success	Largest Nozzle. Blow Down.
7. Strapdown Divert	2007/06/21	21.0 (3050)	Failure	Largest Nozzle. Blow down occurred prematurely
8. Strapdown Divert	2007/06/21	21.2 (3075)	Success	Largest Nozzle. Blow Down.
9. Strapdown Divert	2007/06/21	21.7 (3000)	Success	Largest Nozzle
10. Strapdown Divert	2007/06/21	21.0 (3050)	Success	Smallest Nozzle. Blow Down.
11. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Smallest Nozzle. Blow Down.
12. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Smallest Nozzle
13. Strapdown Divert	2007/06/25	21.3 (2950)	Success	Medium Nozzle
14. Strapdown Divert	2007/06/25	21.0 (3050)	Success	Medium Nozzle. Blow Down.
15. Strapdown Divert	2007/06/25	21.0 (3050)	Success	Medium Nozzle. Blow Down. Ball valve leaking
16. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Medium Nozzle.
17. Strapdown Divert	2007/06/25	21.7 (3000))	Success	Medium Nozzle
18. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Medium Nozzle. Blow Down.
19. Strapdown Divert	2007/06/25	21.0 (3050)	Success	Medium Nozzle. Blow Down.
20. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Smallest Nozzle
21. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Smallest Nozzle.
22. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Smallest Nozzle. Blow Down.
23. Strapdown Divert	2007/06/25	21.0 (3050)	Success	Medium Nozzle
24. Strapdown Divert	2007/06/25	21.0 (3050)	Success	Medium Nozzle. Blow Down. Ball valve leaking.
25. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Medium Nozzle
26. Strapdown Divert	2007/06/25	21.7 (3000)	Success	Medium Nozzle. Blow Down.
27. Strapdown ACS	2007/07/24	0.22 (30)	Success	11 N Thrust
28. Strapdown ACS	2007/07/24	0.65 (90)	Success	16 N Thrust
29. Strapdown ACS	2007/07/24	0.72 (100)	Success	
30. Strapdown ACS	2007/07/24	1.01 (140)	Success	24.5 N Thrust
31. Strapdown ACS	2007/07/24	1.09 (150)	Success	28.5 N Thrust
32. Strapdown ACS	2007/07/24	1.19 (164)	Success	
33. Bungee Pop	2007/11/19	12.7 (1850)	Success	End pressure 21.1 MPa (1760 psi)
34. Bungee Pop	2007/11/19	21.7 (3000)	Failure	Onboard pressure release valve blew. End pressure 15.7 MPa (2280 psi)
35. String/ACS	2007/12/06	6.89 (1000)	Success	
36. String/ACS	2007/12/06	6.89 (1000)	Success	
36. String/ACS	2007/12/13	10.3 (1500)	Success	Closed loop tether test. Main thruster disconnected. End pressure 7.92 MPa (1150 psi)
38. String/ACS	2007/12/17	10.6 (1543)	Success	
39. String/ACS	2007/12/17	10.3 (1500)	Success	0→ 45 deg, 45 deg hold, back to 0 deg
40. String/ACS	2007/12/18	21.7 (3000)	Success	

41. String/ACS	2007/12/18	21.7 (3000)	Success	
42. String/ACS	2007/12/18	21.7 (3000)	Success	
43. String/ACS	2007/12/18	21.7 (3000)	Success	
44. Bungee Pop/ACS	2007/12/20	7.52 (1092)	Success	106dB acoustic noise.
45. Bungee Pop/ACS	2007/12/20	21.9 (3180)	Success	HTV half way up net
46. Bungee Pop/ACS	2008/01/10	19.3 (2800)	Success	
47. Bungee Pop/ACS	2008/01/10	22.0 (3210)	??	
48. Bungee Pop/ACS	2008/01/10	??	Success	
49. Bungee Pop/ACS	2008/01/15	21.3 (2950)	Success	
50. Bungee Pop/ACS	2008/01/15	15.8 (2300)	Success	
51. Bungee Pop/ACS	2008/01/15	15.5 (2250)	Failure	No-Fire of Divert Engine
52. Bungee Pop/ACS	2008/01/15	13.4 (1940)	Success	
53. Bungee Pop/ACS	2008/01/15	21.7 (3000)	Success	
54. Bungee Pop/ACS	2008/01/15	14 (2100)	Success	
55. Bungee Multi Pop	2008/01/15	21.4 (3110)	Success	
56. Bungee Multi Pop	2008/01/17	20.6 (2985)	Success	
57. Bungee Multi Pop	2008/01/17	??	Success	
58. Stand Multi Pop	2008/01/17	21.7 (3000)	Success	With Stand (80% bungee preload)
59. Stand Multi Pop	2008/01/23	21.3 (2960)	Success	With Stand. Bungee loose (slack removed). Landing pos: X=1.4m, Y=0.14m.
60. Free Hover	2008/01/24	21.1 (3065)	Success	First free hover test. Telemetry not saved. Landing pos: X=1.9m, Y=-0.35m, θ=-62 deg.
61. Free Hover	2008/01/24	20.5 (2970)	Success	Second free hover test. End pos: X=-0.57m, Y=-1.3m, θ=-56 deg.
62. Free Hover	2008/01/24	21.3 (2965)	Success	Test landing position repeatability. Landing pos: X=0.79m, Y=-0.85m θ=-51 deg. 3 viz ghost points.
63. Free Hover	2008/01/31	21.3 (2950)	Partial Success	Dry Run. No data logging. HTV flew Y=3m into corner of net. Minor leg damage. Viz data was lost in flight. Kill switch did not work.
64. Free Hover	2008/01/31	$2x10^7$ (2900)	Success	Test landing repeatability. Landing pos: X=-0.2m, Y=-1.2m, Z=-0.87m. Flight to show Centre Director.
65. Free Hover	2008/01/31	$2x10^7$ (3175)	Success	Test landing repeatability. Landing pos: X=-0.51m, Y=-1.4m, Z=-0.79m, θ=-64 deg. Flight to show VIPs

Appendix K: Further Loading Analysis

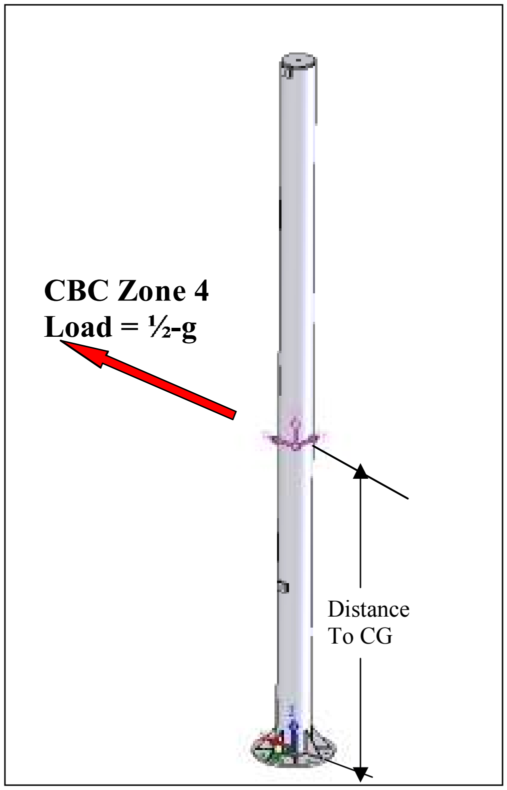


Figure 31: HTF Corner Post Under 1-g Zone-4 Loading

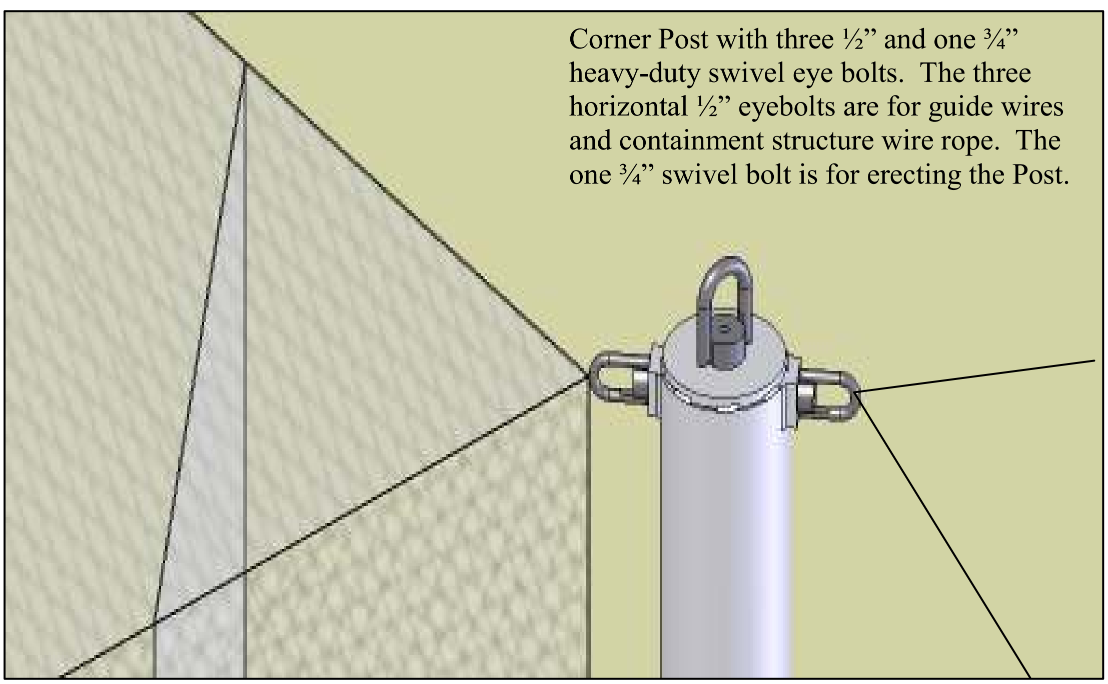
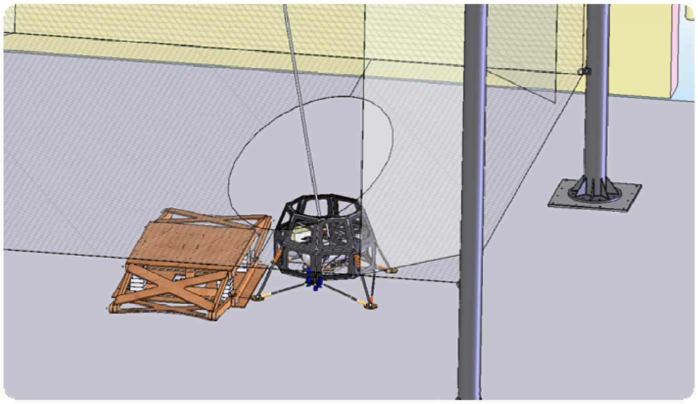


Figure 32: Hover Test Facility Corner Post, Netting and Guide Wires

Appendix L: Operational Flow of Staging the HTV for Flight Tests

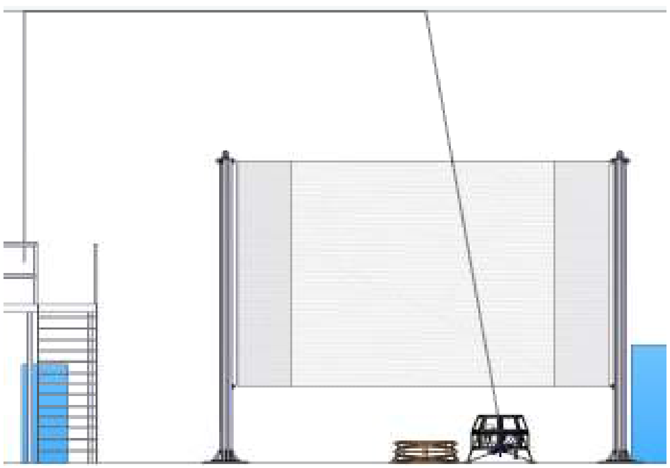


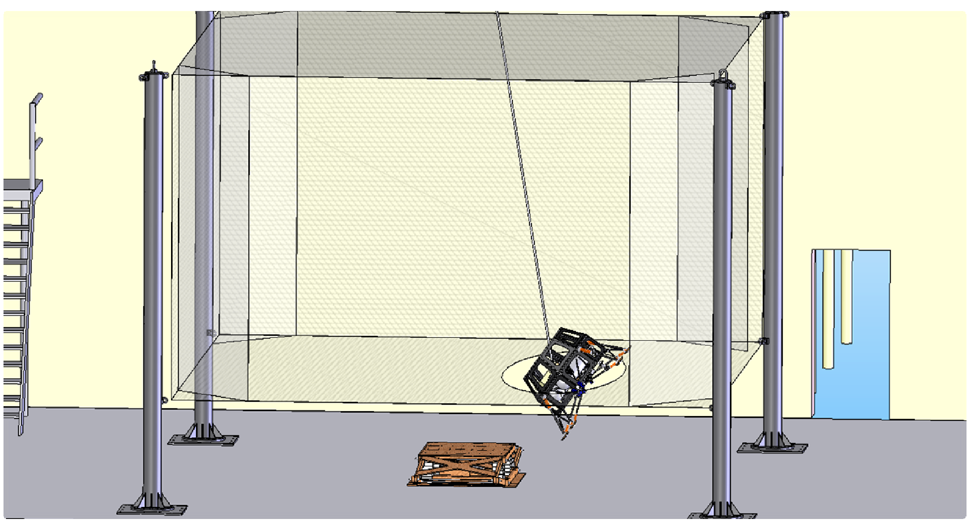
Step 1- Open floor net of Hover Cage

Step 2 Š Transport the unfueled vehicle next to the Scissor Drop Pedestal as shown. Orient Vehicle such that pressure fill valves are facing the South side of the building (away from the table)

Step 3 Š Connect Cable to Vehicle mounting flange

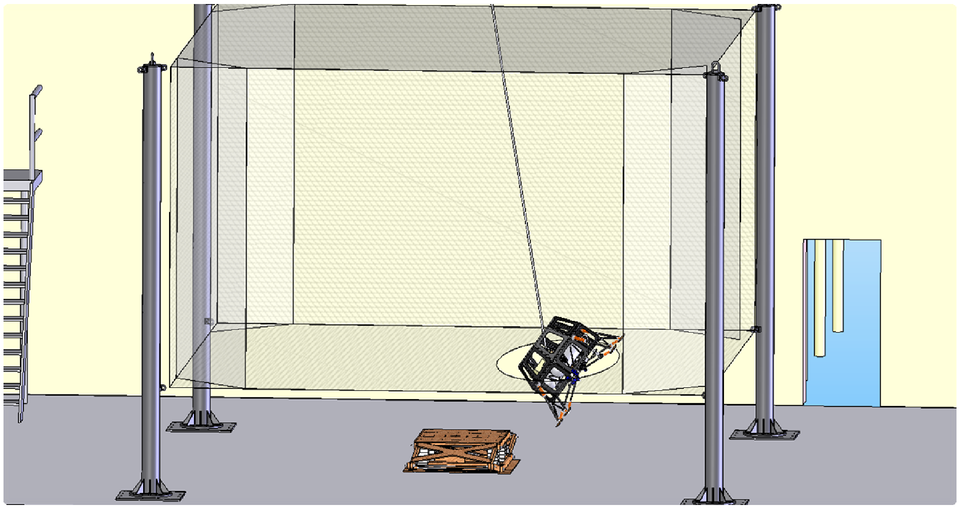
Note: the vehicle may be located on a handcart and it may not be necessary to remove the vehicle from the cart





Step 4 Š Using 2-3 people, open the floor net assembly

Step 5 Š Using 2 people, hold and steady the vehicle while one person on the Mezzanine winches the cable slowly upward and elevates the vehicle. As the Vehicle is raised, the vehicle should be rotated counterclockwise as shown to clear the net.



Step 4 Š Using 2-3 people, open the floor net assembly

Step 5 Š Using 2 people, hold and steady the vehicle while one person on the Mezzanine winches the cable slowly upward and elevates the vehicle. As the Vehicle is raised, the vehicle should be rotated counterclockwise as shown to clear the net.