

## Prognostics Methodology for Complex Systems

Automatic method to detect and react to complex degradation and incipient faults.

NASA's Jet Propulsion Laboratory, Pasadena, California

An automatic method to schedule maintenance and repair of complex systems is produced based on a computational structure called the Informed Maintenance Grid (IMG). This method provides solutions to the two fundamental problems in autonomic logistics: (1) unambiguous detection of deterioration or impending loss of function and (2) determination of the time remaining to perform maintenance or other corrective action based upon information from the system. The IMG provides a health determination over the medium-to-long-term operation of the system, from one or more days to years of study. The IMG is especially applicable to spacecraft and both piloted and autonomous aircraft, or industrial control processes.

Condition-Based Maintenance (CBM) has become popular for complex systems due to its cost and reliability advantages

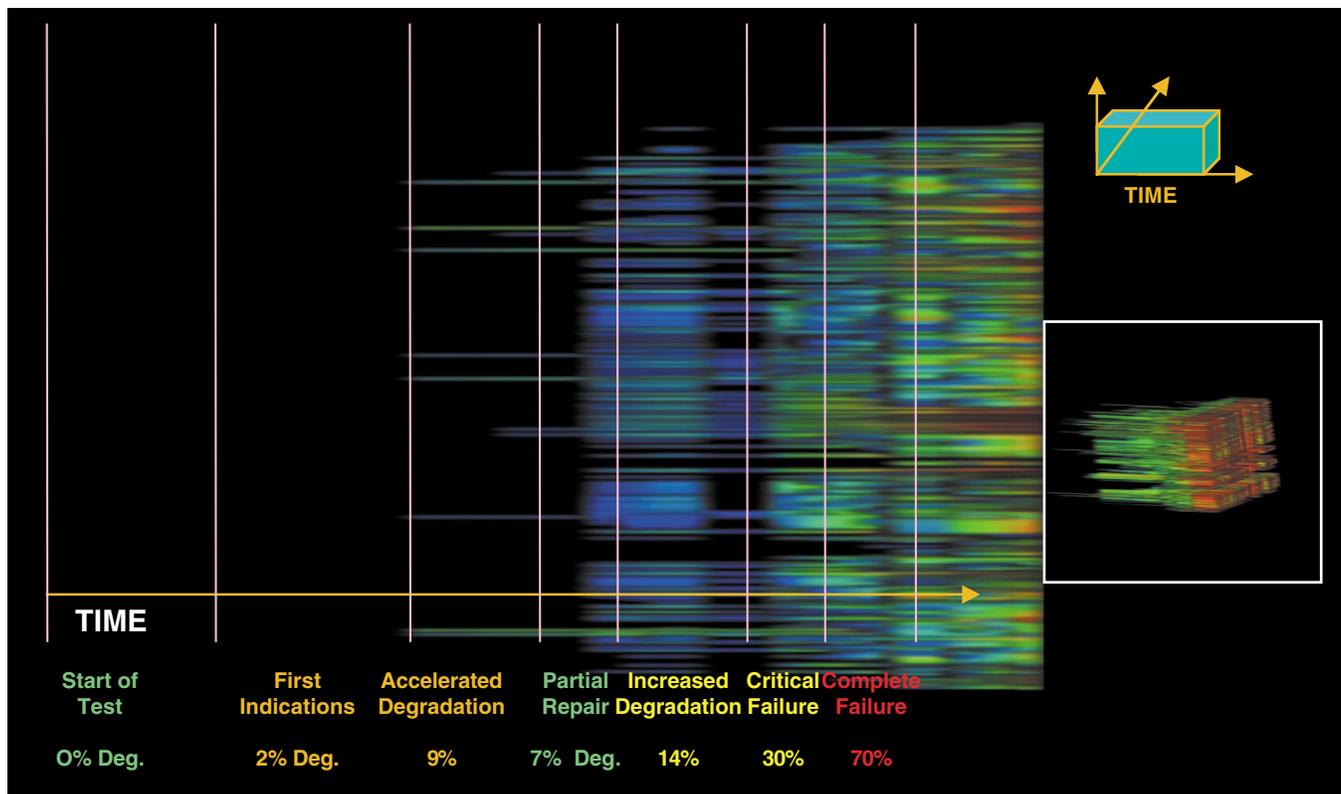
over traditional scheduled maintenance programs. However, CBM is frequently difficult to apply owing to system complexity and the highly stochastic nature of system use and environmental effects. A scalable solution capable of providing a substantial look-ahead capability is required. The IMG method was developed to satisfy this need.

The IMG is based upon a three-dimensional projection, relating successive computations of cross-signal features. The two short axes represent different sensed parameters from the system (typically performance parameters such as temperatures, pressures, etc.), with each pixel representing the coherency between measurements. The third axis represents time, displaying the progression of abnormalities as the system is used.

The IMG is a component of the larger BEAM system ("Beacon-Based Exception Analysis for Multimissions" [NPO-

20827], *NASA Tech Briefs*, Vol. 26, No. 9 (September 2002), page 32). The coherence calculation used in the IMG is derived from the Information State Estimator (ISE) component of BEAM. The ISE computes relationships between large and diverse classes of signals and compares them to an internal statistical model for the purpose of anomaly detection. This notion is extended by the IMG, which combines and normalizes numerous results while providing an operational context.

Graphically, the IMG is represented (see figure) as a color-coded temporal succession of two-dimensional plots, each representing the coherence divergence from the statistical model. From this graphical object, one can easily discern the true functional operability of the system, detect the presence and impact of faults or persistent degradation,



In This Example, the IMG provides a day-to-day assessment of a failing aerospace hydraulic system. Time progresses from left to right on a scale of individual flights. Brighter colors indicate degradation severity, while the density and thickness of lines demonstrates the spread of degradation effects throughout the system. Warning and Failure thresholds as established by existing fault protection are superposed to show the system's sensitivity. Inset: Perspective view of the IMG graphical object.

and assess the effectiveness of repairs or configurational changes. Maintenance recommendations can be derived automatically from this object, providing a continuous evaluation of the need for condition-based maintenance.

The following list outlines the necessary construction steps to apply the IMG:

1. Provide examples of nominal data and partial physics models where possible for purposes of ISE training,
2. Obtain example data of degraded or anomalous performance for training purposes,
3. Compose a listing of preferred maintenance actions to correct faults in

particular components, and

4. Provide a mapping between sensed or manually supplied status variables and system operating mode.

Acceptable operating limits must be established in order to tune prognostic performance for cost effectiveness. These limits must either be set by system experts or “learned” as degradations appear in practice. Like the ISE itself, the IMG is easily upgraded once additional information is available. Limits may also be set using the same thresholds chosen for fault protection.

*This work was done by Sandeep Gulati and Ryan Mackey of Caltech for NASA’s Jet*

**Propulsion Laboratory.** *Further information is contained in a TSP (see page 1).*

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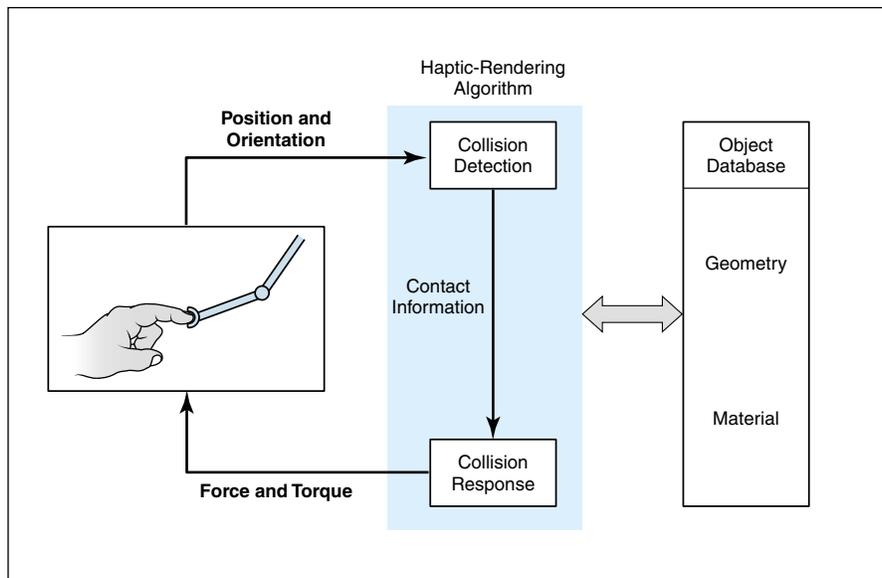
## ➤ Algorithms for Haptic Rendering of 3D Objects

**Tactful displays provide the sensations of touching computationally simulated objects.**

*NASA’s Jet Propulsion Laboratory, Pasadena, California*

Algorithms have been developed to provide haptic rendering of three-dimensional (3D) objects in virtual (that is, computationally simulated) environments. The goal of haptic rendering is to generate tactual displays of the shapes, hardnesses, surface textures, and frictional properties of 3D objects in real time. Haptic rendering is a major element of the emerging field of computer haptics, which invites comparison with computer graphics. We have already seen various applications of computer haptics in the areas of medicine (surgical simulation, telemedicine, haptic user interfaces for blind people, and rehabilitation of patients with neurological disorders), entertainment (3D painting, character animation, morphing, and sculpting), mechanical design (path planning and assembly sequencing), and scientific visualization (geophysical data analysis and molecular manipulation).

Haptic-rendering algorithms enable users to touch, feel, and manipulate 3D objects in virtual environments through force-feedback devices, also known as haptic interfaces. Typically, a haptic-rendering algorithm comprises a collision-detection part and a collision-response part. As the user manipulates the force-feedback device — for example, a fingertip probe as in the figure — the current or recent position and orientation of the probe are acquired and the collision-detection algorithm detects collisions between the fingertip and virtual objects in the vicinity of the fingertip. If a collision is detected, then the collision-response



**A Force-Feedback Device** (in this case, an actuated fingertip probe) commanded by a haptic-rendering algorithm generates a tactual representation of contact between a fingertip and a computationally simulated object.

algorithm computes the forces of interaction between the fingertip and the virtual object(s) and commands the force-feedback device to generate the tactual representation of the object(s). The friction of finger/virtual object contact, the texture of the object, and hardness of the object can be simulated through appropriate spatial and temporal perturbations of the force generated by the force-feedback device. The hardness information for deformable virtual objects can be embodied in geometry- and physics-based mathematical models. So that virtual objects will not feel unnaturally soft, the update rate

of the haptic feedback loop thus described should be at least 1 kHz.

Some elements of the collision-detection algorithms used in computer graphics can be used in computer haptics. For example, haptic-rendering algorithms can easily take advantage of space-partitioning, local-searching, and hierarchical-data-structure techniques of computer graphics to reduce the amount of computation time needed to detect collisions. However, mere detection of collisions as in computer graphics is not enough because how a collision occurs and how it evolves over time are factors that must be