Using Inertial Measurements for the Reconstruction of 6-DOF Entry, Descent, and Landing Trajectory and Attitude Profiles

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Extended Abstract

In 2003, humans on the planet Earth will launch two spacecraft towards the planet Mars. The Mars Exploration Rovers (MER-A and MER-B) are scheduled to land on the surface of the Mars weeks apart in early 2004. They will travel farther in a day than the Mars Pathfinder (MPF) Sojourner rover did in its lifetime. The MER missions have heritage in the MPF mission in that each will enter the atmosphere on a ballistic trajectory, deploy a parachute while traveling at supersonic speeds, and use airbags to survive the impact on the surface of the planet. Understanding MER-A's entry, descent, and landing (EDL) is critical to the success of its twin's EDL twenty-one days later.

Currently, tests of the MER landers' airbag systems are underway, and data collected during these tests are being used at NASA's Jet Propulsion Laboratory (JPL) to develop and test a prototype extended Kalman filter (EKF) for EDL.

The airbag tests are being conducted at the Space Power Facility (SPF) vacuum chamber at NASA's Glenn Research Center Plum Brook Station in Sandusky, Ohio. During these tests, the SPF is evacuated to simulate the approximately five-torr atmosphere near the Martian surface. A mock-up of the MER lander body is suspended above a rocky, inclined plane and, with airbags inflated, it is tethered to the ground with a stretched bungee cable. To initiate a test, the line holding the lander is cut and the bungee cable acts with gravity to accelerate the lander towards the plane. The resulting impact simulates an extreme impact scenario on the surface of Mars. From this test, the material strength of the airbags can be evaluated and the loads from the shock of impact can be determined.

The lander body is outfitted with a suite of instruments, some of which are used in automotive crash tests. Accelerometers and gyroscopes measure translational and rotational data, which can be used in an EKF to reconstruct the trajectory and attitude history of the lander during the drop test. No direct measurements of distance traveled by the test body, or its speed or attitude, are available.

One testing objective, which motivates the work discussed here, is to determine the "maximum stroke" distance during the impact event. Maximum stroke is the shortest distance between the airbag surface and the

tetrahedron-shaped lander body. A full stroke event would occur if the airbags compressed to the point where the rigid body of the lander would no longer be protected from hitting the surface, potentially damaging the lander body and the instrumentation contained within. The maximum stroke distance is a function of airbag test parameters, especially airbag pressure and impact velocity, both of which can be controlled in order to avoid a full-stroke event. The maximum stroke distance is not easily measured, however, because the airbags themselves fully obscure viewing of the lander with a camera or laser device, for example. Hence, an indirect method of sensing maximum stroke distance based on accelerometer and gyroscope data, in addition to geometric and dynamical constraints and other sensed information "as available," was sought.

The authors have developed a suite of software in the Java (TM) Programming Language known as REDLand (for Reconstruction of Entry, Descent and Landing), which uses the accelerometer and gyroscope rate data, as well as other data as available, as measurements in the filter. This represents a departure from the standard practice of simply integrating the noisy acceleration and body rate measurements to determine distance traveled, speed, and attitude. In this case, the accelerations due to the bungee and gravity are modeled in the EKF equations of motion, and the accelerometer and gyroscope measurements are used to adjust dynamics model parameters.

Results from the first version of REDLand are promising. The following figure is taken from a three-dimensional "movie" based on the REDLand output position and attitude solutions. The frame-by-frame motion shows the trajectory and attitude history of the lander body during the drop. After the lander body bounces off the ramp, it is halted by a net and then bounces back to the ramp and settles on the ground. The figure also shows the "roll line" of the center of gravity. The roll line, indicated with red asterisks, shows how the center of gravity would travel if the collision on the ramp was inelastic. The straight-line distance between the center of gravity and the roll line is one measure of stroke distance.

Both MER landers will carry an inertial measurement package, consisting of accelerometers and gyroscopes. These instruments will take data during the EDL and the data will be transmitted or relayed back to controllers on Earth. Using these data and atmospheric entry dynamics models, an extended Kalman filter (EKF) can be constructed to determine the EDL profile of the lander. Since MER-B's arrival on the surface is only twenty-

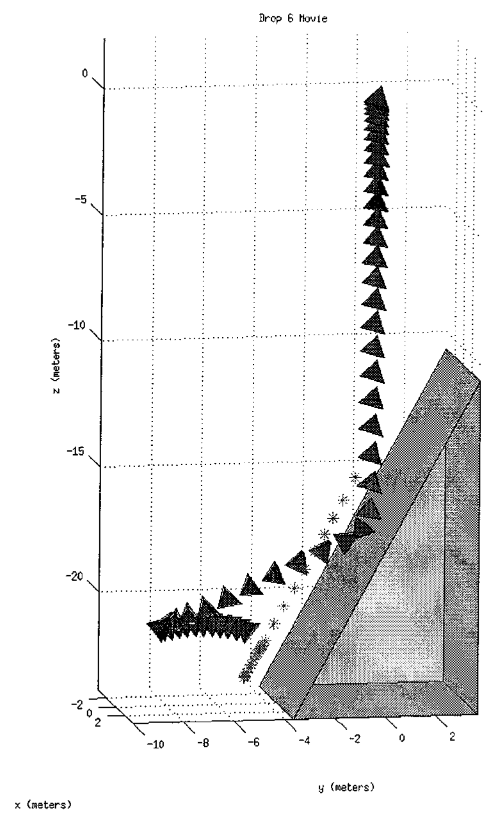

Figure 1: Frame-by-frame image from a 3-D movie of a MER lander drop test. This movie was played at twenty frames per second.

one days after MER-A's, an EKF must be in place to handle the data if the trajectory of MER-A is to reveal anything of use to the EDL of MER-B. It is noted that experience gained with REDLand and the airbag test data are providing significant experience to enable better high-fidelity post-event reconstruction of the MER-A and MER-B EDL 6-degree-of-freedom trajectories.

Condensed Abstract

A method was sought for estimating the "stroke" distance between a Mars Exploration Rover (MER) test lander (protected by airbags) and a surface during impact. The authors at JPL have developed a suite of software known as REDLand (for Reconstruction of Entry, Descent and Landing) to accomplish this. REDLand uses data from accelerometers and gyroscopes on board the lander test body as measurements in an extended Kalman filter, in addition to geometric and dynamical constraints, and other data, where available. This paper is a discussion of the formulation of the REDLand filter algorithms and presents results from actual MER airbag-and-lander impact tests made in 2001.