Planetary Lander Dynamic Model for GN&C

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ABSTRACT

The Boeing Company, with collaborators, is developing an approach to an integrated precision landing and hazard avoidance (PL&HA) system that is capable of incorporating a suite of sensors to achieve terrain-relative navigation, and hazard detection and avoidance. The approach for the powered descent phase of the lander includes the sensors to provide a digital terrain map (DTM), cost map algorithms that identify the safe-landing sites from the DTM, and guidance navigation and control (GN&C) derived from the Delta Clipper (DC-X) project. A future flight demonstration of the GN&C and PL&HA technology to demonstrate precision landing could utilize the XA-0.2 lander model of Masten Space Systems. Boeing is developing a high-fidelity dynamic simulation model of the Masten XA-0.2 lander platform. Masten Space Systems has provided lander computer-aided design (CAD), mass properties data, and propulsion system models to Boeing for inclusion in this high-fidelity dynamic model. Boeing has developed a fuel-slosh model, rocket plume model, and an aerodynamic model of the XA-0.2 lander, and it will conduct wind tunnel testing to determine aerodynamic properties for the GN&C simulation. Boeing will then conduct extensive Monte Carlo simulations using this high-fidelity dynamic model to predict lander dynamic behavior during autonomous ascent, descent, and landing when controlled by Boeing GN&C adapted from the DC-X.
I. Introduction

The Boeing Company, with collaborators, is developing an approach to an integrated precision landing and hazard avoidance (PL&HA) system that is capable of incorporating a suite of sensors to achieve terrain-relative navigation (TRN) and hazard detection and avoidance. The approach for the Powered Descent Phase includes the sensors to provide a digital terrain map (DTM), cost map algorithms that identify the safe-landing sites from the DTM, and guidance and navigation control (GN&C) for precision landing. Different sensors may add different attributes into the cost map optimization process during powered descent. In addition, this approach has a “hopper” capability that can provide PL&HA while the lander traverses lunar terrain; for example, from a crater rim into a dark crater or from the bottom of a crater up to the rim. No \textit{a priori} knowledge of the terrain is required, and with a lidar sensor there are no constraints on lighting conditions for preparing DTM or cost maps.

For Final Descent Phase, our integrated system includes the sensors, cost map algorithms, and GN&C. Many components of this PL&HA system have achieved flight demonstration. “Cost map” algorithms have been developed in Canada to provide a real-time analysis of the digital elevation terrain maps produced by the lidar. The cost maps are intended to provide a basis to select specific landing coordinates for relative navigation use. These coordinates locate a single point selected from the areas on potential landing safe areas. The cost maps evaluate terrain in selecting the designated landing coordinates from a predetermined set of criteria. This set could include site topology and hazards, remaining maneuvering fuel, site scientific importance, or others. Cost maps optimize landing site selection based on the weighted importance of these criteria.

Our technology demonstration roadmap is targeted to achieve technology readiness level (TRL)-6 for the integrated system of sensors, cost map algorithms, and GN&C. This GN&C and PL&HA technology demonstration could utilize the XA-0.2 lander model of Masten Space Systems. Toward that end, Boeing is developing a high-fidelity dynamic simulation model of the Masten XA-0.2 lander platform. Masten has delivered lander computer-aided design (CAD) and mass properties data and propulsion system models to Boeing for inclusion in this high-fidelity dynamic model. Boeing has developed a fuel-slosh model and plume mode, is also developing an aerodynamic model of the XA-0.2 lander, and will conduct wind tunnel testing to determine aerodynamic properties for the GN&C simulation. Boeing will then conduct extensive Monte Carlo simulations using this high-fidelity dynamic model to predict lander dynamic behavior during autonomous ascent, descent, and landing when controlled by GN&C adapted from the DC-X.

The dynamic simulations will include six flight demonstration scenarios that have been established as criteria for achieving TRL-6 for the GN&C and PL&HA. These are to successfully generate cost maps and use them for PL&HA navigation under conditions of (1) thruster plume effects, (2) dust effects, (3) rotation of the lander bus, (4) shock and vibration, (5) horizontal velocity, and (6) descent velocity.

II. Role of Dynamic Simulation

Dynamic simulation plays an important role in design and development of aerospace vehicles, including landers. Essential to dynamic simulation is building a vehicle “plant model,” which dynamically represents the vehicle, including mass properties, propulsion parameters, aerodynamics, plume modeling for ground effects, fuel slosh, and others. The preliminary vehicle model is based on conceptual design; as design parameters are codified they are included to update the vehicle model. During fabrication, specific component performance parameters are incorporated into the dynamic model.

Lander dynamic simulation is performed
- During conceptual and preliminary design of lander architecture to assess dynamic performance.
- During GN&C design to assess control software performance.
- During parts selection to assess performance of components such as engines, pumps, and valves on the vehicle.
- During design of the aeroshell for performance during ascent and landing in Earth’s atmosphere (e.g., at the Mojave Airport), including ground effects.
- To model expected performance during hardware-in-the-loop (HWIL) testing.
- To model expected performance during hover test and flight test.

In building the vehicle dynamic plant model, parametric data from many sources serve as inputs. During conceptual and preliminary design, lander architecture parameters used in the model to assess dynamic performance, include
- CAD design.
- Mass properties.
- Moments of inertia.
III. **Rapid Prototype Development Methodology**

Boeing has used a rapid prototyping methodology (RaPIDS) for the Delta Clipper and other programs to accelerate the development schedule and control software cost growth\(^1\). One prominent feature of this RaPIDS process is to couple the flight simulation and flight software development.

The simulation is partitioned into three modules: (1) vehicle dynamics and associated environment models, such as atmospheric models and planetary surface characteristics; (2) lander hardware models, including sensors and actuators (the “plant model”); and (3) flight software implementing the vehicle management, control, and communication functions. The partitioning feature is important to support real-time processor-in-the-loop and hardware-in-the-loop simulations. The control software is autocoded, inserted into a real-time operating system environment, and run on a candidate flight computer. The environment, vehicle dynamics, and sensor/actuator models are also autocoded and run in a separate processor (or separate partition of the same processor) to provide a realistic data stream to the flight software, simulating realistic interfaces. At an appropriate time in the development cycle, sensor and actuator hardware would replace their models and be inserted into the lander simulation for performance evaluation.

These simulations are necessary for concept development as well as for testing later in actual flight software and hardware. Early attention to building these simulations provides cost efficiency during the actual vehicle development, when simulation results support many program decisions, early specification and procurement of flight hardware, integration testing, and even flight data interpretation.

Features of the rapid software development and systems integration method include the following:

1. Strong systems engineering oversight.
2. Early creation of a core simulation of vehicle kinematics and dynamics (including use of ADAMS software).
3. Early use of the flight processor(s) in an integrated testbed.
4. Use of hardware-in-the-loop (e.g., inertial measurement units (IMU), mechanisms, cameras, science instruments) during early software development and testing all interfaces.
5. A natural evolution of the simulation software code to flight code.
6. Frequent integration tests to ensure compatibility; spiral development approach of “build a little, test a little.”
7. Acceptance of evolving requirements and use of tools such as STATEMATE to manage effects of requirements evolution.
8. Use of autocode for the computer software configuration items (CSCI) whenever possible.
9. Use of automated software verification testing.
10. Use of small integrated teams, allowing direct working relationships across systems.

The RaPIDS process is illustrated in Figure 1. Figure 2 illustrates the compression of seven steps in the traditional (manually coded) software development process (top row) into two steps (in blue, bottom row) in the RaPIDS process. Using this process on Delta Clipper and other programs demonstrated a significant decrease in software development cost and schedule over more traditional methods.

![Figure 1. RaPIDS development process.](image)
IV. Sensors for Lander GN&C and PL&HA

The planetary lander GN&C is used for measuring vehicle state (attitude and velocity) with the lander’s suite of sensors, calculating the desired landing location relative to the current vehicle position, and commanding proper actuation of the vehicle engines and thrusters to achieve a soft landing in the proper location.

Vehicle sensors include an IMU, such as the Litton LN-200 sensor; a radar altimeter; a global positioning system/inertial navigation system (GPS/INS); and a lidar. The LN-200 sensor provides angular rate and linear acceleration in body coordinates. Rate and acceleration data are integrated to provide an estimate of the change in vehicle position and attitude relative to a starting position. Vertical position (relative to the ground) of the vehicle is obtained from the radar altimeter data as well as the lidar. The GPS/INS system provides very accurate position data for post-flight assessment of performance of the system and for trajectory reconstruction. GPS navigation data are not used by the control law. (The Moon has no GPS system, and we are developing our GN&C for lunar landers.) The lidar system provides terrain data for the “cost map” algorithms, which locate safe landing areas and provide estimates of horizontal velocity, vertical velocity, and vertical position relative to the terrain.

The navigation function combines the lidar, LN-200 IMU, and radar altimeter data using a Kalman filter to provide an optimal estimate of vehicle state. The guidance approach currently in the simulation is similar to that flown on the DC-X. The desired landing location is determined by analyzing the lidar data to locate a spot that has a low roughness value (free of hazardous boulders) and a small slope. Once the desired location is identified, the guidance system estimates position and velocity errors and determines the proper control commands to land softly in the proper location. The relationship of the lander’s sensors to the GN&C software is shown in Fig. 3. This relationship is played out first in simulation and then on the flight vehicle.

The Canadian lidar sensor used in our simulation is developed and built by Optech and MacDonald Dettwiler Associates (MDA). The hardware is based on the sensor that has flown on the XSS-11 satellite. Scanning time-of-flight (ToF) lidar functions by:

- Transmitting and receiving pulses of collimated laser light.
- Accurately measuring the time required for the pulse to transit and return.
- Determining range from this measured time.
- Directing the pulses using a two-axis mirror, to scan an image of the surface.
- Determining bearing (azimuth and elevation) by accurately measuring the angles of the steering mirror.

![Figure 2. Software development with RaPIDS process.](image-url)
By measuring the range and bearing of thousands of pulses, a three-dimensional terrain image can be created. These “range map” data can be used to identify safe landing sites from real-time terrain images, independent of local lighting conditions. Figure 4 shows the MDA Rendezvous Lidar System (RLS) used for the XSS-11. The leftmost component is the optical head, which contains the laser transmitter, fine steering mirror, receiver, and all of the time-critical functions required for ToF measurement. The avionics box on the right contains the power supply, processor, and support electronics. This component is responsible for controlling the steering mirror, the functions of the laser transmitter, the handling of telemetry and sensor data, any computations that depend on three-dimensional range map data, and the interface with the spacecraft. The hazard detection function processes lidar data (and GN&C data) to provide a measurement of the degree of hazard (slope and surface roughness) in the landing area. This measurement is used to provide a list of safe sites and a ranking for each site. The integration of this functionality into a flight-equivalent lidar system is one objective of the PL&HA program.

V. Stages of Dynamic Simulation

The simulation development process uses three fundamental paradigms. The simulation and what will later become the flight code are built concurrently using the MATRIX\textsubscript{X} System Build toolset. These tools allow control
designers to move directly from block diagrams to simulations. Discipline is enforced in the simulation to keep blocks that will produce code to run in the flight computer separate from all other portions of the simulation. This minimizes the changes that are needed in the simulation in order to generate the flight code. Finally, the simulation and environment are used during all testing, including Monte Carlo analysis, unit testing of new blocks, processor-in-the-loop, and hardware-in-the-loop testing. Figure 2 shows the difference between the traditional method of software development (upper row) and this method shown by the yellow blocks, replacing the blocks in the upper row.

During conceptual and preliminary design, vehicle dynamics are simulated as a rigid body free to rotate and translate with a total of six degrees of freedom (6DOF). The mass properties are varied as fuel is used by means of a table lookup mechanism. All external forces and moments about the center of gravity due to main engines, reaction control system (RCS) thrusters, aerodynamics, gravity, and even forces on the legs on landing on a rigid surface are summed and input to the dynamic equations. Moments of inertia, products of inertia, and center of gravity location are all calculated using lookup tables with vehicle mass as the independent variable. The main engine and thruster models output mass flow and total mass used of oxidizer and propellant (or only propellant if a monopropellant engine is used). A mass properties block uses the individual engine’s mass usage and initial vehicle, fuel, and oxidizer mass to calculate the current mass of the lander.

As specific hardware components (e.g., fuel pumps and valves, thrusters, and others) are chosen and modeled, the “generic” model of the hardware component is replaced by the measured model of each component. Thus the fidelity of the model is increased to reflect the actual hardware performance.

As the vehicle design advances, a rigid-body 6DOF model is no longer adequate. For example, the principal axes and moments of inertia vary relative to the body axes as a result of fuel depletion, fuel slosh, and other factors. Aerodynamic forces also must be added. Thus, in its mature stages, the dynamic model can become very complex. Dynamic testing at every stage of development becomes increasingly necessary to assure that the dynamic model remains a faithful rendition of the vehicle flight system.

The first stages of simulation are performed strictly in software, using the MATRIXX models. The second stage of simulation uses the LN-200 IMU on the rate table as hardware-in-the-loop. Following this, the flight code is migrated to a real-time flight processor-in-the-loop (such as an SBS RL4, MDA ESP-603, a RAD-750, or other processor). After adequate software development and testing, the flight simulation will evaluate the flight performance of the GN&C on the vehicle hardware. Following static engine testing, a tethered flight test is used to evaluate flight control performance stability. The progression from HWIL in the laboratory to a tethered flight test in the field is illustrated in Fig. 5. This figure shows Boeing’s HWIL testbed with rate table on the left, and the Masten XA-0.1B vehicle during tether testing on the right. The Masten XA-0.1B (a rebuild of the XA-0.1 vehicle) is also known as “Xombie.”

Monte Carlo simulations with the complete GN&C will determine system performance in the presence of sensor and actuator errors. Simulations and analysis included initial conditions to simulate highly dynamic lander motions representative of the aerodynamic environment, tether dynamics, lidar sensor accuracy (angle and range), resolution, and update rate variations. Monte Carlo simulations are planned with and without the precision landing and hazard avoidance system to provide a measure of percent improvement in probability of successful landing. The major subsystem component performance values would be established during breadboard simulations to verify that the components will support integrated system performance requirements.

A Monte Carlo analysis involves simulating a scenario multiple times while varying
multiple stochastic variables that affect the model. These can include, for example, sensor errors, wind data, and actuator errors.

Potential sensor errors include the lidar, radar altimeter bias and noise variance, and IMU drift rate and scale factor. The lidar sensor errors would be modeled as a position error in the desired landing location. Additional variables to be modeled would include sensor angular and position offsets from nominal mounting conditions. The environment model changes used in simulation in a Monte Carlo set would be limited to wind speed and direction. The Monte Carlo simulations would also vary individual thruster performance and mounting accuracy (position and angle data). Thruster performance would possibly include maximum/minimum thrust and thrust variations off-nominal performance and plume impingement estimate errors.

One significant feature used in Delta Clipper is the Onboard Flight Simulation. This feature places the vehicle dynamic model in a separate partition in the flight processor. The onboard flight simulation is a “mini 6DOF” within the onboard flight code, which can then be used during vehicle flight testing to run a simulation of the upcoming flight test with the actual vehicle hardware for performance evaluation prior to the flight test. During the actual flight test the onboard simulation software model is disabled. Using the onboard simulation model has multiple benefits, including

- Flight program code/mission constants checkout.
- System-level ground test firing exercise.
- Operations crew training (telemetry uplink/downlink, display drivers).

VI. Masten Lander Development

The Boeing Company and Masten Space Systems are cooperating in the undertaking of developing a dynamic and aerodynamic model of the Masten XA-0.2 lander design, currently under development. Masten Space Systems has previously developed the first-generation XA-0.1 vehicle, which has recently been rebuilt as the XA-0.1B vehicle. CAD design files have been developed for the next-generation XA-0.2 vehicle, and this vehicle is under construction at Masten’s Mojave Airport facility. Figure 6 shows both vehicles: the XA-0.1B (on the left) and the XA-0.2 (on the right). The XA-0.1B on a tether is shown in Fig. 5. Figure 7 illustrates the XA-0.2 CAD design files. The XA-0.2 will incorporate the 750-lbf (3336 Newton) LO2/IPA (liquid oxygen and isopropyl alcohol) engines, which will be proven on the XA-0.1B. The XA-0.2 vehicle features much larger propellant tanks at lower pressure, lighter weight carbon-fiber-reinforced pressurant gas tanks, a much lighter sheet metal frame, and new landing gear that are both lighter weight and provide a wider landing base. The flight duration goal for the vehicles is over 200 seconds.

We are modeling the Masten XA-0.2 mass properties, propulsion parameters, aerodynamics, and fuel slosh for the dynamics models for the lander plant simulation. The mass properties, relative to a defined set of body coordinates, include

- The output coordinate system.
- Density.
- Mass = 1429.52 lb.
- Volume.
- Surface area.
- Center of mass: (inches): X, Y, Z.
- Principal axes of inertia and principal moments of inertia: (pounds * square inches), taken at the center of mass.
- Moments of inertia: (pounds * square inches), taken at the center of mass and aligned with the output coordinate system.
The 750-lbf (3336 Newton) engines (shown in Fig. 8) for the XA-0.2 vehicle were designed and developed in-house by Masten Space Systems. They are to be both “throttleable” and “gimbalable” in two axes on the XA-0.2 vehicle. The engine on the test stand at Mojave is shown in Fig. 9. Boeing is performing simulations, including Monte Carlo runs, to assess the stability and controllability of the Masten XA-0.2 lander and model its performance under typical landing scenarios when under control of Boeing GN&C (derived from the DC-X). In addition to control law parameters and engine performance, two issues to investigate and model are (1) ground effects can lead to instabilities in the vehicle, and (2) can imaging lidar see through the plume?

VII. Aerodynamic Modeling of the Masten Lander

Aerodynamic and computational fluid dynamics (CFD) modeling of the Masten lander is being performed to model the aerodynamic forces on the lander during landing in Earth’s atmosphere. The results will be confirmed by wind tunnel testing, and then used to provide inputs into the G&C system.

The Masten lander configuration development for both CFD analysis and wind tunnel testing is being planned using the Dassault System’s CATIAv5. In our CFD analysis process, surface grids for the full Masten lander XA-0.2 configuration are generated directly on the CATIAv5 geometry using the Advanced Mesh generation workbench in the CATIAv5 tool set. In addition to the tool’s automatic grid-tightening capability near high-curvature regions of the geometry, user-specified control for local surface grid size and edge grid point distributions are also available to improve the quality of the surface grid over the entire geometry. Smoothing of the surface unstructured grid distribution on the geometry is also made using Boeing’s Modular Aerodynamic Design and Analysis Process (MADCAP) grid-generation tool. The present surface-grid-generation process not only helps to accurately resolve the full geometric complexity in the model, but also provides the flexibility that whenever the geometry is changed in the original CATIAv5 model, the surface grids for the changed geometry are automatically updated because of the linked parts of the geometry assembly. Because the generation of a good quality surface grid generation over a complex configuration is a crucial and time-consuming element of the unstructured grid generation step, the present approach is very efficient.

Hybrid unstructured three-dimensional volume grids for the complete flow field region between the Masten lander surface and the far field is generated using the advancing front local reconnection (AFLR) algorithm. The near wall boundary layer part of the volume grid contains triangular prismatic cells, followed by pyramids that bridge between the prism layers and the outer tetrahedral elements. To capture free shear layers, the volume-grid-generation algorithm also includes anisotropic tetrahedral elements. Grid density increase can be made based on seeds imposed at different segments of the flow field. This capability is particularly needed to adequately capture the plume region for the power-on aerodynamic simulations. It is important to note that the grid sizes of these complex flow simulations were quite large and exceeded 35 to 40 million cells (see Fig. 10).

With an adequate quality unstructured volume grid generated using the steps described in the grid-generation process above, Navier-Stokes solutions are obtained using both MetaComp’s CFD++ and Boeing’s BCFD solvers. Flow solutions for the Masten lander in free flight without power, as well as power-on solutions at different heights from the ground in both ascending and descending flights, were obtained. In addition, CFD simulations for full and partial throttle settings were also performed in close ground proximity. The boundary conditions necessary at the
nozzle exit faces for the power-on CFD simulations were derived from standard nozzle performance decks. Force and moment coefficients for the various parts of the Masten lander flight regime described above were extracted from the different CFD analyses. Detailed flow visualizations were also performed to understand the complex flow field.

Computed force and moment data will be compared with the wind tunnel test data at specific flight conditions to serve as the CFD prediction validation. However, the complete aerodynamic database for the flight control system design can be obtained based on the CFD simulations over the entire flight trajectory. Boeing design for the Masten lander wind tunnel model, for development of launch and landing environments, is shown in Fig. 11, and Fig. 12 shows a photograph of the Boeing low-speed wind tunnel in Huntington Beach, California. This tunnel provides six-component force and moment testing.

VIII. Modeling of Engine Plume

Engine plume modeling is needed for two reasons: (1) to model ground effects from the plume and (2) to model the effects of shining the lidar through the plume. The plume models depend on the engine nozzle characteristics and the fuel composition. Models must be built for the vacuum case (e.g., landing on the Moon), the Mars atmosphere (if we plan to land on Mars), and the Earth atmosphere (for landing tests at, for example, Mojave or White Sands).

Ground effects are caused by a cushion of high-pressure air created by the aerodynamic interaction between the plume and the ground, below ~50-m altitude. This can cause aerodynamic instability that must be controlled by the lander control law. If the control law does not adequately handle ground effects, these instabilities could possibly cause loss of control. Thus an accurate model of the ground effects should be included in the G&C law before conducting the first flight test. The FLUENT Navier-Stokes solver is used to simulate the plume flow fields at sea level and on Mars. The RAMP method of characteristics code is used to characterize the plume flow field in vacuum conditions. We have modeled ground effects for various fuels (hydrazine; LO₂ and LH) and engine designs. Figure 13 provides an example of plume modeling for hydrazine in Earth atmosphere and on the Moon. We will develop a plume model and ground effect model for the Masten 750-lbf engine (Fig. 8), for isopropyl alcohol and liquid oxygen.
Figure 11. Boeing designed the Masten lander wind tunnel model for development of launch and landing environments.

Figure 12. Boeing’s low-speed wind tunnel in Huntington Beach, California.

The lidar-through-the-plume test objective is to demonstrate the degree of opacity of the rocket engine plume to the lidar laser beam, and the degree of degradation of lidar signal strength. A study of exhaust plume flow fields is essential in evaluating the effectiveness of the lidar system. The effect of rocket engine plumes on the lidar imaging performance is assessed for image clarity. During landing and hazard avoidance, there are instances in which the lidar line-of-sight must traverse the exhaust plume(s), potentially degrading system performance as a result of laser attenuation. Depending on laser wavelength, the extent of attenuation that occurs within exhaust plumes is a function of the chemical species concentrations, gas temperature, and static pressure. Plumes may also subject laser
transmissions to scattering should there exist particulates (i.e., soot or droplets) in the flow field. The degree of scattering is a function of both the number density of the particles and their size. In our model, the composition and properties of exhaust plumes resulting from various propellant systems will be characterized. The analysis of the laser attenuation and scattering will also be considered. The HITRAN database used in conjunction with the LIDARPC code, distributed by Ontar Corp., will be used to facilitate the attenuation study.

IX. Fuel-Slosh Modeling

Liquid propellants can have substantial movement within the tanks. This leads to control concerns due to the moving masses and associated changes in vehicle mass distribution. The ability to hold a particular attitude becomes more difficult if the vehicle mass moments of inertia are varying. At times in flight when propellant levels are low within the tanks, liquid acquisition also becomes a concern as the liquids may flow away from the tank outlets and thereby allow gas ingestion into the engines, which can lead to thrust variations, premature engine shutdown, or catastrophic engine failure. Finally, unexpected propellant slosh can waste valuable propellant during each maneuver as the vehicle control system tries to adapt to flight disturbances.

Propellant slosh in the GN&C flight models is often simulated using pendulum-based mechanical analogy models of moving liquids. For many vehicles and missions with simple slosh modes, this approach works well. This is because the near-steady back and forth motions of the liquids are well represented by masses at the ends of a pendulums swinging at the tank and fluid natural frequencies that generally change during flight and propellant consumption. For more complex vehicle maneuvers, propellant motion is typically modeled by using CFD codes that predict free surface motion for pre-specified vehicle trajectories. With proper application, this leads to high-fidelity estimates for the propellant locations as functions of time. Multiphase options within the CFD codes also permit prediction of the slosh effects on cryogenic tank thermodynamics, such as for LO₂. Using such an open-loop approach wherein the trajectory is specified a priori, resulting fluid dynamics are determined and iteratively fed back into the GN&C design process for an improved model update. This often becomes laborious for complex vehicle dynamics such as that experienced by precision planetary landers and when a closed-loop method is desired.

Numerically coupling CFD software to the GN&C flight simulation model has been performed for the FLOW-3D and MATRIXX software. This permits them to run together, sharing results at specified intervals. Using this method, improved GN&C laws are developed that adapt better to the slosh disturbances and mass movements than traditional open-loop CFD or pendulum approaches. Propellant use is reduced as the desired vehicle trajectory is achieved more quickly, with less overshoot or undershoot of the target flight performance metrics, and higher pointing accuracy is achieved.

The FLOW-3D software is a general Navier-Stokes solver, developed by Flow Science of Santa Fe, New Mexico. It offers many advanced submodels directly applicable to aerospace modeling of propellants. Options include interface dynamics and slosh prediction with surface tension, simultaneous solution of liquid and gas governing equations, heat transfer between the container and all fluids, buoyancy effects, variable heating and acceleration, multispecies ullage gases, and many other models optimized for various physical phenomena and
design problems. For most Earth-storable liquids, heat transfer is neglected; however, in cryogenic problems FLOW-3D's multiphase capabilities address the heat transfer as well as its effect on tank pressurization. FLOW-3D has been used previously to support many flight vehicle programs such as DC-X, Delta II/III/IV, Space Shuttle, X-37, Ares I, and various satellites. Figure 14 illustrates some results of a typical slosh analysis performed for the X-37 H₂O₂ oxidizer tank. Similar modeling is being performed for the Masten XA-0.2 lander.

IX. Conclusions

The Boeing Company and Masten Space Systems are collaborating to develop a high-fidelity dynamic simulation model of Masten’s second-generation XA-0.2 lander design. Inputs to the model include mass properties, propulsion system parameters, CAD model of aero surfaces, models of valves and actuators, etc. Elements of the modelling and simulation include the GN&C derived from DC-X, Aero CFD, high-fidelity fuel-slosh model, rocket plume model and ground effects, and wind tunnel testing. The resulting model will then be available for simulations aimed at predicting stability and performance of the GN&C for autonomous controlled landing. Modeling of ground effects and performance of a PL&HA system will utilize this high-fidelity dynamic vehicle model.

References


2http://www.optech.ca/space-flighthardware.htm

Figure 14. Example of FLOW-3D propellant slosh model — results for the X-37 hydrogen peroxide tank.