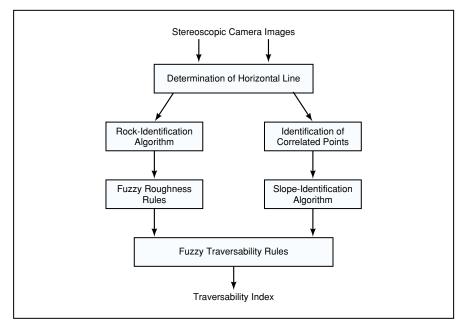generate the control actions. The operational strategies of the human expert driver can be transferred, via fuzzy logic, to a robot-navigation strategy in the form of a set of simple conditional statements composed of linguistic variables. These linguistic variables are defined by fuzzy sets in accordance with user-defined membership functions. The main advantages of a fuzzy navigation strategy lie in the ability to extract heuristic rules from human experience and to obviate the need for an analytical model of the robot navigation process.

The basic building block of the present navigation strategy is a behavior, defined here as a representation of a specific sequence of actions aimed at attaining a given desired objective. Each behavior comprises a set of fuzzy-logic rules of the form

IF C, THEN A,

where the condition C is composed of fuzzy input variables and fuzzy connectives (AND, OR, NOT), and the action A is a fuzzy output variable. Such an IF, THEN rule represents a typical rule in a set of natural linguistic rules that express the actions taken by an expert human driver based on the prevalent conditions. The output of each behavior describable by such a rule set is a recommendation over all possible control actions from the perspective of attaining the objective.

Multiple behaviors, each aimed at one specific goal, can be active simultaneously in the navigation strategy. Blending of multiple behaviors is implemented by combining the outputs (recommendations) of all the behaviors using gain rules of the form

IF S, THEN K,

where S is a logical statement that describes a physical situation, and K represents a fuzzy expression of the gains with which the recommendation of the individual behaviors are weighted in the prevalent situation. The result of the weighted combination of recommendations is then issued as a command to the wheel actuators of the mobile robot.

Image Data Acquired by Onboard Stereoscopic Cameras is processed into terrain-quality information and summarized in a fuzzy traversability index.

The present robot-navigation strategy involves three such behaviors, denoted seek-goal, traverse-terrain, and avoid-obstacle:

• The navigation rules for the seek-goal behavior utilize the global information about the goal position to generate the steering and speed commands that drive the robot to the designated destination.

• The navigation rules for the traverse-terrain behavior utilize regional information about the quality of the terrain to produce steering and speed commands that guide the robot toward the safest and the most traversable terrain. The regional terrain-quality information is generated from readings of onboard sensors by use of a set of fuzzy-logic rules. This behavior constitutes a major novel aspect of the present strategy (see figure).

• The navigation rules for the avoid-obstacle behavior employ local information about obstacles en route to develop steering and speed commands to maneuver the robot around the obstacles.

The recommendations of these three behaviors are blended through gains or weighting factors to generate the final steering and speed commands to be executed by the wheel actuators of the robot. The gains are also generated by fuzzy-logic rules that take into account the current status of the robot.

This work was done by Homayoun Seraji, Ayanna Howard, and Bruce Bon of Caltech 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-21199.

Designing Facilities for Collaborative Operations

A methodology is emerging from efforts to design a mission operations facility.

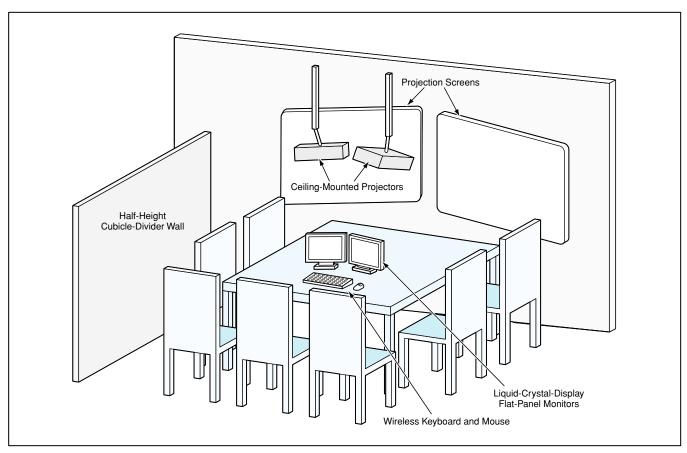*NASA's Jet Propulsion Laboratory, Pasadena, California*

A methodology for designing operational facilities for collaboration by multiple experts has begun to take shape as an outgrowth of a project to design such facilities for scientific operations of the planned 2003 Mars Exploration Rover (MER) mission. The methodology could also be applicable to the design of military "situation rooms" and other facilities for terrestrial missions.

It was recognized in this project that modern mission operations depend heavily upon the collaborative use of computers. It was further recognized that tests have shown that layout of a facility exerts a dramatic effect on the efficiency and endurance of the operations staff. The facility designs (for example, see figure) and the methodology

developed during the project reflect this recognition.

One element of the methodology is a metric, called effective capacity, that was created for use in evaluating proposed MER operational facilities and may also be useful for evaluating other collaboration spaces, including meeting rooms and military situation rooms. The effective capacity of a facili-

This **Proposed Work-Space Design** would enable seven participants to collaborate while using a single workstation.

ty is defined as the number of people in the facility who can be meaningfully engaged in its operations. A person is considered to be meaningfully engaged if the person can (1) see, hear, and communicate with everyone else present; (2) see the material under discussion (typically data on a piece of paper, computer monitor, or projection screen); and (3) provide input to the product under development by the group. The effective capacity of a facility is less than the number of people that can physically fit in the facility. For example, a typical office that contains a desktop computer has an effective capacity of ≈4, while a small conference room that contains a projection screen has an effective capacity of around 10. Little or no benefit would be

derived from allowing the number of persons in an operational facility to exceed its effective capacity: At best, the operations staff would be underutilized; at worst, operational performance would deteriorate.

Elements of this methodology were applied to the design of three operations facilities for a series of rover field tests. These tests were observed by human-factors researchers and their conclusions are being used to refine and extend the methodology to be used in the final design of the MER operations facility.

Further work is underway to evaluate the use of personal digital assistant (PDA) units as portable input interfaces and communication devices in future mission operations

facilities. A PDA equipped for wireless communication and Ethernet, Bluetooth, or another networking technology would cost less than a complete computer system, and would enable a collaborator to communicate electronically with computers and with other collaborators while moving freely within the virtual environment created by a shared immersive graphical display.