force to enforce the closure constraints; and (c) correcting the unconstrained accelerations with correction accelerations resulting from the correction forces.

This constraint-embedding technique shows how to use direct embedding to eliminate local closure-loops in the system and effectively convert the system back to a tree-topology system. At this point, standard tree-topology techniques can be brought to bear on the problem. The approach uses a spatial operator algebra approach to formulating the equations of motion. The operators are block-partitioned around the local body subgroups to convert them into aggregate bodies. Mass matrix operator factorization and inversion techniques are applied to the reformulated tree-topology system. Thus in essence, the new technique allows conversion of a system with closure-constraints into an equivalent tree-topology system, and thus allows one to take advantage of the host of techniques available to the latter class of systems.

This technology is highly suitable for the class of multibody systems where the closure-constraints are local, i.e., where they are confined to small groupings of bodies within the system. Important examples of such local closure-constraints are constraints associated with four-bar linkages, geared motors, differential suspensions, etc. One can eliminate these closure-constraints and convert the system into a tree-topology system by embedding the constraints directly into the system dynamics and effectively replacing the body groupings with virtual aggregate bodies. Once eliminated, one can apply the well-known results and algorithms for tree-topology systems to solve the dynamics of such closed-chain system.

This work was done by Abhinandan Jain and Rudranarayan Mukherjee of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov. NPO-46950

Improved Systematic Pointing Error Model for the DSN Antennas

NASA's Jet Propulsion Laboratory, Pasadena, California

New pointing models have been developed for large reflector antennas whose construction is founded on elevation over azimuth mount. At JPL, the new models were applied to the Deep Space Network (DSN) 34-meter antenna's subnet for corrections of their systematic pointing errors; it achieved significant improvement in performance at Ka-band (32-GHz) and X-band (8.4-GHz). The new models provide pointing improvements relative to the traditional models by a factor of two to three, which translate to approximately 3-dB performance improvement at Ka-band. For radio science experiments where blind pointing performance is critical, the new innovation provides a new enabling technology.

The model extends the traditional physical models with higher-order mathematical terms, thereby increasing the resolution of the model for a better fit to the underlying systematic imperfections that are the cause of antenna pointing errors. The philosophy of the traditional model was that all mathematical terms in the model must be traced to a physical phenomenon causing antenna pointing errors. The traditional physical terms are: antenna axis tilts, gravitational flexure, azimuth collimation, azimuth encoder fixed offset, azimuth and elevation skew, elevation encoder fixed offset, residual refraction, azimuth encoder scale error, and antenna pointing de-rotation terms for beam waveguide (BWG) antennas.

Besides the addition of spherical harmonics terms, the new models differ from the traditional ones in that the coefficients for the cross-elevation and elevation corrections are completely independent and may be different, while in the traditional model, some of the terms are identical. In addition, the new software allows for all-sky or mission-specific model development, and can utilize the previously used model as an *a priori* estimate for the development of the updated models.

This work was done by David J. Rochblatt, Philip M. Withington, and Paul H. Richter of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov. NPO-46852

Observability and Estimation of Distributed Space Systems via Local Information-Exchange Networks

An agreement protocol is used as a mechanism for observing formation states from local measurements.

NASA's Jet Propulsion Laboratory, Pasadena, California

Spacecraft formation flying involves the coordination of states among multiple spacecraft through relative sensing, inter-spacecraft communication, and control. Most existing formation-flying estimation algorithms can only be supported via highly centralized, all-to-all, static relative sensing. New algorithms are proposed that are scalable, modular, and robust to variations in the topology and link characteristics of the formation exchange network. These distributed algorithms rely on a local information exchange network, relaxing the assumptions on existing algorithms.

Distributed space systems rely on a signal transmission network among multiple spacecraft for their operation. Control and coordination among multiple spacecraft in a formation is facilitated via a network of relative sensing and inter-spacecraft communications. Guidance, navigation, and control rely on the sensing network. This network becomes more complex the more spacecraft are added, or as mission requirements become more complex.

The observability of a formation state was observed by a set of local observations from a particular node in the formation. Formation observability can be parameterized in terms of the matrices appearing in the formation dynamics and observation matrices. An agreement protocol was used as a mechanism for observing formation states from local measurements. An agreement protocol is essentially an unforced dynamic system whose trajectory is governed by the interconnection geometry and initial condition of each node, with a goal of reaching a common value of interest. The observability of the interconnected system depends on the geometry of the network, as well as the position of the observer relative to the topology.

For the first time, critical GN&C (guidance, navigation, and control estimation) subsystems are synthesized by bringing the contribution of the spacecraft information-exchange network to the forefront of algorithmic analysis and design. The result is a formation estimation algorithm that is modular and robust to variations in the topology and link properties of the underlying formation network.

This work was done by Nanaz Fathpour and Fred Y. Hadaegh of Caltech and Mehran Mesbahi and Amirreza Rahmani of the University of Washington for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov. NPO-46812

More-Accurate Model of Flows in Rocket Injectors

Marshall Space Flight Center, Alabama

An improved computational model for simulating flows in liquid-propellant injectors in rocket engines has been developed. Models like this one are needed for predicting fluxes of heat in, and performances of, the engines. An important part of predicting performance is predicting fluctuations of temperature, fluctuations of concentrations of chemical species, and effects of turbulence on diffusion of heat and chemical species. Customarily, diffusion effects are represented by parameters known in the art as the Prandtl and Schmidt numbers. Prior formulations include *ad hoc* assumptions of constant values of these parameters, but these assumptions and, hence, the formulations, are inaccurate for complex flows.

In the improved model, these parameters are neither constant nor specified in advance: instead, they are variables obtained as part of the solution. Consequently, this model represents the effects of turbulence on diffusion of heat and chemical species more accurately than prior formulations do, and may enable more-accurate prediction of mixing and flows of heat in rocket-engine combustion chambers. The model has been implemented within CRUNCH CFD, a proprietary computational fluid dynamics (CFD) computer program, and has been tested within that program. The model could also be implemented within other CFD programs.

This work was done by Ashvin Hosangadi, James Chenoweth, Kevin Brinckman, and Sanford Dash of Combustion Research and Flow Technology, Inc. for Marshall Space Flight Center. Inquiries concerning rights for the commercial use of this invention should be addressed to Sammy Nabors, MSFC Commercialization Assistance Lead, at sammy.a.nabors@nasa.gov. Refer to MFS-32533-1.

In-Orbit Instrument-Pointing Calibration Using the Moon as a Target

NASA's Jet Propulsion Laboratory, Pasadena, California

A method was developed for in-orbit measurement of the relative pointing of spectrometer channels, and the relationship between the spectrometer channels and the spacecraft coordinate system. In this innovation, individual scans of the Moon, from the three channels, were used to determine the position of the center of the Moon, with respect to channel-specific coordinates. Comparing the coordinates of the center of the Moon, obtained from individual channels, yields the relative pointing between the channels. Comparing the coordinates of the center of the Moon in one of the channels with the Moon ephemerides and with the spacecraft coordinate measurement, using the onboard star tracker, yields the relative orientation of the channel optical axes with respect to the spacecraft coordinates.

This work was done by Alex Abramovici and Harold R. Pollock of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov. NPO-47526