

measurements to estimate the state of all of the segments and to predict the wavefront error; segment actuator commands are computed that minimize the wavefront error.

Translational or rotational motions of one segment relative to the other cause lateral displacement of the light beam, which is measured by the imaging sensor. For high accuracy, the collimator uses a shaped mask, such as one or more slits, so that the light beam forms a pattern on the sensor that permits sensing accuracy of better than 0.1 micron in two axes: in the z or local surface normal direction, and in the y direction parallel to the mirror surface and perpendicular to the beam direction.

Using a coaligned pair of sensors, with the location of the detector and collimated light source interchanged, four degrees of freedom can be sensed: transverse x and y displacements, as well as two bending angles (pitch and yaw). In this approach, each optical edge sensor head has a collimator and an imager, placing one sensor head on each side of a segment gap, with two parallel light beams crossing the gap.

Two sets of optical edge sensors are used per segment-to-segment edge, separated by a finite distance along the segment edge, for four optical heads, each

with an imager and a collimator. By orienting the beam direction of one edge sensor pair to be +45° away from the segment edge direction, and the other sensor pair to be oriented -45° away from the segment edge direction, all six degrees of freedom of relative motion between the segments can be measured with some redundancy.

The software resides in a computer that receives each of the optical edge sensor signals, as well as telescope pointing commands. It feeds back the edge sensor signals to keep the primary mirror figure within specification. It uses a feed-forward control to compensate for global effects such as decollimation of the primary and secondary mirrors due to gravity sag as the telescope pointing changes to track science objects.

Three segment position actuators will be provided per segment to enable controlled motions in the piston, tip, and tilt degrees of freedom. These actuators are driven by the software, providing the optical changes needed to keep the telescope phased.

A novel aspect of this design is the angled optical edge sensor configuration. By angling the light beam of each edge sensor pair at + and -45°, a full four degrees of freedom can be sensed at each segment edge by each sensor pair. This configuration results in full observability of

the segment optical state, and is crucial in achieving the needed performance.

The software incorporates a structural/optical model of the telescope in a least-squares or Kalman filter-based estimator/controller, which processes the optical edge sensor signals in a low-bandwidth control loop. The estimator produces an estimate of the optical state of the mirror, and predicts the resulting wavefront error, balancing current against previous measurements in a least-squares optimization. The controller calculates the segment actuator commands that will minimize not the sensor signals, but the predicted wavefront error. This formulation allows the controller to compensate for the optical effects of motions (such as lateral sag of the segments) that are not directly actuated. The result is far better performance than could be achieved using a conventional sensor-nulling approach.

*This work was done by David C. Redding, John Z. Lou, Andrew Kissil, Charles M. Bradford, David Woody, and Stephen Padin of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

*The software used in this innovation is available for commercial licensing. Please contact Daniel Broderick of the California Institute of Technology at [danielb@caltech.edu](mailto:danielb@caltech.edu). Refer to NPO-47964.*

## Long-Life, Lightweight, Multi-Roller Traction Drives for Planetary Vehicle Surface Exploration

**These drives can be used for Earth-based applications where extreme temperatures are involved.**

*John H. Glenn Research Center, Cleveland, Ohio*

NASA's initiative for Lunar and Martian exploration will require long lived, robust drive systems for manned vehicles that must operate in hostile environments. The operation of these mechanical drives will pose a problem because of the existing extreme operating conditions. Some of these extreme conditions include operating at a very high or very cold temperature, operating over a wide range of temperatures, operating in very dusty environments, operating in a very high radiation environment, and operating in possibly corrosive environments.

Current drive systems use gears with various configurations of "teeth." These gears must be lubricated with oil (or grease) and must have some sort of a lubricant resupply system. For drive sys-

tems, oil poses problems such as evaporation, becoming too viscous and eventually freezing at cold temperatures, being too thin to lubricate at high temperatures, being degraded by the radiation environment, being contaminated by the regolith (soil), and if vaporized (and not sealed), it will contaminate the regolith. Thus, it may not be advisable or even possible to use oil because of these limitations.

An oil-less, compact traction vehicle drive is a drive designed for use in hostile environments like those that will be encountered on planetary surfaces. Initially, traction roller tests in vacuum were conducted to obtain traction and endurance data needed for designing the drives. From that data, a traction

drive was designed that would fit into a prototype lunar rover vehicle, and this design data was used to construct several traction drives. These drives were then tested in air to determine their performance characteristics, and if any final corrections to the designs were necessary.

A limitation with current speed reducer systems such as planetary gears and harmonic drives is the high-contact stresses that occur at tooth engagement and in the harmonic drive wave generator interface. These high stresses induce high wear of solid lubricant coatings, thus necessitating the use of liquid lubricants for long life.

Because of their near-pure rolling contact, traction drives can operate unlubricated at very cold temperatures or

at high temperatures by using low-wear, high-traction materials or coatings. Oil-less traction drives will not encounter the temperature swing problems of other proposed planetary vehicle drives. Traction drives also will be less sensitive to dusty conditions if sealed properly, and will also not contaminate a planetary environment because there is no liquid lubricant used.

The oil-free traction drive is a “toothless” drive system that is capable of dry operation using low-wear, high-friction mate-

rials and coatings. Multi-roller traction drive configurations offer high reduction ratios (>30 to 1) in a single stage, reducing motor size and providing a lightweight wheel drive system.

A traction drive with nearly pure rolling action provides much longer life than could be achieved with gear or harmonic drive systems in applications where liquid lubricants could not be used. Use of ceramic-coated titanium or polymer rollers will reduce the weight of the drives and also reduce the cost to launch.

*This work was done by Richard C. Klein, Robert L. Fusaro, and Florin Dimofte of NASTEC, Inc. for Glenn Research Center. Further information is contained in a TSP (see page 1).*

*Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18826-1.*

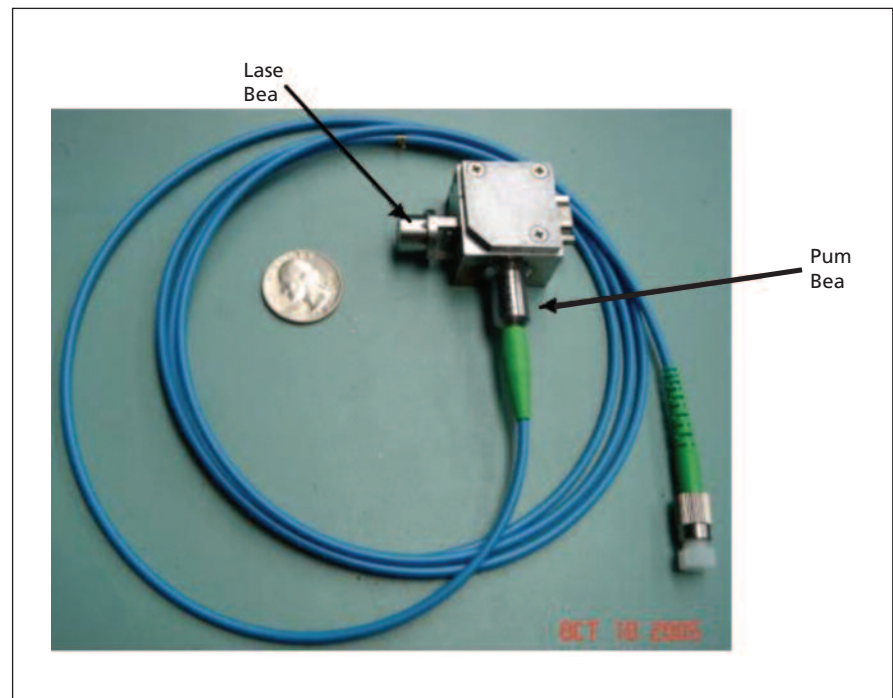
## Reliable Optical Pump Architecture for Highly Coherent Lasers Used in Space Metrology Applications

**This design also can be used in scientific instrumentation where repair is difficult such as in underwater deployment.**

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

The design and initial demonstration of a laser pump module (LPM) incorporating single-mode, grating-stabilized 808-nm diode lasers and a low-loss, high-port-count optical combiner are completed. The purpose of the developed LPM is to reliably pump an Nd:YAG crystal in the laser head (LH), which serves as the optical metrology source for SIM-Lite mission. Using the narrow-linewidth, single-mode laser diodes enables placement of the pump power near Nd adsorption peak, which enhances pumping efficiency. Grating stabilization allows for stable pump spectra as diode operating temperature and bias current change. The low-loss, high-port-count optical combiner enables efficient combining of tens of pumps. Overall, the module supports 5+ years of continuous operation at 2 W of pump power with reliability approaching 100 percent.

The LPM consists of a laser diode farm (LDF) and a pump beam combiner (PBC). An array of 807- to 808-nm fiber-pigtailed laser diodes makes up the LDF. A Bragg grating in each 5- $\mu\text{m}$  core single-mode (SM) fiber pigtail acts to stabilize the lasing spectra over a range of diode operating conditions. These commercially available single-mode laser diodes can deliver up to 150 mW of optical power. The outputs from the multiple pumps in the LDF are routed to the PBC, which is a 37-input by 1-output all-fiber device. The input ports consist of 5- $\mu\text{m}$  core SM fiber, while the output port consists of 105- $\mu\text{m}$  core, 0.15 NA (numerical aperture) multi-mode (MM)



Picture of SIM-lite NPRO based LH. The optical pump is delivered to the NPRO via multimode optical fiber. The laser beam is free spaced coupled to remainder of metrology system.

fiber. The combiner is fabricated by fusing the 37 input fibers while simultaneously tapering the fused region. At the completion of this process, the MM fiber is spliced to the end of the adiabatic taper, and, for protection, the combiner is sheathed by a capillary tube. A compact and robust metal housing was designed and fabricated to protect the PBC during space deployment.

Finally, the combined pump light is delivered to the LH via MM optical fiber. Within the head, the pump beam optical train matches the pump beam to the lasing mode profile, which enhances pumping efficiency. The LH houses non-planar resonant oscillator (NPRO), and provides all conditioning necessary for proper NPRO operation. Two large magnets ensure unidirectional propagation through