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).*

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

Intellectual Property group
JPL
Mail Stop 202-233
4800 Oak Grove Drive
Pasadena, CA 91109
(818) 354-2240

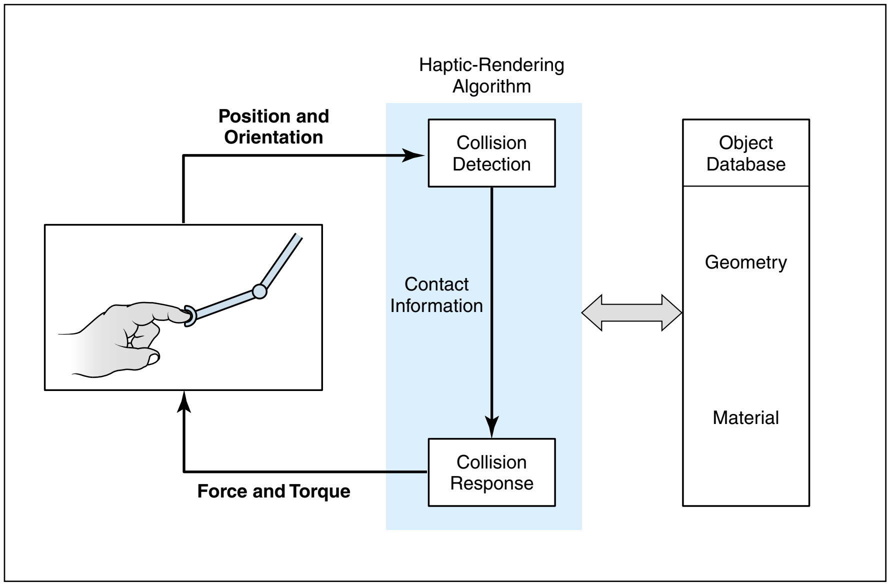
Refer to NPO-20831, volume and number of this NASA Tech Briefs *issue, and the page number.*

Algorithms for Haptic Rendering of 3D Objects

Tactual 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).



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.

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 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 taken into account to compute interaction forces accurately. Going beyond computer-graphics collision-detection algorithms, it is necessary to develop algorithms according to a client-server model to provide for synchronization of visual and haptic displays in order to make update rates acceptably high. For example, by use of multithreading techniques, one can calculate the contact forces at rate of 1 kHz in one thread while updating visual images at 30 Hz in another thread.

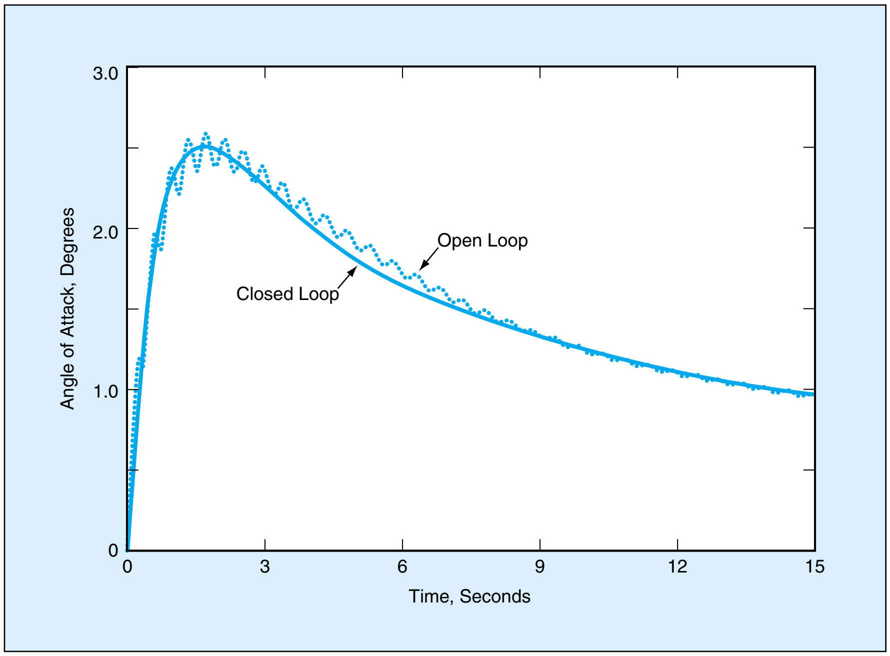
This work was done by Cagatay Basdogan of Caltech, Chih-Hao Ho of Cambridge Research Associates, and Mandayam Srinavasan of MIT for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*

This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. Refer to NPO-21191.

Modeling and Control of Aerothermoelastic Effects

This method makes it possible to design controls to compensate for aerothermoelasticity.

Dryden Flight Research Center, Edwards, California



The **Responses of a Hypersonic Vehicle** to elevator commands were computationally simulated for an open-loop case and for a case of closed-loop control designed according to the present method.

Aerothermoelasticity comprises those aspects of the dynamics of an aircraft that are caused by flexibility and heating during flight. The concept of aerothermoelasticity is particularly important for hypersonic vehicles that operate at extremely high dynamic pressures. The design requirements for such vehicles often introduce long and thin fuselages subject to elastic bending in low-frequency vibrational modes. Furthermore, surface heating can significantly change the stiffness characteristics of these modes. These aerothermoelastic effects must be considered in the synthesis and analysis of control systems.

A method to include the effects of aerothermoelasticity in designing controls has been developed. Heretofore, large, finite-element mathematical models have typically been used to compute the aerothermoelastic effects; however, these models are not suitable for control engineering. The present method makes it possible to incorporate the results of computational analysis into the small linear models that are typically used in designing controls.

In this method, the procedure to include aerothermoelastic effects in linear models begins with noting the relationship between an effect and a temperature. Essentially, computational studies have indicated the changes in the natural frequencies (that is, frequencies of resonance) and damping parameters of structural vibrational modes that occur at various flight conditions and associated temperatures. In the present method, one simply describes the natural frequency and damping parameter of a linear model as functions of temperature that match the variations observed in the computational studies.

The linear models with associated temperature dependence are described by use of a formulation known as linear parameter-varying systems. This formulation enables the efficient description of systems that contain elements that are functions of such time-varying parameters as temperature. Furthermore, there is a set of previously developed theoretical concepts and associated computer programs that enable the design of control systems that incorporate scheduled-gain compensation for dependences on time-varying parameters.

A generic representation of a hypersonic vehicle has been used to demonstrate this method. A range of natural frequencies and damping parameters for the structural dynamics of the vehicle, based on previous computational studies, was assumed. A linear model including representations of the aerothermoelastic effects was formulated by describing the parameters of the structural dynamics as functions of temperature. A flight controller to actively damp the bending-mode response of this model was designed. The figure shows the open-loop and controlled (closed-loop) responses to an elevator command during a simulated flight with a fast variation of temperature. The open-loop response includes an oscillatory component from the bending mode, whereas the closed-loop response shows that the controller is able to continuously damp this elastic effect despite the time-varying temperature.

This work was done by Rick Lind of **Dryden Flight Research Center**. *For further information, contact the Dryden Commercial Technology Office at (661) 276-3689.*
DRC-01-21