System Verification of MSL Skycrane Using an Integrated ADAMS Simulation

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Abstract— **Mars Science Laboratory (MSL) will use the Skycrane architecture to execute final descent and landing maneuvers. The Skycrane phase uses closed-loop feedback control throughout the entire phase, starting with rover separation, through mobility deploy, and through touchdown, ending only when the bridles have completely slacked. The integrated ADAMS simulation described in this paper couples complex dynamical models created by the mechanical subsystem with actual GNC flight software algorithms that have been compiled and linked into ADAMS. These integrated simulations provide the project with the best means to verify key Skycrane requirements which have a tightly coupled GNC-Mechanical aspect to them. It also provides the best opportunity to validate the design of the algorithm that determines when to cut the bridles. The results of the simulations show the excellent performance of the Skycrane system.**

Table of Contents

1. Introduction

This paper is concerned with an integrated simulation technique that delivers high-fidelity dynamics modeling of the coupling between GNC (Guidance, Navigation and Control) , Mechanical and Propulsion subsystems during Entry, Descent and Landing, with a particular focus on the final descent and landing phases.

Various missions have handled this coupling with different architectures. The Mars Pathfinder and MER missions entirely eliminated the coupling by dropping an inflated airbag once the entry vehicle reaches a certain distance above the surface, thereby severing the GNC/Prop connection with mechanical. The Phoenix mission used a soft-landing system in which GNC controlled velocity of the lander to the moment that first contact was detected, at which point the propulsion system was shut down. Similar to the airbag architecture, this soft-landing scheme leaves the lander in an uncontrolled state as it negotiates the terrain interaction.

In contrast to these two previous architectures is the MSL Skycrane architecture, as depicted in Figures 1 and 3 and detailed in reference [2]. In the Skycrane architecture, the interaction between GNC and the lander persists throughout the touchdown event until the point that the bridles are fully unloaded, a time period that can extend for up to 3 seconds after the rover makes first contact. An additional feature of the MSL implementation of Skycrane is Mobility Deploy event. This is an energetic uncontrolled deployment and latch-up of approximately 200 kg of rover hardware (wheels, motors, and suspension tubes) that takes place during the deployment of the rover under the Descent Stage. Both of these GNC-Mechanical interactions make it desirable to have an integrated GNC-Mechanical-Propulsion model of the flight system that can generate highly accurate predictions of flight behaviors.

Figure 1 depicts the event timeline of the MSL descent and landing phase. An exhaustive description is found in [2]. Powered flight begins upon release of the PDV (Powered Descent Vehicle) from the backshell. Following release, the

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PDV is guided to a zero horizontal velocity and a constant vertical velocity of 20 m/s. A constant deceleration phase brings the PDV to a vertical speed of 0.75 m/s, and subsequently 4 of the 8 landing engines are shut down to maintain efficiency.

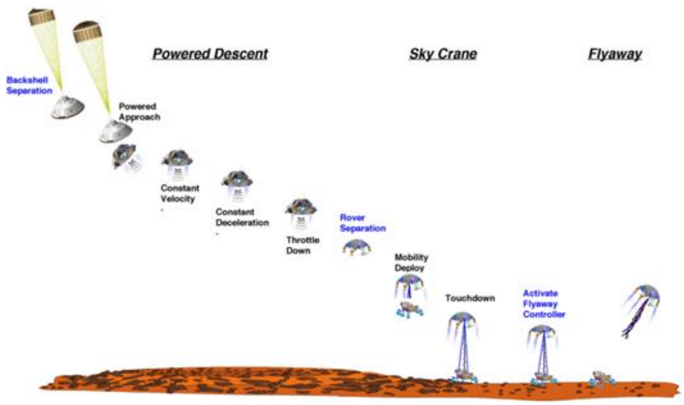

Figure 1 MSL Powered Descent and Skycrane Timeline

After allowing the throttle-down transients to dissipate, the Skycrane maneuver commences with the separation of the rover from the DS (Descent Stage). This occurs at an altitude of approximately 19m. As the rover deploys from underneath the DS, the rover mobility system (see Figure 6) is released from the stowed configuration and locks into position, and the rover is ready for surface touchdown. The touchdown event occurs as the DS continues at a controlled descent rate of 0.75 m/s. Once the rover is on the surface and the bridles have gone slack, the descent stage momentarily halts the vertical descent, the bridles and the electrical umbilical to the descent stage are severed, and the descent stage accelerates upwards and away to crash at a safe distance from the rover.

One of the key approaches to developing the Skycrane architecture has been of course to minimize the coupling of subsystems, using system-level and subsystem-level requirements. A second aspect of the development approach has been to rely on appropriately simplified subsystem models. For example, the mechanical subsystem models for loads and stability can approximate the GNC subsystem behavior by using only a spring and dashpot, and appropriately chosen initial conditions. Likewise, the entry and descent phases can be well approximated using rigid body models. A third aspect is to perform final verification of system behavior using high-fidelity system-level simulations which integrate the best subsystem models.

To address this final aspect of verification, and to provide a final opportunity to validate the algorithms which trigger bridle cut and flyway, the team has developed a GNC-Mechanical integrated model using the standard commercial ADAMS simulation program (Advanced Dynamic Analysis of Mechanical Systems). The simulation integrates compiled versions of key modules of the flight software from the GNC subsystem, and the most faithful and test-validated mechanical models of the flight hardware into a single integrated model. The simulations are used to explore and ultimately to confirm the excellent performance of the MSL skycrane architecture.

This paper continues with a description of requirements levied on the flight system that are relevant to the integrated performance simulations. The third section describes the approaches used for modeling the Mechanical and GNC subsystems, and how these models were integrated in the ADAMS environment. Also covered in this section are the models of the martian terrain used for touchdown simulations. System performance in the context of requirements verification is described in section 4. The fifth section discusses the touchdown trigger and bridle cut algorithm, and Section 6 provides the conclusions to this work.

2. MSL SKYCRANE REQUIREMENTS

The critically important function of the MSL Skycrane system is to place the rover on the surface without damaging the rover, and to leave it in a stable configuration, ready to begin its surface mission.

The driving function of the GNC design for Skycrane is to maintain a constant-velocity, stable platform from which to mechanically lower a rover for touchdown. The driving function for mechanical is to successfully execute the rover lowering, mobility deployment, and subsequent touchdown. To achieve these goals, a set of system-level requirements was derived as the framework to drive the subsystem design. It is these system-level requirements that the integrated ADAMS simulations are verifying.

The first relevant requirement relates to the stability of the vehicles during Skycrane. During most of the descent, the DS and rover are rigidly attached to each other in a configuration called the Powered Descent Vehicle (PDV). In this configuration, there are elements of the Descent Stage which extend near and around various hardware elements on the rover and vice versa. This configuration is shown in Figure 2. In order to ensure clean separation, it is desired to have the PDV as stable as possible. Therefore there are tight velocity, attitude, and angular rate requirements imposed at the moment of separation. In fact, these performance requirements are imposed on the DS throughout the entire Skycrane maneuver, to ensure the stable platform throughout. Of particular note is that the rover separation is being performed while under closed-loop control.

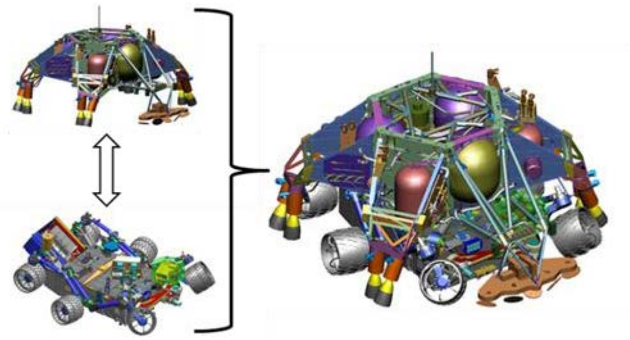

Figure 2 Powered Descent Configuration

The second requirement of interest relates to the pendulum motion of the rover under the DS. Once the rover has separated from the DS, the rover is lowered on a triple-bridle as shown in Figure 3. In this 2-body configuration it is desired to not excite the pendulum mode both from a control standpoint as well as to keep the rover from entering the plumes of the engines, which are on either side of the rover. During the rover lowering, the rover mobility system is released and deployed into locked configuration, which delivers a series of large impulsive force disturbances to the DS and into the GNC, resulting in some pendulum motion.

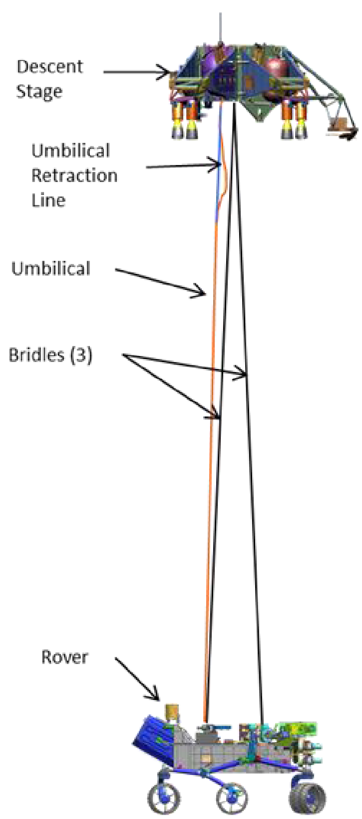

Figure 3 MSL Skycrane configuration

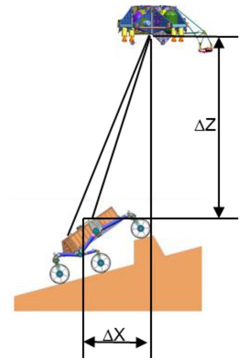

Figure 4 MSL offset configuration at touchdown

The third requirement relates to the separation of the rover and DS during and after touchdown. As the rover is touching down, it can take up to 3 seconds for the full weight of the rover to be supported by the surface, depending on the specific terrain features. During this time, it is necessary to track the displacement between the rover and the DS to ensure that plumes of the engines and the bridles do not contact the rover. In order to prevent either scenario, it is required that both the horizontal and vertical displacements between the DS and rover be within certain bounds. This scenario is shown in Figure 4.

The fourth requirement relates to the cutting of the bridles once touchdown has completed, and this will be covered in detail in Section 5 of this paper.

The requirements stated here are certainly not sufficient to ensure a safe landing on Mars. However, these flight system-level requirements are used as the basis for the subsystem designs. When these subsystems are modeled and brought together in a system-level simulation, they are shown to achieve the goal of a safe landing on Mars.

3. ADAMS System Model Description

Mechanical Subsystem Model

The MSL mechanical model in ADAMS can be most simply described as three components: the descent stage, the BUD (bridle-umbilical device) and the rover. Prior to rover separation from the PDV, there is no need for a detailed ADAMS model, so the following description is focused on modeling events which occur between rover separation and end of touchdown.

The Descent Stage (DS) is a relatively stiff structure with vibration modes far above the bandwidth of the controller, and with relatively benign flight loads during the skycrane maneuver. As such, the vehicle has been modeled as a rigid body with mass properties prescribed and held fixed throughout the simulation. The eight Mars Lander Engine (MLE) loads are applied to the rigid body at the appropriate locations, and magnitudes that are determined from the GNC module, to be described later.

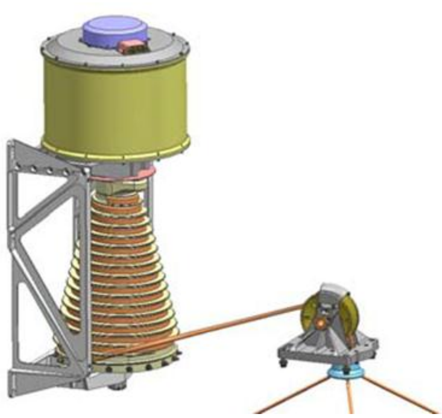

Figure 5 Depiction of the Bridle Umbilical Device (BUD), showing the spool, brake, bridles, and confluence pulley.

The DS is connected with the rover through three bridles that attach to the rover top deck. These bridles pass through a confluence point on the z-axis of the DS (see Figure 5), are wound around the BUD spool, and terminate on a clevis on the BUD spool. When the bridles have been completely unwound from the spool, a sudden snatch event occurs and the rover ends its deployment from the DS. The BUD spool is an electromagnetically-braked conical drum housed in the DS. The bridle payout length, and therefore the BUD speed, is represented in ADAMS by a series of 2^{nd}-order differential equations that incorporate the time-dependent variations in spool radius and bridle angle, using spool and brake angular displacements as the primary variables. These equations are explicitly written into the ADAMS model using the command language syntax, and are internally and automatically appended to the system equations of motion and solved simultaneously by the ADAMS numerical integrator. The bridle stiffness is a variable quantity throughout the rover deploy event, and is assigned a value from a lookup table based on the instantaneous bridle length.

The MSL Rover 'Curiosity' is a complex vehicle which for the purposes of these integrated simulations can be considered as having only two main assemblies: a rigid chassis, and a flexible and articulating mobility system (see Figure 6). The ADAMS model of the mobility system is comprised of flexible beam elements, lumped masses, and kinematic connections at joints. Many of these joints are modeled with compliance, dead zones, normal-force friction models, and hysteretic behavior, with certain degrees of freedom rigidly constrained out.

Initially the rover mobility system is stowed and the rover chassis is connected rigidly to the DS through 3 separation bolts located adjacent to the bridle attach points (Figure 2). Shortly after the start of rover deployment under the DS, the aft and forward rockers are released, and under the action of gravity, rotate independently about the Rocker Deploy Pivot, travel through their angular range of motion, and lock in place (each independently and at slightly different times) by means of a tooth-and-latch assembly. This rocker latch up is the source of very significant loads on both the mobility system itself, and on the entire 2-body Skycrane configuration. Once the fore and aft rockers are latched together, they are able to rotate as a unit about the Main Differential Pivot. The rotation on each side is connected through the differential assembly, which pivots about a Central Differential Pivot on the rover top deck. This Center Pivot is restrained against rotation by a stiff spring which is pyrotechnically removed moments prior to touchdown. Similarly, the bogies are held stowed through BUD deploy, then released to deploy into position under gravity. At the conclusion of the rover and mobility deployments the rover is in the ready-for-touchdown state.

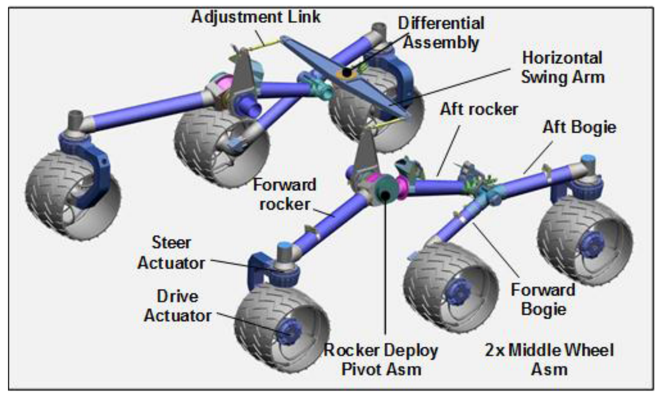

Figure 6 The MSL rocker-bogie mobility system shown in the traverse configuration

The ADAMS model has been test-verified against several static and dynamic tests to validate the model's predictive ability during the mobility deployment and touchdown events, which induce the highest loads in the mobility system. Extensive discussions of the test verification programs can be found in [1, 5].

GNC Subsystem Model

Within the context of the entire EDL sequence shown in Figure 1, the Powered Flight segment begins more than 1 km above the Martian surface, with the vehicle in the PDV configuration. Several phases must transpire before the conditions suitable for rover release can be realized. Vehicle horizontal velocity is removed first, during the Powered Approach (PA) segment. Vehicle attitude at the end of the PA phase is constrained by requirements such that the Terminal Descent Sensor (TDS) is looking straight down. Following the PA segment, the vehicle is forced to follow a controlled vertical descent trajectory during which the vehicle is decelerated to the desired rover separation conditions (altitude and descent rate) at the start of the Skycrane phase. The trajectory during the Skycrane phase is vertical, descending at the fixed, desired rate. Some pre-determined time after acquiring the desired state, the rover is separated and the DS continues to follow a constant velocity trajectory until touchdown confirmation. After depositing the rover on the ground and touchdown confirmation, a bridle cut is performed and the descent stage performs a controlled fly-away to crash some distance away from the Rover.

During the actual Mars EDL sequence, a Honeywell Miniature Inertial Measurement Unit (MIMU) and JPL-developed Touchdown sensor (TDS) provide the essential sensor inputs to the Guidance Navigation and Control subsystem. The vehicle is controlled in all six degrees of freedom by eight Mars Lander Engines (MLE).

The primary GNC algorithms are: State Estimator, Guidance (*aka* Trajectory Commander and Control), Attitude Commander and Control, and Thrust Allocation Logic. The GNC "model" integrated in the ADAMS environment consists of exact copies of the flight versions of the GNC algorithms, compiled and linked within the ADAMS program. Avionics latencies and MLE dynamics are modeled appropriately.

The State Estimator function provides surface-relative position and velocity estimates, inertial-relative attitude and angular rate estimates, and the coordinate transformation from the surface frame to the inertial frame to the rest of GNC entities.

The principal function of the Guidance function (Trajectory Command and Control) is to establish a surface-relative reference trajectory, and follow it by commanding an appropriate force vector. Estimates of surface relative position and velocity are needed to close the loop around the reference trajectory. Since the actuators (MLEs) are body-fixed entities, the reference trajectory is followed by commanding and appropriate force vector. This force is to be applied along the vehicle –Z axis, the vehicle attitude must therefore be such that –Z axis is aligned with the Guidance-commanded force vector.

The realization of the appropriate attitude is the responsibility of the Attitude Command and Control functions. Attitude Commander computes a reference attitude which allows the vehicle thrust axis (-Z Body axis) to be pointed in the direction of the Guidance-commanded inertial force vector. It profiles a turn to this attitude in the event that there is a large offset between the Guidance-desired attitude and the current attitude estimate.

Except at the beginning of powered flight (the PA phase), no such turns are required. The reference attitude is passed on to the Attitude Control function, which computes an appropriate torque value such that the errors between the reference attitude and rate, and the respective estimates provided by the State Estimator, are minimized. The torque desired by the Attitude Controller and the magnitude of the force desired by Guidance are provided to the Thrust Allocation Logic function. The logic computes realizable throttle settings such that the resulting force and torque agrees as well as possible with the commanded values.

Coupling Subsystem Models

Exact copies of the GNC flight software were compiled and linked as object files into the ADAMS program. An ADAMS user-defined subroutine (written in FORTRAN) was used as the top interface layer between the two. The inputs from the ADAMS database into this interface layer include the translational and rotational displacements and velocities of the DS. The outputs are simply the force levels for each of the eight thrusters. The GNC module is called by the ADAMS model at a frequency of 1 kHz.

In addition to the three guidance and control functions described above, the simulation also relies on the GNC algorithms for switching between various modes of flight. The two most relevant mode changes are 'rover release' and 'touchdown detected'. The first is a request to separate the rover from the PDV configuration, and the second is a request to sever the bridles and umbilical. These GNC flags are modeled as SENSOR elements in ADAMS, and serve to control the initiation of rover separation and bridle cut during the simulation. The release of rockers, bogies and center differential during mobility deploy are all controlled by the ADAMS model, and are specified as relatively simple time increments relative to the rover release flag.

The integrated ADAMS-GNC code has been a joint effort of the JPL Mechanical Loads and Simulation group and the JPL GNC group. The final integrated ADAMS simulation has been verified by comparing the results to those from the GNC's CAST simulation (Control Analysis Simulation Testbed, a JPL in-house computer program). The CAST simulation has identical GNC code as the ADAMS simulation. The rover model in the CAST simulation has the same mass properties as those of ADAMS, but it lacks the full mechanical fidelity of the ADAMS model. As a result of the limited mechanical fidelity, the excellent agreement between the two models (Figure 7) diverges somewhat after 5.75 sec.

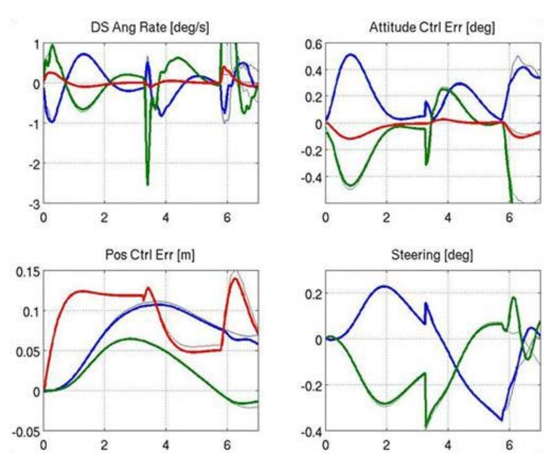

Figure 7 Validation of the ADAMS results against CAST results. ADAMS – thick line, CAST, thin line.

Modeling Martian Terrain

As with the Phoenix mission, MSL enjoys a large benefit from the availability of images from the HiRISE imager on the Mars Reconnaissance Orbiter (MRO). These images provide resolution of terrain features better than 25 cm, and through stereoscopic processing, Digital Elevation Maps (DEMs) have been produced at 1m resolution. Using these DEMs, 2m-length scale slopes can be determined with an accuracy of approximately 1 deg. [3].

Working with DEMs from four candidate landing sites, landing terrain slope statistics at a 2m baseline were derived and binned within each 150m by 150m cell on a gridded surface. The probability of landing within each cell in the grid was also determined via an end-to-end EDL flight dynamics simulation. The distribution of landing probabilities is centrally weighted with the ellipse. Thus, pixels on the edge of the landing ellipse have a lower weight than the pixels near the center. An empirical cumulative distribution function of 2m baseline surface slopes that will be encountered during touchdown was then derived by convolving binned surface slope statistics with the landing probability distribution.

The ADAMS simulations implemented these slope CDFs by randomly sampling from each CDF, then applying that slope to a planar surface of dimension 100m by 100m with a contact definition that approaches a rigid loss-less surface. Figure 8 illustrates the surface slope distribution realized in the ADAMS Monte Carlo Simulations.

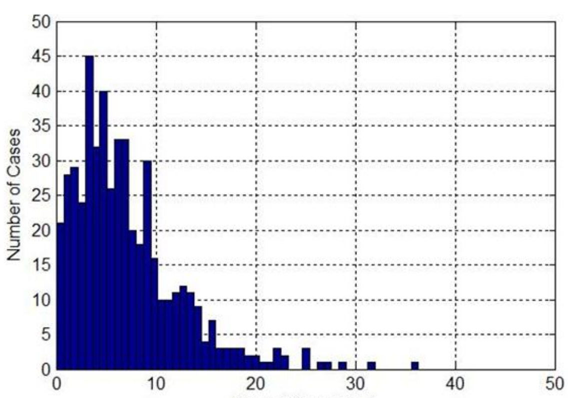

Figure 8 Distribution of surface slopes that results from convolving simulated landing location probabilities with observed slopes from MRO DEMS.

A slightly different process was followed to model rocks. The HiRISE images were used to directly detect all rocks greater than 1.5 m diameter (0.75m hemispherical radius). Using an automatic rock-counting algorithm, the cumulative fractional area (CFA) of rocks 1.5m – 2.25m in diameter covering each 150m x150m cell within the landing ellipse was determined. From this data set, Golombek's Power Law [4] was fit and used to estimate total rock CFA in each cell. For simplicity, only three discrete rock sizes were used for the ADAMS simulation: 30cm, 40cm, and 55cm. The local CFA power law model was used to determine the number of rocks of each size that would most faithfully reproduce the desired rock distribution. The specified number of hemispherical, rigid rocks of these sizes were then randomly dispersed throughout the 20m by 20m simulated landing site. An example of the randomly generated rock field for total CFA of 20% is shown in Figure 9.

A simple normal-force friction model was applied in conjunction with the planar slope and hemispherical rocks, using a coefficient of friction of μ=1.0. This value was chosen as a result of a sensitivity study on key rover loads, and is a bounding value for design loads, and represents a very 'sticky' surface. A second set of runs was made using μ=0.5, a bounding low value.

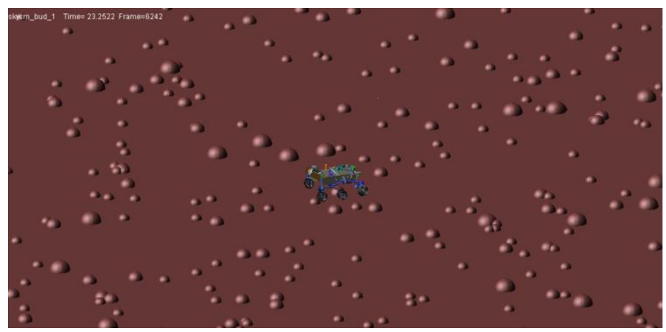

Figure 9 The rocks are modeled as rigid hemispheres uniformly distributed on the surface. Image shows CFA=20%.

Skycrane Simulations

The entire Skycrane simulation was performed in ADAMS using probabilistic Monte Carlo analysis controlled by JPL-programmed scripts.

The integrated ADAMS simulation was started at the beginning of the constant deceleration phase with the following initial conditions on the Powered Descent Vehicle:

- Altitude = 55 m
- Vertical Velocity = 20 m/sec
- Horizontal Velocity = 0 m/sec
- Attitude = Z-axis "down"
- Attitude Rates = 0 deg/sec all axes

Dispersions on the target touchdown vertical and horizontal velocities were provided to the GNC control algorithms by way of a look-up table created by sampling a desired distribution function. This allowed for introduction of reasonable navigation errors. An additional 'de-tuning' of the MLE forces was provided for in each sample simulation by randomly choosing a scale factor which was applied to all eight thrusters. This provided a small degree of additional conservatism, particularly in the PDV states at rover separation. Dispersions on other model parameters were made in accordance with the ranges used throughout subsystem development. These other parameters include items such as joint friction, bridle stiffness, rover and DS mass properties, BUD brake coefficients, etc.

By examination of the 95% confidence interval on results of interest, it was determined that 500 runs provided a sufficiently accurate estimate of the 1% and 99% statistics of the response quantities.

4. System Requirements Verification

Key system level response quantities are shown in this section. Verification of the flight system-level requirements is made by comparison of either the 1% or the 99%-ile statistic, the confidence interval, and the values set forth in the requirements.

The excellent stability of the DS during the Skycrane maneuver can be seen in the results of Figure 10. The stability is maintained throughout the rover-terrain interaction phase, which is a major source of disturbance in the post-TD results. The rover pendulum angle is no greater than 1 degree as seen in Figure 11.

The results of Figure 12 indicate that the rover lateral motion is predicted to be approximately 25cm (mean), essentially independent of friction coefficient, with a 99%-ile figure around 75 cm; this is on the order of one-half the rover length or width. The insensitivity to friction coefficient is an indication that the presence of rocks and the direction of lateral motion relative to the slope are more significant variables than friction is to the lateral translation during touchdown.

Finally, note that the rover is expected to see about 8 degrees of top-deck tilt (mean), and in no cases is the rover expected to overturn (Figure 13).

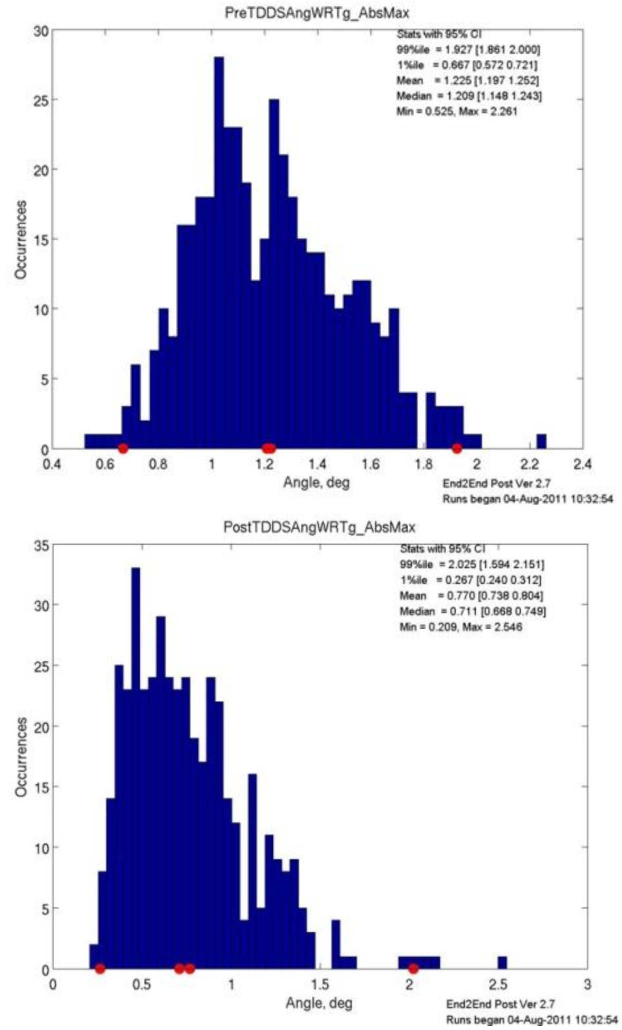

Figure 10 DS Tilt Angles throughout Skycrane: top, pre-touchdown, bottom, during touchdown

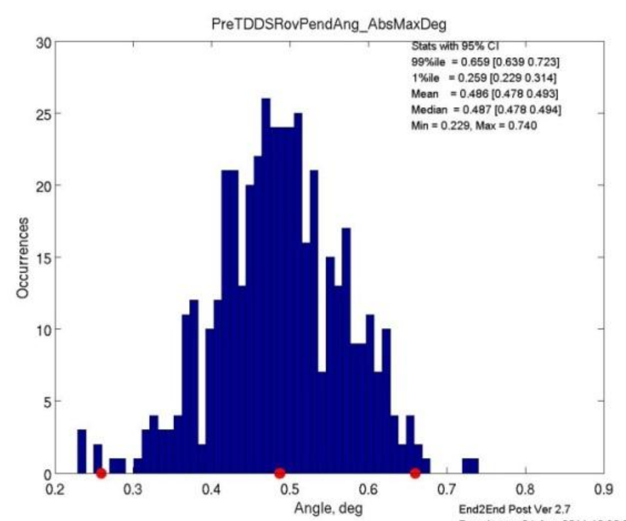

Figure 11 Rover Pendulum angle

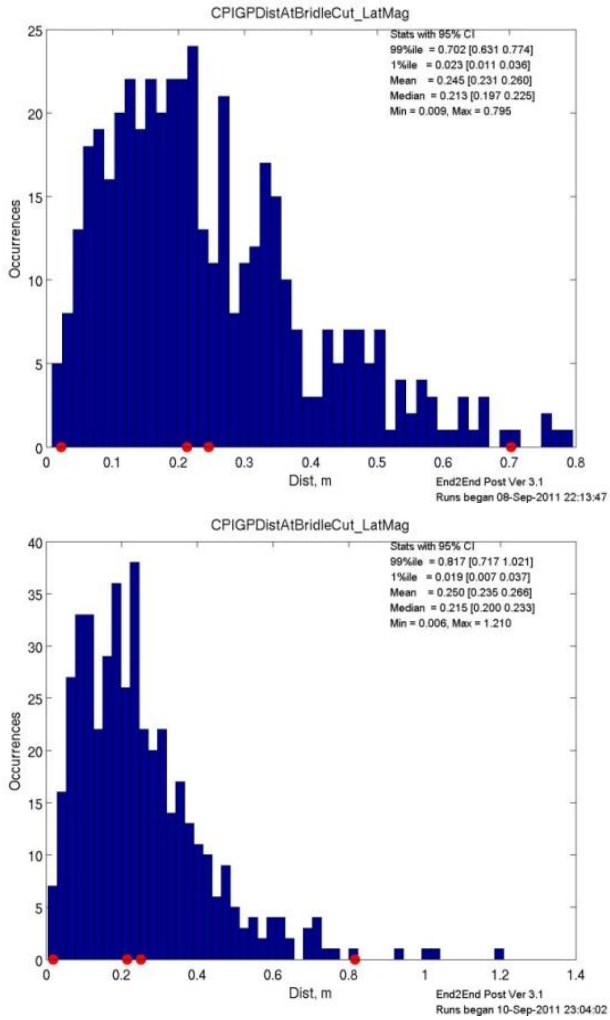

Figure 12 Rover lateral translation during touchdown: top mu=1.0, bottom, mu=0.5

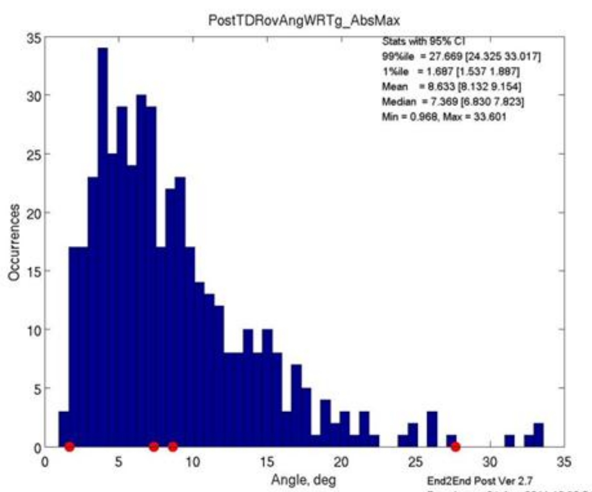

Figure 13 Maximum Rover Top Deck Angle throughout touchdown

5. TOUCHDOWN TRIGGER DESIGN AND PERFORMANCE VALIDATION

The touchdown trigger is the algorithm responsible for detecting the rover touchdown. The objective is to detect when the bridles have been offloaded so the bridles can be severed and the DS can perform the flyaway maneuver. The touchdown trigger concept is based on sensing the change in weight carried by the DS at touchdown. Upon fully slacking the bridles, this weight change corresponds to the 900 kg rover weight; however, the touchdown trigger algorithm is designed to robustly detect the touchdown, even when the rover is landing on slopes or rocks. The algorithm is depicted in Figure 14.

The algorithm uses the MLE throttle settings to compute an estimate of the effective mass that the DS is carrying. Then it calculates the moving average and moving standard deviation of the effective mass over a window duration of N seconds. Touchdown is declared the instant the following two conditions are met:

(a) moving average is below a threshold (M_a), which indicates that a substantial fraction of the rover weight has been offloaded;

(b) moving standard deviation is below threshold (M_s), which indicates the flatness of the effective mass estimate.

The ADAMS integrated simulations were used to tune the touchdown trigger parameters (N = 1.5 seconds, Ms = 600 kg, Ma = 1200 kg). It was found that this selection of parameters led to a rate of 99.78% successful touchdown detections. The remaining 0.22% of the cases, the touchdown trigger declared touchdown when over 90% of the rover weight was offloaded, which occurred when the rover was landing on slippery rocky slopes.

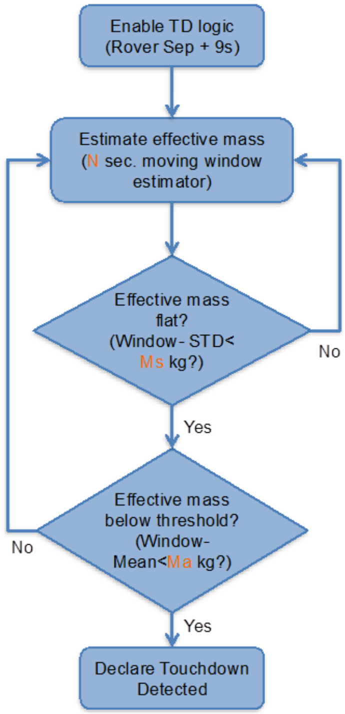

Figure 14 Touchdown Trigger Algorithm

6. CONCLUSION

This paper has explained the ideas behind successfully integrating extremely complex models of the GNC, Mechanical, and Propulsion subsystems into a single simulation running in the ADAMS platform. A significant feature of this work is that the actual GNC algorithms used in the MSL flight software have been compiled and linked into this simulation. Thus, these integrated simulations provide another venue for verifying the flight GNC implementation.

Additionally, the flight system has taken advantage of the integrated, complex model to verify by simulation several key requirements where the complete GNC-mechanical interactions may be important, namely that of Skycrane and touchdown. Furthermore, the validation of the touchdown trigger algorithm, a function of the GNC algorithms, has been validated through this integrated platform.

This application is more than a *pathfinder* effort; this work has clearly expanded the capability of the JPL team to perform complex GNC-Mechanical simulations in the Monte Carlo sense, using actual flight software, in the ADAMS environment. Additional applications of these techniques would have utility in any application with GNC-mechanical interactions; the automotive, aerospace, computer peripherals, and wind turbine industries are all potential users of this technology.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

Dr. Christopher White *is a mechanical systems engineer in the EDL and Mechanical Systems Group at JPL. Since joining JPL in 1999, Chris has been instrumental in the analysis, design and testing of many unusual structural systems, including Titan blimp concepts, airbag landing system analysis for Mars Exploration Rovers, and precision shape control research for the DART membrane telescope project. Before joining the MSL team, Chris was the Structures Group Leader for the Thirty Meter Telescope, a ground-based telescope with a segmented 30m diameter primary mirror. He received his PhD from Cornell University in 1995.*

George Antoun *joined the aerospace analysis group at ATA Engineering in 2003. George has worked extensively on ADAMS model validations and loads predictions for various configurations of the MSL rover. George earned a B.S in Engineering Science from Trinity University and an M.S in Engineering Mechanics from the University of Wisconsin.*

Dr. Paul B. Brugarolas *is a senior engineer at the Jet Propulsion Laboratory. He received the Electrical Engineer degree from the University of Navarra, San Sebastian, Spain, and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Southern California, Los Angeles. He joined the Guidance and Control Analysis Group at the Jet Propulsion Laboratory in1997. He has been involved in the application of modern control and estimation techniques to a wide range of emerging spacecraft and missions, including the Spitzer Space Telescope, the Shuttle Radar Topography Mission, the Cassini Mission, and research and technology developments. He is currently an Entry Descent and Landing GN&C engineer for the Mars Science Laboratory. His research interests include robust control, estimation theory, system identification and model validation. He received the NASA Exceptional Achievement Medal for contributions to the Shuttle Radar Topography Mission. He is a senior member of the IEEE and AIAA.*

Dr. Chia-Yen Peng *is a technical lead in the Spacecraft Structures and Dynamics Group of Jet Propulsion Laboratory. His responsibilities are in the areas of Loads Analyses and Dynamic Simulations for JPL flight projects. He has worked in the aerospace and computer industries for more than 20 years. Dr. Peng received his M.S. and Ph.D. degrees from California Institute of Technology, Pasadena, California, USA.*

Dr. Shyh-shiuh Mike Lih *received his PhD in Mechanical and Aerospace Engineering from UCLA in 1992. His research includes nondestructive evaluations, smart and composite materials, elastic wave propagation, adaptive optics, electro-mechanical devices and advanced actuators. Dr. Lih has over 50 technical publications and holds patents in the fields of piezoelectric pump, NDE ultrasonic applications, and precision mechanical devices. Dr. Lih is now working on the ADAMS simulations for the rover mobility deployment and landing dynamics for the Mars Science Laboratory project at JPL.*

Steven Sell *is the Group Supervisor for the Entry Descent and Landing Systems and Advanced Technologies Group and is the Powered Flight EDL Systems Engineer for MSL. Prior to joining JPL in 2006, Steve served as the Special Projects Group lead for Payload Systems, Inc. where he was responsible for several university payloads for ISS and Shuttle. Steve holds a B.S. from Florida Institute of Technology and an M.S. from the University of Maryland.*

Miguel San Martin received *his B.S.Degree in Electrical Engineering with honors from SyracuseUniversity in 1982, and his M.S. Degree in Aeronautics and Astronautics Engineering from the Massachusetts Institute of Technology in 1985. He joined the Jet Propulsion Laboratory in 1985. His area of interest is the analysis, design, implementation, and testing of spacecraft articulation and attitude control systems, with an emphasis on applied estimation theory. He has participated in several flight projects and has been a member of numerous flight anomaly tiger teams. He was the designer of the Cassini spacecraft Attitude Estimator, the TOPEX/Poseidon Altimeter pointing calibration ground software, and was the technical lead for the Mars Pathfinder Attitude Control Subsystem flight software. More recently he was the Guidance and Control System Manager and Chief Engineer for the Mars Exploration Rover Project, which successfully landed the Spirit and Opportunity rovers in January 2005. He is currently the Guidance Navigation and Control System Chief Engineer for the Mars Science Laboratory project. He has received two NASA Exceptional Achievement Medals for contributions to the Mars Pathfinder and the Mars Exploration Rovers Missions.*

Dr. Gurkirpal Singh *is a Principal Engineer in the*

Guidance and Control Analysis Group at the Jet Propulsion Laboratory in Pasadena, California. He received his M.S. and Ph.D. in Aerospace Engineering from The University of Michigan. He has been with the Jet Propulsion Laboratory since 1989, where he has developed Guidance and Control algorithms for several flight projects including Galileo, Cassini, Mars Pathfinder, Deep-Space 1, Mars Exploration Rovers, and Mars Science Laboratory missions. He is currently developing terminal descent guidance and control algorithms for the Mars Science Laboratory Project.