intensity across the pupil, superposed on the bright, uniform illumination of the undiffracted component. In the small-signal approximation, the total intensity in the re-imaged pupil would be proportional to $1 \pm 2\phi$, the sign of 2ϕ depending on whether the focal-spot filter advances or retards the phase.

Figure 2 schematically illustrates an optical assembly, according to the proposal, for implementing the 90°-phase-shift filter needed in a phase-contrast sensor like that of Figure 1. An incident beam from a telescope would strike a 50:50 beam splitter. The reflected and transmitted beams would be recombined by an arrangement of mirrors, schematically represented by flats M1 in Figure 2; one component is directed through a diffraction-limited pinhole in two-sided mirror M2. The pinhole would pass the central $\approx\lambda/D$ portions of the beams, while the M2 surfaces surrounding the pinhole would reflect the off-axis portions. The total beam going to the output port on each side of M2 would comprise the desired combination of central rays and 90°-shifted off-axis rays. The output beams could be directed into telescope-pupil-re-imaging optics equipped with a charge-coupled-device (CCD) or similar quantum detector, as in Figure 1. Optionally, the phase-contrast images contained in both beams could be combined optically or electronically to increase the signal-to-noise ratio.

This work was done by Eric Bloemhof and J. Kent Wallace 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:

Innovative Technology Assets Management
JPL
Mail Stop 202-233
4800 Oak Grove Drive
Pasadena, CA 91109-8099
(818) 354-2240
E-mail: iaoffice@jpl.nasa.gov

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Progress in Insect-Inspired Optical Navigation Sensors

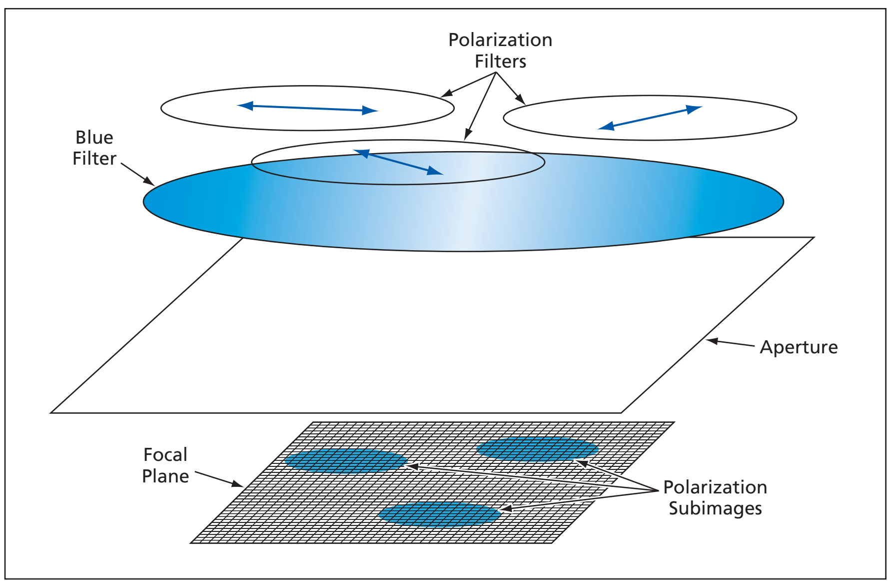
Some details of implementation have become available.

NASA's Jet Propulsion Laboratory, Pasadena, California

Progress has been made in continuing efforts to develop optical flight-control and navigation sensors for miniature robotic aircraft. The designs of these sensors are inspired by the designs and functions of the vision systems and brains of insects. Two types of sensors of particular interest are polarization compasses and ocellar horizon sensors.

The basic principle of polarization compasses was described (but without using the term "polarization compass") in "Insect-Inspired Flight Control for Small Flying Robots" (NPO-30545), *NASA Tech Briefs*, Vol. 29, No. 1 (January 2005), page 61. To recapitulate: Bees use sky polarization patterns in ultraviolet (UV) light, caused by Rayleigh scattering of sunlight by atmospheric gas molecules, as direction references relative to the apparent position of the Sun. A robotic direction-finding technique based on this concept would be more robust in comparison with a technique based on the direction to the visible Sun because the UV polarization pattern is distributed across the entire sky and, hence, is redundant and can be extrapolated from a small region of clear sky in an elsewhere cloudy sky that hides the Sun.

Three different implementations of a polarization compass are under consideration. Each implementation offers distinct advantages and disadvantages relative to the others:



Three Differently Oriented Polarization Filters are used in projecting subimages on a CMOS image detector. In addition, a short-wavelength-pass (blue) filter contributes to image contrast because the polarization signal is strongest in blue light.

- In the lightest and least power-consumptive implementation, the polarization in the sky is sampled in, typically, 10 fields of view, each centered on a different direction and having an angular width between 10° and 20°. An eight-bit microcontroller suffices to do all required data processing. A production version of a sensor according to this implementation could be self-contained. One disadvantage of this implementation, as determined in experiments performed thus far, is that bearing accuracy is characterized by an uncertainty of about 2°. Another disadvantage is that this sensor cannot be used for imaging.
- In the second implementation, three differently oriented polarization filters are used to produce three subimages of the sky scene in separate focal-plane areas of a complementary metal oxide/semiconductor (CMOS) video camera (see figure). This implementation is amenable to sophisticated processing of polarization-image data and possible sub-degree accuracy in determining the relative angular position of the Sun. Unfortunately, for a

production version, power consumption and mass would be much greater than in the first-mentioned implementation because an embedded computer or digital signal processor would be necessary for processing video data. Design and fabrication of the camera optics would present a challenge, inasmuch as the field of view should, ideally, be 150° wide. The challenge is compounded by the need to avoid reflective optics, which would disrupt the polarization pattern.

- In the most elegant implementation, not yet realized, each pixel of a charge-coupled-device (CCD) camera would be subdivided into three subpixels, each covered with a differently oriented polarization filter. The resulting device would be small and lightweight and would demand little power, but manufacturing would be complex.

The basic principle of ocellar horizon sensors was also described in the cited prior article. These sensors are based partly on dragonfly ocelli — simple eyes that exist in addition to the better-known compound eyes of insects and that sense only light, dark, and motion. In dragonflies, the ocelli play an important role in stabilizing attitude with respect to dorsal light levels.

An ocellar horizon sensor of the type under development includes UV/green pairs of photodiodes and utilizes dragonfly-inspired principles of color-opponency processing. The reason for choosing UV and green is that at these wavelengths, spectral sensitivity of dragonfly ocelli and the contrast between the sky and ground are greatest: On Earth, the contrast is greatest in the near UV during the day and is greatest in green at twilight.

This work was done by Sarita Thakoor of Caltech, Javaan Chahl of Australian National University, and Steve Zornetzer of NASA Ames Research Center for **NASA's Jet Propulsion Laboratory**. *For further information, contact the JPL Innovative Partnerships Office at (818) 354-3821. NPO-41269*