hammer. Otherwise, negative work is performed and the drill experiences a loss of performance (i.e., reduced impact energy) and an increase in Joule heating (i.e., reduction in energy efficiency). This observation has motivated many drilling products to incorporate the standard bang-bang control approach for driving their percussive drills. However, the bang-bang control approach is significantly less efficient than the optimal energy-efficient control approach solved herein.

To obtain this solution, the standard tools of classical optimal control theory were applied. It is worth noting that these tools inherently require the solution of a two-point boundary value problem (TPBVP), i.e., a system of differential equations where half the equations have unknown boundary conditions. Typically, the TPBVP is impossible to solve analytically for high-dimensional dynamic systems. However, for the case of the spring-loaded vibro-impactor, this approach yields the exact optimal control solution as the sum of four analytic functions whose coefficients are determined using a simple, easy-to-implement algorithm. Once the optimal control waveform is determined, it can be used optimally in the context of both open-loop and closed-loop control modes (using standard real-time control hardware).

Future NASA *in situ* exploration missions increasingly require extensive drilling and coring procedures that stress the demand for more energy efficient methods to accomplish these tasks. For example, when rover-based autonomous drills are controlled non-optimally for long periods of time, the energy loss can grow at a rate that cannot be sustained by the rover's internal energy supply. Motorized percussive units can be especially energy-draining (when controlled non-optimally), making this technology especially relevant to this type of future NASA work.

This work was done by Jack B. Aldrich and Avi B. Okon of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-48467

Low-Cost Telemetry System for Small/Micro Satellites

Marshall Space Flight Center, Alabama

A Software Defined Radio (SDR) concept uses a minimum amount of analog/radio frequency components to up/downconvert the RF signal to/from a digital format. Once in the digital domain, all other processing (filtering, modulation, demodulation, etc.) is done in software. The project will leverage existing designs and enhance capabilities in the commercial sector to provide a path to a radiation-hardened SDR transponder.

The SDR transponder would incorporate baseline technologies dealing with improved Forward Error Correcting (FEC) codes to be deployed to all Near Earth Network (NEN) ground stations. By incorporating this FEC, at least a tenfold increase in data throughput can be achieved.

A family of transponder products can be implemented using common platform architecture, allowing new products to be more quickly introduced into the market. Software can be reused across products, reducing software/hardware costs dramatically. New features and capabilities, such as encoding and decoding algorithms, filters, and bit synchronizers, can be added to the existing infrastructure without requiring major new capital expenditures, allowing implementation of advanced features in the communication systems.

As new telecommunication technologies emerge, incorporating them into the SDR fabric will be easily accomplished with little or no requirements for new hardware. There are no preferred flight platforms for the SDR technology, so it can be used on any type of orbital or sub-orbital platform, all within a fully radiation hardened design.

This work was done by William Sims and Kosta Varnavas of Marshall Space Flight Center.

This invention is owned by NASA, and a patent application has been filed. For further information, contact Sammy Nabors, MSFC Commercialization Assistance Lead, at sammy.a.nabors@nasa.gov. Refer to MFS-32871-1.

Operator Interface and Control Software for the Reconfigurable Surface System Tri-ATHLETE

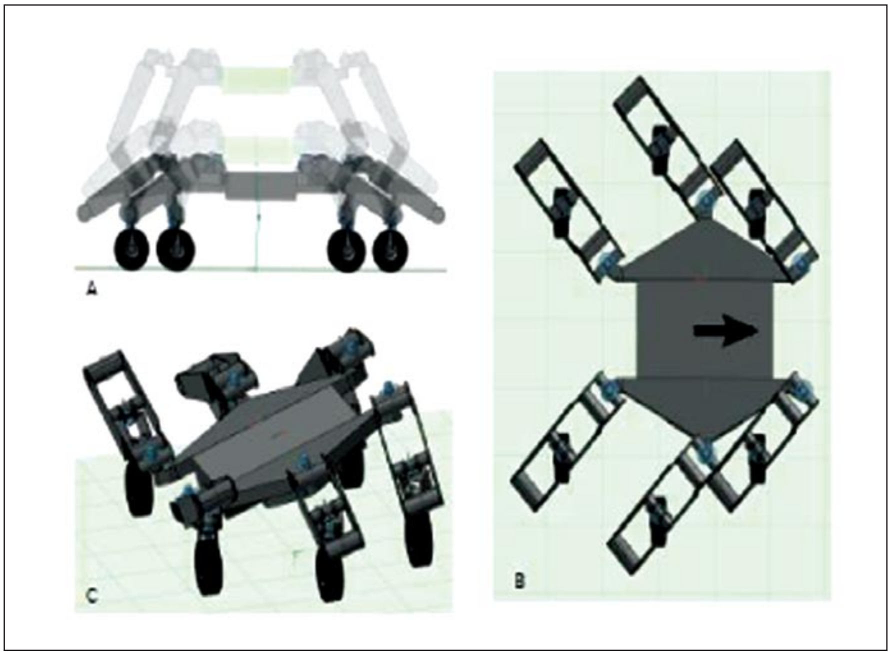
The capability of future exploration missions may be greatly extended for a small additional cost.

NASA's Jet Propulsion Laboratory, Pasadena, California

Graphical operator interface methods have been developed for modular, reconfigurable articulated surface systems in general, and a specific instantiation thereof for JPL's Tri-ATHLETE. The All-Terrain Hex-Limbed Extra-Terrestrial Explorer Robot (ATHLETE) has six limbs with six kinematic degrees of freedom each (see figure).

The core advancement of this work was the development of a novel set of algorithms for dynamically maintaining a reduced coordinate model of any connected assembly of robot modules. The kinematics of individual modules are first modeled using a catalog of 12 standard 3D robot joints (this modeling step needs to be done only once). Then, individual modules can be assembled into any closed- or open-chain topology. The system automatically maintains a spanning tree of the overall configuration, which ensures both efficiency and accuracy of the on-screen representation.

Until now, JPL has used generic CAD (computer-aided design), simulation, and animation tools as a substitute for a



Any **Assembly of Kinematic Modules** may be directly operated in the system by click-and-drag direct manipulation. Here the canonical configuration of two Tri-ATHLETE modules and one pallet is operated in lifting (A), sliding (B), and tilting (C) motions.

true modular robot operator interface. This workflow is extremely time-consuming, and is not suited for use in an operations context. Current operator interfaces, both at JPL and in the broader exploration robotics community, are largely focused on non-reconfigurable hardware.

Reconfigurable modular hardware such as Tri-ATHLETE promises to extend greatly the capability of future exploration missions for a relatively small additional cost. Whereas existing missions based on monolithic hardware can only perform a limited set of pre-defined operations, modular hardware can potentially be reconnected and recombined to serve a range of functions. The full realization of these promises is contingent not just on the development of the hardware itself, but also upon the availability of corresponding software systems with algorithms that enable operators to rapidly specify, visualize, simulate, and control particular assemblies of modules. In the case of articulated, reconnectable hardware like Tri-ATHLETE, operators also can determine feasible motions of the assembly, and disconnect/reconnect actions that change assembly topology.

This work was done by Jeffrey S. Norris of Caltech, Marsette A. Vona of Northeastern University, and Daniela Rus of MIT for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

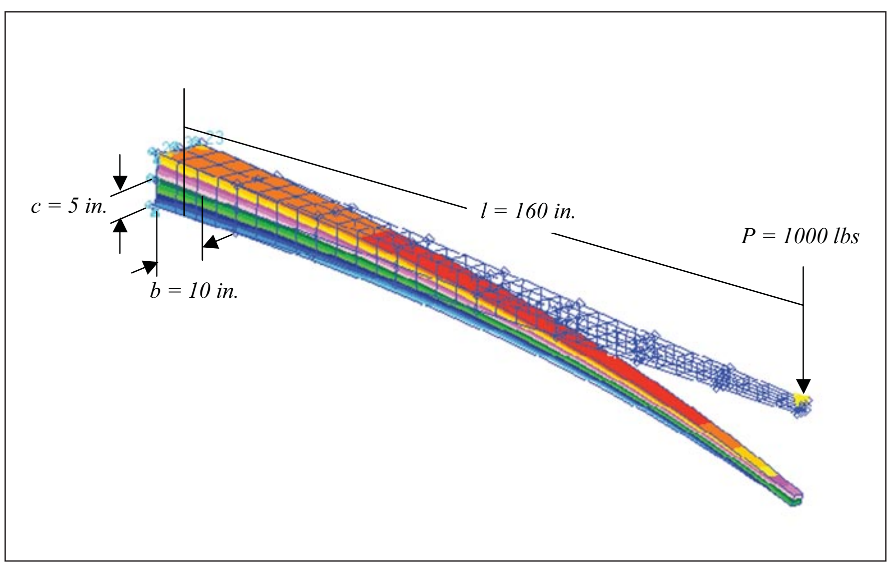
This software is available for commercial licensing. Please contact Daniel Broderick of the California Institute of Technology at danielb@caltech.edu. Refer to NPO-47777.

Algorithms for Determining Physical Responses of Structures Under Load

Structure can be monitored in real time while in actual service.

Dryden Flight Research Center, Edwards, California

Ultra-efficient real-time structural monitoring algorithms have been developed to provide extensive information about the physical response of structures under load. These algorithms are driven by actual strain data to measure accurately local strains at multiple locations on the surface of a structure. Through a single point load calibration test, these structural strains are then used to calculate key physical properties of the structure at each measurement location. Such properties include the structure's flexural rigidity (the product of the structure's modulus of elasticity, and its moment of inertia) and the section modulus (the moment of inertia divided by the structure's half-depth). The resulting structural properties at each location can be used to determine the structure's bending moment, shear, and



Cantilever Beam of tapered cross section subjected to tip loading.