



POD Model Reconstruction for Gray-Box Fault Detection

Low-order models that give robust, close approximations can be constructed.

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Proper orthogonal decomposition (POD) is the mathematical basis of a method of constructing low-order mathematical models for the "gray-box" fault-detection algorithm that is a component of a diagnostic system known as beacon-based exception analysis for multimissions (BEAM). POD has been successfully applied in reducing computational complexity by generating simple models that can be used for control and simulation for complex systems such as fluid flows. In the present application to BEAM, POD brings the same benefits to automated diagnosis.

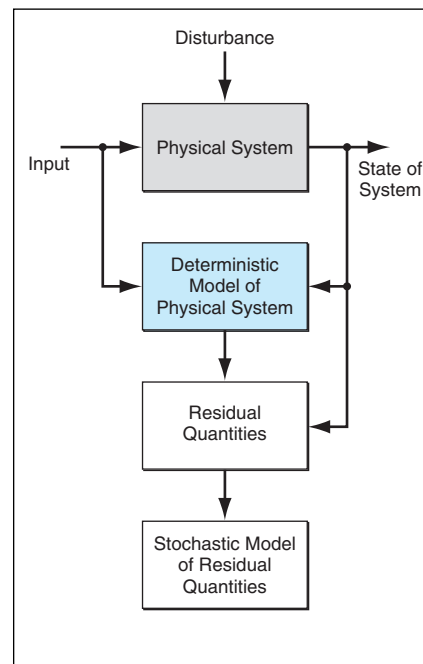
Selected aspects of BEAM have been described in numerous prior *NASA Tech Briefs* articles. To summarize briefly: BEAM is a method of real-time or off-line, automated diagnosis of a complex dynamic system. The gray-box approach makes it possible to utilize incomplete or approximate knowledge of the dynamics of the system that one seeks to diagnose. In the gray-box approach, a deterministic model of the system is used to filter a time series of system sensor data to remove the deterministic components of the time series from further examination. What is left after the filtering operation is a time series of residual quantities that represent the unknown (or at least unmodeled) aspects of the behavior of the system. Stochastic modeling techniques are then applied to the residual time series (see figure). The procedure for detecting abnormal behavior of the system then becomes one of looking for statistical differences between the resid-

ual time series and the predictions of the stochastic model.

The need for POD or another method to construct simple approximate models for use in the gray-box approach arises because in a typical case, a detailed deterministic model of the system to be diagnosed may not exist, or, if it exists, may be too complex for real-time computations. One or more simplified deterministic model(s) that describe the system to acceptable degrees of accuracy are therefore desired. The simplified deterministic models can be created from computational simulations of the system and/or empirical data on the operation of the system.

POD modeling requires two steps. The first step is to extract the "mode shapes" or basis functions from experimental data or detailed simulations of the system. This step can involve principal-component analysis, i.e., singular-value decomposition. In the second step, the basis functions are projected to a low-order or few-dimensional approximate dynamical model by use of the Galerkin method.

The present POD-based method has been verified by creating a low-order dynamical model of a system represented by Burgers' equation, which is a partial differential equation that describes a diverse set of wave phenomena such as flowing gases, flood waters, glaciers, and automobile traffic. It was demonstrated that a low-order (7 POD modes) dynamical model that exhibited high fidelity could be created, even in the presence of



In the **Gray-Box Method**, the present POD-based method is used to construct a low-order deterministic model that closely approximates the behavior of the physical system.

noise. In the absence of noise, the model was found to simulate the system with 1 percent error. In the presence of 10-percent uncorrelated Gaussian noise, the model was found to simulate the system with 5 percent error.

This work was done by Han Park and Michail Zak of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov. NPO-30871.

System for Estimating Horizontal Velocity During Descent

Estimates are generated from images and other sensor outputs.

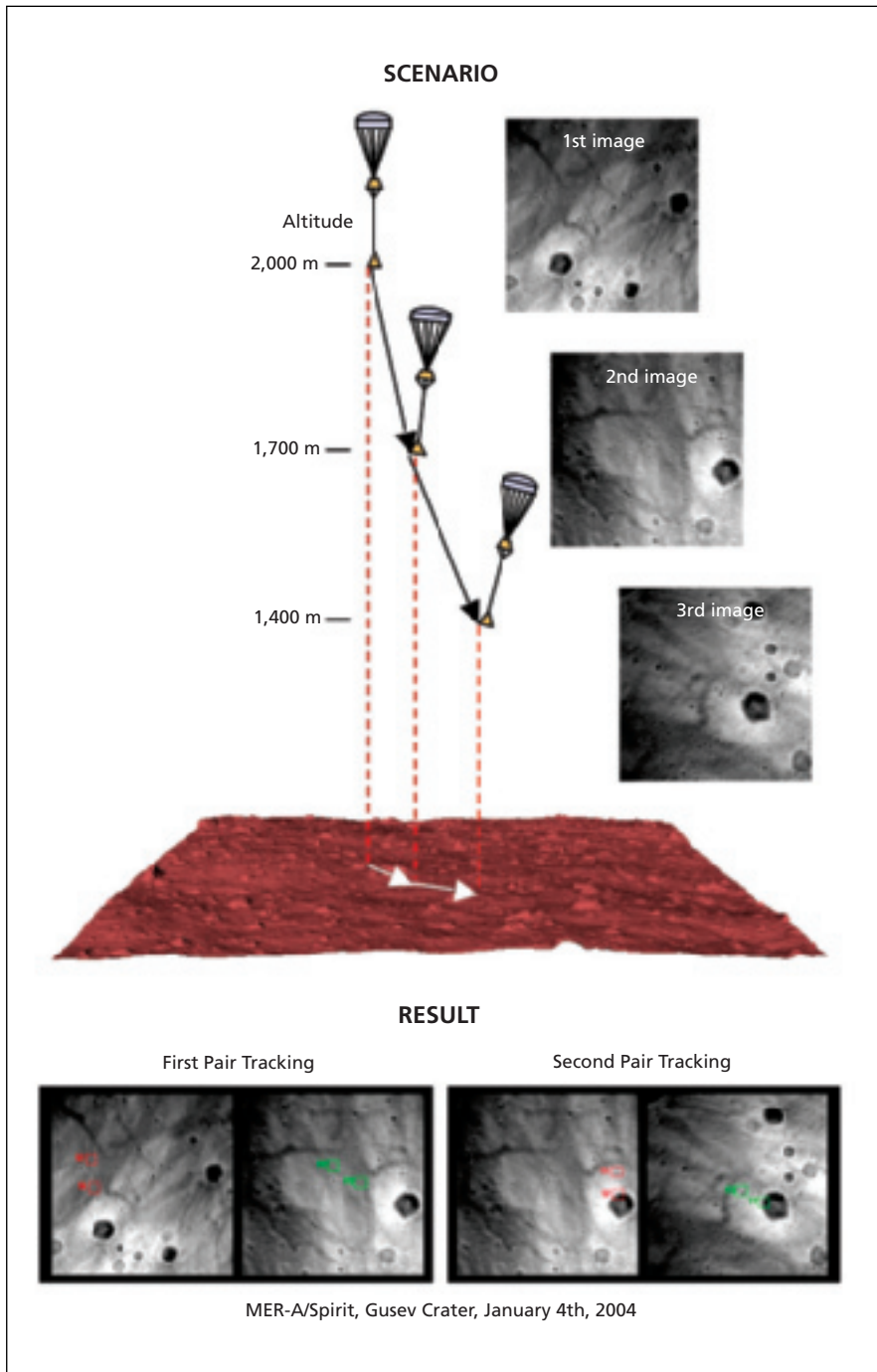
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The descent image motion estimation system (DIMES) is a system of hardware and software, designed for original use in estimating the horizontal velocity of a spacecraft descending toward a landing

on Mars. The estimated horizontal velocity is used in generating rocket-firing commands to reduce the horizontal velocity as part of an overall control scheme to minimize the landing impact.

DIMES can also be used for estimating the horizontal velocity of a remotely controlled or autonomous aircraft for purposes of navigation and control.

DIMES was developed by the Mars Ex-



The **DICES Algorithm** fuses images of terrain below with IMU data and radar-altimeter readings to estimate horizontal velocity.

ploration Rover (MER) Project and was used successfully by the MER Entry Descent and Landing (EDL) system during both landings. In the original spacecraft application, when the need to determine horizontal velocity was discovered,

it was too late to install traditional horizontal-velocity-measuring radar in the spacecraft. DICES was conceived as a means of estimating the horizontal velocity by augmenting data acquired by sensors already installed in the space-

craft with data from an easy to accommodate descent imager.

The DICES sensors include a descent imager (an electronic camera that acquires images of the approaching terrain), a radar altimeter, and an inertial measurement unit (IMU). The DICES flight software implements an algorithm for combining measurement data from the aforementioned sensors to estimate horizontal velocity.

The input required by the DICES software includes three descent images. For each descent image, the software also requires the following elements of the state of the landing spacecraft at times when the images were acquired: the attitude of the spacecraft relative to the surface, the horizontal velocity estimated by the IMU, and the altitude. Using this state information, the software warps each image to the ground plane, then computes horizontal displacements between successive images by use of image correlation, applied to two locations in each of the first and second images and two locations in each of the second and third images. This process yields four image-based estimates of horizontal velocity. These estimates are compared to each other for consistency. As a further consistency check, accelerations are computed from differences of these velocities and these accelerations are compared with accelerations as measured by the IMU.

The results of the consistency checks are used, along with image-correlation metrics to decide whether the estimate of horizontal velocity is correct. In the original application, if the estimate of velocity is determined to be correct, it is sent to the rocket-firing subsystem; if the estimate of horizontal velocity is found to be incorrect, then the rocket-firing subsystem is commanded to proceed without a DICES velocity estimate.

This work was done by Andrew Johnson, Yang Cheng, Reg Willson, Jay Goguen, Alejandro San Martin, Chris Leger, and Larry Matthies of Caltech for NASA's Jet Propulsion Laboratory.

The software used in this innovation is available for commercial licensing. Please contact Karina Edmonds of the California Institute of Technology at (626) 395-2322. Refer to NPO-40920.