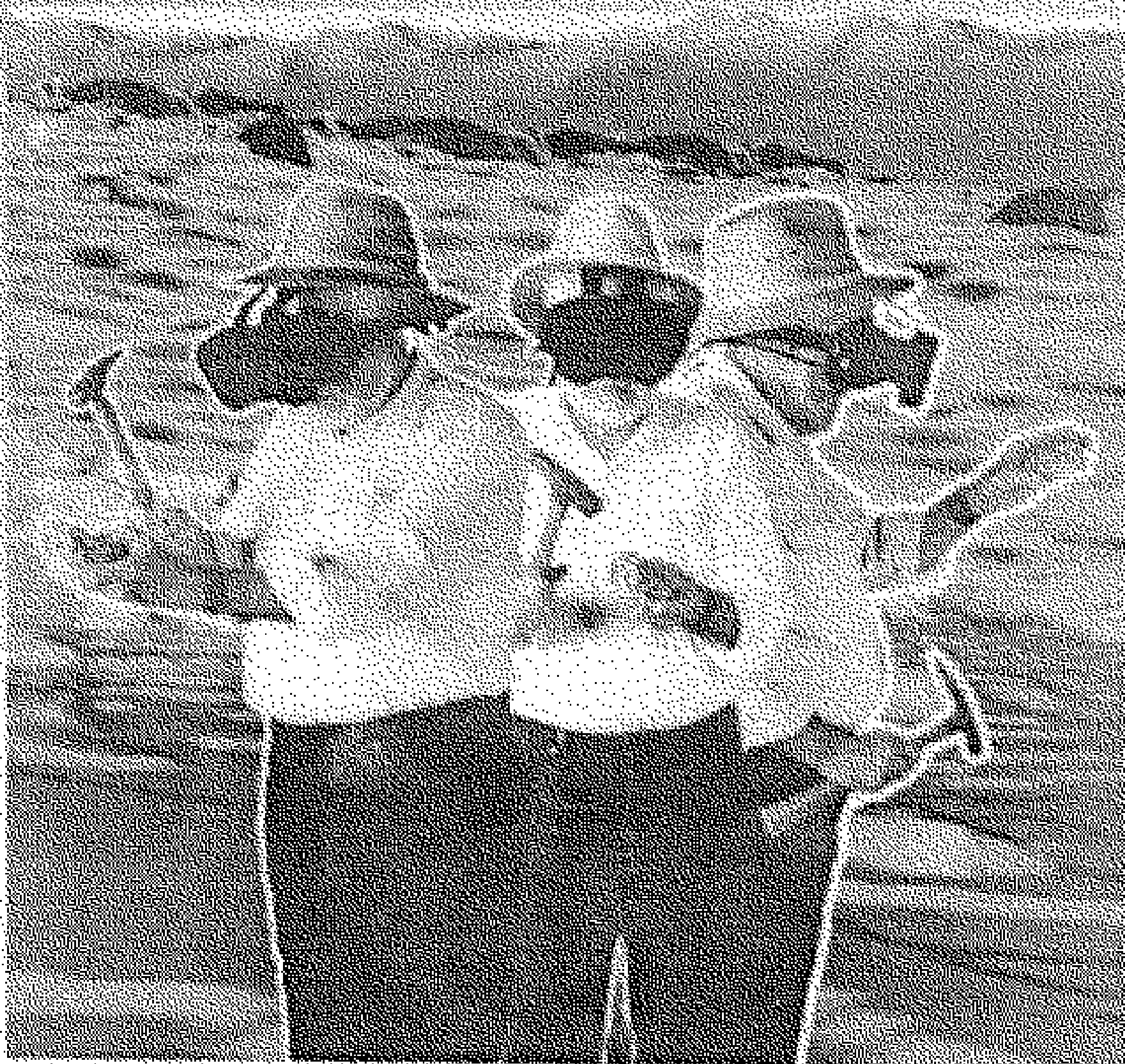
PRESENCE

TELEOPERATORS AND VIRTUAL ENVIRONMENTS



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ARTICLES

FORUM

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The Presence of Field Geologists in Mars-Like Terrain

Abstract

The presence of human geologists is held by some to be essential to the conduct of field geology on remote planetary surfaces, so a field study was conducted to observe and characterize the nature of that presence. This study was conducted in the Mojave Desert of Southern California at the Amboy lava field, a landscape that is analogous to terrain on Mars. Two experienced planetary geologists were interviewed and observed during the conduct of surface operations. Each subject then wore a head-mounted video camera/display system, which replaced his natural vision with video vision, while attempting to conduct further surface explorations.

In this study, methods of ethnographic observation and analysis have been coupled with object-oriented analysis and design concepts to begin the development of a clear path from observations in the field to the design of virtual presence systems. The existence of redundancies in field geology and presence allowed for the application of methods for understanding complex systems. As a result of this study, some of these redundancies have been characterized. Those described are all classes of continuity relations, including the continuities of continuous existence, context-constituent continuities, and state-process continuities. The discussion of each includes statements of general relationships, logical consequences of these, and hypothetical situations in which the relationships would apply. These are meant to aid in the development of a theory of presence. The discussion also includes design considerations, providing guidance for the design of virtual planetary exploration systems and other virtual presence systems. Converging evidence regarding continuity in presence is found in the nature of psychological dissociation. Specific methodological refinements should enhance ecological validity in subsequent field studies, which are in progress.

1 Introduction

1.1 The Human Role in Planetary Field Geology

Historically, the manned and unmanned space programs have been thought to be at odds, with more scientific benefit supposedly derived from the unmanned missions. Certainly it made sense to send unmanned probes to Jupiter, Saturn, Uranus, and Neptune. Flyby imaging, plasma measurements, observation of star occultations, and other activities were brilliantly performed by the Voyager spacecraft without the aid of onboard humans. Scientific surface exploration of the rocky planetary bodies will, however, benefit significantly from human presence.

Field geologists are acutely aware of the limitations of autonomous robotic spacecraft relative to the demands of planetary surface exploration. According to Taylor and Spudis (1991), human presence is essential: "The complex yet

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subtle nature of geological materials requires powers of observation, pattern recognition, and synthesis not possessed by automated devices. Such preprogrammed machines are also not capable of taking advantage of surprises" (p. 247).

"Field study . . . absolutely requires human geologists to be involved intimately. The goal is to understand planetary processes, geologic formations, and planetary history at all levels of detail. Field study is therefore a protracted and complex operation. It requires time and ability to think about observations made in the field. It is an iterative process, requiring the capability of repeated visits to a field area interspersed with laboratory analyses and revision of working hypotheses and conceptual models" (p. 247).

"The most important factor in doing field work properly, besides the training, talent, and experience of the geologist, is the presence of human powers of thought and observation at the field site" (p. 254).

Establishing that presence on Mars, for example, will be a challenge, not only because of the obvious technical difficulties of the flight and the habitation, but also because adequate exploration of Mars requires traversals of thousands of kilometers. Given the likely constraints of life support systems, human surface mobility, and safety, limiting the manned traversal radius to perhaps 50 km, much of this work is likely to be done via remote control from a central Mars base (Stoker, McKay, Haberle & Anderson, 1989; NASA, 1989). However, geologists (Taylor & Spudis, 1989) warn: "[I]f remote operation becomes too cumbersome . . . the operator will concentrate more on mechanical aspects of the work and less on the intellectual ones" (p. 254).

During the preparations for Apollo missions to the moon in the 1960s, related concerns regarding lunar surface operations and tools were addressed in field studies conducted by the U.S. Geological Survey office at Flagstaff, Arizona in cooperation with NASA (e.g., Swann, Bailey, & Regan, 1967). These analog field studies were central to the design of NASA's manned lunar surface exploration missions (e.g., NASA, 1973). Similarly, human factors questions regarding future exploration technologies might also benefit from analog field studies. As technologies for future manned exploration missions advance, machines are likely to increasingly mediate between remote geologic sites and human explorers. Thus, it is increasingly important to ensure that these more complex tools, and the associated operations, accommodate the actualities of human exploration of planetary terrain. One way to approach this is to observe geologists at work in the field, to analyze the role of presence in geologic field work, and to derive user-based guidelines for exploration systems that mediate presence.

1.2 Mediated Presence

Telepresence is a form of mediated presence in which local behavior is referenced to a remote environment. In the ultimate telepresence system, the human would be able to explore the remote environment in a manner quite similar to that of exploring the proximal environment. This can be conceptualized as the projection of natural human capabilities to a distant environment, or as the distant environment being virtually recreated at the location of the operator. In the former view, the user's vision could be linked to remote cameras, other sensory links could be established, and the user's gestures could drive the motions of remote actuators. This is the usual conceptualization of telepresence (Akin, Howard, & Oliveira, 1983a; Akin, Minsky, Thiel, & Kurtzman, 1983b,c). In the latter view, the task environment could be digitized and recreated as a virtual interactive environment surrounding the human operator, with proximal actions transformed into remote ones.

Given that over 99% of the surface of Venus has recently been digitized at resolutions approaching 300 m/pixel by the Magellan spacecraft, and that Venus is being explored virtually via computer graphics techniques (De Jong, Saunders, Hall, & McAuley, 1991), it is not hard to imagine the emergence of such a model-based approach to remote planetary surface exploration via telepresence. Further confidence in the concept can be gained from work in preparation for future surface rover missions. As an engineering test of equipment and algorithms conducted by a NASA-industry-university planetary rover imaging team, 10 cm/pixel digital terrain model data of a 150 by 60 m area in Death Valley has been acquired by laser ranging. That dataset, along with terrain data from the Viking Mars missions, has been used to create virtual planetary terrain environments in a virtual presence system developed by the author and his colleagues at NASA Ames Research Center (McGreevy 1984, 1988, 1989, 1990, 1991, 1993; "Computerized reality," 1990; Daviss, 1990; Philbin-Ziv, 1991; Rayl, 1991; Stewart, 1991; "Planets of the mind's eye," 1991). The next step is to link these virtual terrains to rovers at remote sites to enable action at a distance via model-based telepresence.

Many planetary surface exploration objectives (Stoker et al., 1989) can be met through the use of unmanned rover vehicles that are teleoperated via telepresence by scientist/astronauts on the surface of the planet itself, in orbit around it, or back on Earth. The collective objectives of a generation of explorers could be met by an advanced form of computer-supported cooperative work in which a distributed team of explorers could work at many sites, exploring in concert. Still, a certain amount of rover autonomy will be necessary, since even very short transmission delays will degrade driving and other low level tasks, despite the potential for some operator adaptation (Held & Durlach, 1991). In fact, even when time delay is not considered a significant factor, driving via telepresence, "can lead to poor control capabilities and hazardous operating conditions" (McGovern, 1991, p. 194). Thus, the very remote rover should be able to get itself from place to place, and do other low level tasks, with only supervisory control from the human operator(s).

It will be important that the rover system itself, not just the user interface at the control site, be compatible with the demands of the field geologist. Recent conceptual designs of planetary rovers (David, 1990; Pivirotto & Dias, 1989; and Fig. 1 from Cal Tech's Jet Propulsion Lab) raise some doubts about the potential for "eye-hand-terrain" interaction of a sort comparable to that of human geologists in the field. It is imperative to have design guidelines based on actual geologic field work to present to rover designers in order to ensure the best possible design.

Augmented telepresence systems could provide superhuman sensory capabilities, such as multispectral vision

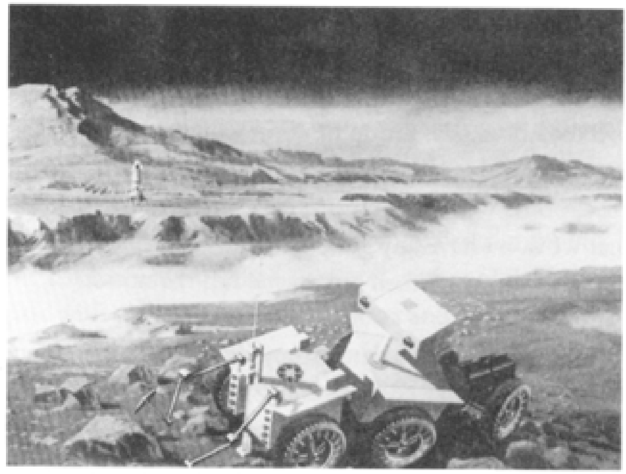

Figure 1. *Conceptual design of a robotic roving vehicle for planetary surface exploration (credit: JPL).*

to aid in the identification of materials, and could also combine archival environmental data with currently sensed data to provide a more complete picture of the task environment to the user. Telepresence systems augmented with such "forward simulation" capabilities, and utilizing judicious and temporary decouplings between the local and remote environments, have been shown to allow greater efficiency in teleoperations (Conway, Volz, & Walker, 1990).

Telepresence technology can be available sooner than truly intelligent autonomous robots, and it provides a mode of operation that complements total automation, augmenting the robustness and flexibility of surface exploration capabilities. Properly orchestrated, telepresence has the potential to combine human intelligence with achievable robotic capabilities to enable extensive surface exploration, with reduced technical risk and enhanced safety, while enabling the planetary geologist to conduct field work in a (nearly) natural manner.

1.3 Presence

At a NASA/NRC symposium on telepresence, automation, robotics, and human factors, the late Allen Newell of Carnegie-Mellon University suggested a fresh approach to the study of telepresence (Sheridan, Kruser, & Deutsch, 1987, p. 324): "It seems to me this notion of telepresence provides a very interesting example in which before one can get very far . . . one has an immense need for a theory of presence." Later in his informal remarks to the group he commented, "[T]rying to move to produce devices that get [the effect of] telepresence, one is working on extremely soft sand in the sense that we don't have any good theories of what's happening in the human when [experiencing] the notion of 'presence.' "

Theoretical issues related to presence and telepresence are receiving renewed attention. Sheridan (1992) is seeking objective measures of presence so that theory can be grounded on repeatable observations. Loomis (1992) is gaining insights via reviews of literature on closely related phenomena. These works serve as essential elements of a theoretical foundation.

As a further step toward a theory of presence, it seems altogether worthy to start with the humble act of observing humans experiencing presence in the real world. This is, however, rather too diffuse in itself. Since planetary surface exploration is conducted both remotely and via actual presence, it seems an appropriate task domain in which to observe presence. Some practical good might come of it. While it is beyond the scope of any one paper to develop a complete theory of presence, empirical study of human–terrain interaction is a worthwhile and perhaps fresh place to start.

Beyond any practical utility of the potential results of such a study, it is evident that field geologists are particularly *appropriate* subjects for the study of presence. The essential purpose of field work in geology is to establish the presence of the geologist within the terrain of interest so that he or she can exploit that presence in order to understand the environment. One might ask how presence aids in the understanding of geologic environments, and what is the nature of that understanding from the point of view of a field geologist?

Field geologists are also particularly appropriate for a study of presence because they are so *intensely* present, so assiduously engaged with the environment, and so intensely interested in the layout and component details of the terrain environment as it is revealed by virtue of their explorations. The field geologist does not follow the paths of least resistance, nor merely the "available paths of locomotion" (Gibson, 1979, p. 43). The individual field geologist does not "move through the same paths of its habitat as do other animals of its kind" (Gibson, 1979, p. 43). Thus, field geologists are acutely sensitive to subtle "affordances" (Gibson, 1979, p. 127).

Finally, terrain itself provides richly complex, highly structured, and varied environments in which to be present. Rather than study presence among the rectilinearities, the clutter of readily named discrete objects, and the human-scale conveniences that typify the artificial world of culture, one might find a more raw and direct form of presence among the natural terrains of planetary surfaces. But terrain is more than a static collection of shapes to be among. It is a record of its own creation by a complex series of events, that is, terrain preserves a geologic record that is readable. It has stories to tell. "They have a different vocabulary, a different alphabet, but you learn how to read them" (McPhee, 1982, p. 19). It is this terrain language and this story that the field geologist seeks to decipher by virtue of being present.

2 Method

The observation and characterization of the behaviors of one culture by another are the domain of anthropology, and specifically, of ethnography. This ethnographic field study was intended to provide initial familiarization with the field activities of field geologists as they explore a scientifically interesting terrain environment. It was done to gain an understanding of presence and virtual presence as they apply to planetary exploration. The study represents only the first of several planned field trips, so is not intended to be complete in itself. This first trip was not designed to prove anything, but rather to search out clues and insights for further investigation. The study is a first attempt by the author to observe the actual behavior of field geologists in the field, and to test methods for doing so.

In terms of theory, ethnography has a vital role, which is eloquently described by Hammersley and Atkinson (1983, p. 179): "An important feature of ethnography is that it allows us to feed the process of theory generation with new material, rather than relying on our previous knowledge of cases relevant to the theoretical ideas we wish to pursue. In this way the fertility of the theoretical imagination can be enhanced."

The data collection methods employed included: pretrip questionnaires (a list of open-ended questions with written responses), unstructured (i.e., depth) interviews conducted in the field, direct observation (as a nonparticipant) of typical tasks, and comparison of tasks conducted using direct vision with those conducted using a head-mounted videocamera/display system. Much of the activity was recorded on videotape for later review and analysis.

Interviews are particularly helpful, but must be applied with caution so as not to impose structure on what the user has to say until that structure has a more solid grounding. As a result, so called "unstructured" interview techniques are often used early in an ongoing ethnographic investigation, and increasingly structured interviews come later. The initial interviews, therefore, included open ended questions, in which each subject was encouraged to fully answer a general question, and was often further prompted for elaboration, rather than being steered too rigidly along a preconceived line of thought. It is important to note that the purpose of depth interviewing is to provide freedom for the respondent to answer the questions as fully as he or she sees fit, and to provide ample opportunity for the subject to introduce ideas as needed to complete the response.

Berelson and Steiner (1964, p. 31) point out that "Characteristic depth interviewing involves extensive use of the 'nondirective probe,' a query designed to produce further elaboration without influencing the content of the response in any way." This kind of query was used as appropriate, and to good effect. While such verbal subtleties may read as mere anecdotal excess to some, the coercive or noncoercive qualities of key interview segments are a source of evidence for the enthnographer. Thus, for example, while it may be no surprise that two different subjects comment that they can, say, calibrate their sense of space by moving about and comparing predicted distances and locations with those observed by ad hoc experimentation, it is indeed a very significant finding when the specificity of the response is unprovoked by the interviewer. Also, when a simple "Okay . . ." from the interviewer, after a pause by the subject, when an important topic seemed not yet played out, prompts the subject to reveal an unanticipated and surprising fact, the value of the nondirective probe is made clear.

The principal goal of ethnographic reporting is to share what was observed. To share the description of one culture with another, in this case, that of field geologists with virtual presence engineers and scientists, is known as "ethnographic translation" (Spradley, 1979, p. 205). An ethnography can embody such a translation. In the words of Fetterman (1989, p. 139), "An ethnography is primarily descriptive in nature." The most substantial data produced by this method, as it was applied at Amboy, are the statements of the informants and the record of their field behaviors. Key excerpts and descriptions of both are provided in the Results section. It should be noted that the method used was intentionally ethnographic, and as such, an ethnographic narrative is an appropriate form of data. Such a narrative provides a more contextual description of the behaviors of the subjects than, say, a list of their behaviors. In addition, rather than considering lengthy or numerous quotes as anecdotal, as one might in a classic engineering paper, in an ethnography they are essential. Fetterman goes so far as to write (1989, p. 115) that verbatim quotations are a "sine qua non of ethnography." Narrative and quotes may be rather more difficult to interpret than a graph of quantities, but they serve to document the rich interactions among the exploration behaviors, as well as the interactions between the explorer and the environment.

2.1 Site

The study was conducted at the Amboy lava field in the Mojave Desert of Southern California. This site was chosen because of its scientific interest to planetary geologists, and because its geology has been extensively studied in the field by the first subject. It was also reasonably accessible to the participants. General timing of the trip was determined by the desert climate, which is tolerably warm in springtime. The timing also allowed the study team to take part in a JPL-led field trip to Mars analog sites in Death Valley and environs just prior to the Amboy field study.

2.2 Subjects

Both subjects are planetary geologists from major universities who have participated in previous planetary explorations, are active in current research, and will likely participate in future exploration of Mars and other terrestrial bodies. The first subject is an expert on the Amboy lava field. The second subject is experienced with the scientific use of telepresence equipment in the field. Two informal subjects were participants of the JPL field trip.

2.3 Procedure

Geologists were accompanied into the field, and observed and interviewed as they worked in an exploration environment. Similar field activities were repeated with each geologist wearing a head-mounted video camera/display/recorder to replace his natural vision. Wearing the video vision system, the geologist was essentially using a telepresence simulator, simultaneously playing the roles of operator and teleoperated field system. (Alternatively, the real terrain can be thought of as simulating the ultimate virtual terrain, and the geologist is thus seen as exercising the user interface of a virtual environment system.) The field activities were videotaped by the study team. The idea was to obtain a baseline understanding of exploration behavior, and then to step back from presence as a way to elicit comment and to stimulate observations regarding electronically mediated presence. The ability of the user to think and act effectively could be expected to be reduced by an attenuation of the natural sense of presence, and it was hoped that this would bring out useful information about user requirements. The Amboy trip was a first attempt at this procedure.

2.4 Equipment

An 8-mm camcorder (Sony "Video Walkman" model GV-9) was used to record the field activities, supported by several battery packs and recharging units, and numerous videotapes. The head-mounted camera/display/recorder worn by the subjects was configured according to the specifications provided by the author, and was implemented by Jim Humphries and Joe Deardon of Sterling Federal Systems, a contractor to NASA Ames Research Center. The head-cam system consisted of a head-mounted platform, a pair of video cameras, two video displays with eyepieces (video viewfinders), an 8-mm video cassette recorder in a "fanny pack," a boom microphone, a belt-mounted battery pack, belt-mounted support electronics, and connecting cables (Fig. 2a). A camera field-of-view of 20° vertical by 25° horizontal was displayed on each of the displays without magnification or minification, so that objects subtended the same visual angle whether viewed with or without the head-cam. Figure 2b is a typical view of a hand-held sample. One camera could supply imagery to both displays for biocular imagery, or each camera could provide a separate image to each eye for stereo imaging. The primary mode used at Amboy was biocular, with stereo capability intended only for system development use in the field.

3 Results

The results of the field study, as explained in the Method section, are narrative descriptions and verbatim quotes derived from observations of the activities of field geologists at the Amboy lava field, queries about those activities, and interviews conducted at the site.

3.1 First Subject

The first subject initially gave a concise lecture to outline his interest in the field site in a planetary context. He described the relationship between features observed on Mars, dark and light streaks downwind of prominences such as cinder cones, and a potentially analogous feature at the Amboy site. He used orbital photos of regions of Mars containing the streaks, and aerial photos of the Amboy lava field, to illustrate his comments (Fig. 3a). His interest centered on the processes that created

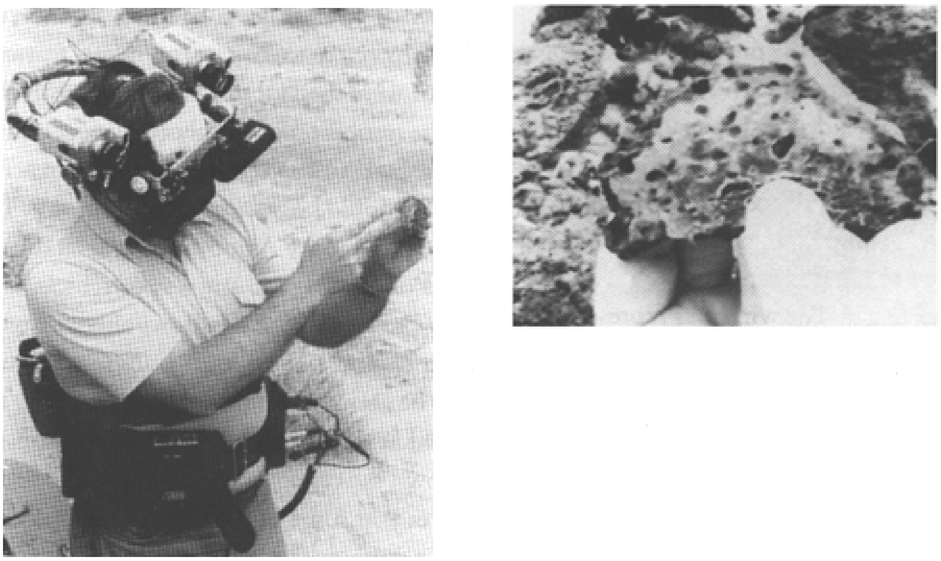

Figure 2. *Head-mounted display system in use. (Left) Geologist wearing the head-mounted camera/display/recorder system, and belt containing battery packs and controls, inspects a rock sample. (Right) The sample as seen by the geologist. The extreme depth of focus causes the background to obscure the boundaries of the sample in this still image but motion parallax eliminated the problem in the field.*

Figure 3. *Stills from videotaped interview with, and demonstrations by, the first geologist. (Left) The geologist points to the cinder cone in the air photo and its associated dark streak. The cinder cone itself looms behind. (Center) Fine dexterity is used to pick apart mosaicked desert pavement, which is comparable to that in the dark streak. (Right) Geologist at a local maximum of elevation, gesturing to emphasize the importance of oblique viewing from small aircraft.*

the features, and he explained three hypotheses to be tested against observations in the field. He then traversed the field to demonstrate and discuss these observations. When asked about the selection of specific sites for field work, the subject described the process of aerial reconnaissance.

3.1.1 Gestures Augment Descriptions. As the subject explained each of the candidate processes responsible for the feature, his gestures acted out the process, referenced to the aerial photo of the Amboy lava field and sometimes to the field itself. After unfolding the map of the Amboy region, the subject oriented the map so it would spatially correspond to the environment. Thus, gestures representing the prevailing wind, for example, were made alternately relative to the environment and relative to the map, aided by the spatial correspondence between the environment and its representation. Gestures referencing the cinder cone were small circles drawn with the index finger around the cone on the map. The streak was indicated repeatedly with a linear sweep of the index finger. The wind was represented by a flat hand, sweeping over the map from the upwind to the downwind direction, the palm indicating the direction of the wind. Such gestures were used, for example, to describe the hypothesis that the cone acted as a wind shadow for wind-driven sand, thus leaving the dark streak in the shadow zone.

Erosion of the cinder cone, the basis for the second hypothesis to explain the formation of the dark streak, was acted out with a pecking gesture of the index finger on the image of the cinder cone. The movement of the eroded material downwind was acted out with a series of gestures. First, there was a gesture like picking up fine particles with all of the fingers straight, the tips forming a circle around the cone, and coming together at the cone, followed by a picking-up gesture. Then with the fingers "holding" the eroded material, the hand was moved along the streak on the map as if to sprinkle the cinders along the streak. To describe the third hypothesis, that the cone creates a turbulent wake that creates the streak by sweeping it free of material, the subject made a scoop-like hand shape and then made a spiraling, brushing-off gesture where the axis of the spiral ran along the streak away from the cone.

3.1.2 Sand Sampling Traversal. The subject related stories about previous field trips to Amboy and discussed the deposition of material by wind. He explained a strategy of sampling wind-driven sand that determined a traversal. To sample the distribution of windblown sand parallel to the streak, a linear array of sample sites was required. A compass was used to determine the azimuth of the path. The sampling crew sighted on a feature in the distant mountains and traversed in that direction toward the landmark, sampling every *n* paces. They judged the location of each sample site by reference to environmental features around them that were then located on a high resolution aerial photo. The resolution of the photo was such that they could resolve creosote bushes of about 1 m across.

It should be noted that an arbitrary linear traversal in the hummocky Amboy lava field landscape would be a major challenge to any sort of vehicle. Curvilinear outcrops of solidified lava flows alternate with sand-filled depressions. The outcrops are sometimes steep, appear to be about 6 feet in height on average, and generally are split at the top (pressure ridges) creating a steep crevice down the center of the outcrop. The subject commented later that some of the best rock samples are near the vent of a volcanic flow, and that the ability of a rover to traverse from the edge of the flow to the vent is an issue, given the distance and the hummocky terrain. He added, "We have to be able to get to the little nooks and crannies, or over the pressure ridge, or down into the crack in the pressure ridge. We have to have that degree of mobility to look for the things that are useful to us in the field."

The subject demonstrated the taking of sand samples. These included bulk samples with a scoop that collects a few handsful of sand, and surface samples using tape. Each sample was collected and placed into a plastic bag. The bag was then labeled with a marking pen with an alphanumeric code indicating collector, field site, and date. Ad hoc experiments to obtain a rough estimate of the proportions of the components of sandy material included the trickle test and the "taste" test, both of which were demonstrated by the subject. The subject scooped up a handful of sandy material and allowed a thin, steady stream to fall, while observing the behavior of the falling material. The sand falls pretty much straight down, while the silt and clay are carried on the breeze by suspension. The "taste" test is really a fine texture test to differentiate between silt and clay. Silt "tastes" gritty on the teeth, its particles being larger than clay particles, while clay is "smooth and chocolatey," the subject said, as he tasted some, and simultaneously rubbed his thumb and forefinger together.

3.1.3 Rock Sampling. Rock sampling was then demonstrated and discussed. The key petrologic question is to identify the rock. A rock sample, "typically fist sized," needs to be representative and not weathered. Asked about recognition of good samples, the subject said that acquisition is a problem, requiring that "we smash a lot of rocks" to find a good sample, and that a geologist always has a hand lens to look at crystals in detail to observe possible alteration due to weathering. As he acted out the actions he described, the subject described the visual evaluation of the sample: "We have to be able to pick a rock up. We have to be able to break it open. We have to be able to orient it with respect to the illumination, so that we can see the texture, or so that we can see the crystal faces. . . . If we have our own illumination source, then some of those problems are solved, but it's not quite that direct because sometimes we want the light so that it's glancing off of the crystal faces. It's not simply a case of floodlighting the sample. . . . So typically what we do in the field is pick a rock up, get it into position with the sun, and then rotate it so that we can see what we're after."

The subject found and discussed several examples of desert pavement, a surface arrangement of materials in which rocky fragments are mosaicked together, jostled together by water and wind, on top of fine sandy material. The subject exhibited fine dexterity in gently lifting "paving" materials from their bed of sand, silt, and clay (Fig. 3b). He observed that such surfaces are common in the dark streak zone, contributing to the low albedo of the streak. "That's a reflection of this high turbulence in the wake of the cinder cone, where the wind is coming along and scouring, removing the loose sand, and carrying it away," he said.

3.1.4 Aerial Photos and Oblique Views. The subject led the interviewers to high ground, from which he pointed out different kinds of terrain within the lava field. When asked about his decision to visit a particular site on the ground, based on its appearance on the high-resolution aerial photo, the subject was asked, "What if you were here for the first time and didn't have an aerial photograph?" The subject replied, "I don't think I could [make such a decision]. It takes the air photo, it takes seeing the position of this [kind of site] in relation to other occurrences which one would want to go and look at on the ground, too. It's not a simple call made at one location. But instead takes looking at the surface in many places and putting the geometry together for the field as a whole."

Aerial photography, and direct viewing from the air, were held to be very important to the process of conducting field geology. "Doing this kind of field work, it's fairly common for us to start in the laboratory by looking at the available remote sensing data. And not just conventional air photos like this, but any other kind of data we can get, as well. And then going into the field, doing a reconnaissance of the field as a whole. And then overflying it. We commonly will rent small planes to fly over the area. It gives you a perspective that you can't get any other way. The air photos are not adequate. There are things that the eye can detect that remote sensing cannot. There are relationships that we can see from that low altitude perspective that you can't get, either on the ground or from orbit, let's say. And so that intermediate altitude aerial reconnaissance is an important part of the kind of field work that we do."

The subject was asked to elaborate on the utility of overflight in a small plane. "It's difficult to describe, certainly in a quantitative sense, what one does on an aerial reconnaissance. It's the perspective of geometric relationships of different units that you can't appreciate when you're standing right on the surface. You don't have that overview. It's also because you're there. You're seeing it in color. You're seeing it with your own eyes. And from an *oblique perspective.* And from many *different* perspectives, because the plane can fly around [Fig. 3c] and give you whatever geometry you want, to see the areas that you're interested in." [Italics indicate subject's emphasis.]

Asked about the altitudes of choice for the overflights, the subject responded: "Typically what we do, and this is a good case in point here, we begin at about 10,000 feet and do a spiral descent over the whole field, coming lower and lower, and then we begin to identify specific areas of interest. It may be the cone or it may be the flow. And then concentrate on making specific observations in these areas." Uninterrupted during his pause to think, and then prompted for his thoughts with, "Okay . . . ," the subject then continued: "I guess the other thing I'd say about doing that aerial reconnaissance is, generally it's more than one person who does that. One person is assigned to take photographs. The other person is assigned to make the observations. He can't do both at the same time. And it's interesting that when we get back and we debrief each other, the person who was making the observations will bring out much more detail than the person making the photographs. The person making the photographs will focus on features of interest, but that person won't really understand what it is they were photographing."

Asked to describe the sort of information the observer has that the photographer doesn't, the subject replied: "The person who's making the observations sees the whole field of view, and sees the geometric relations of one feature to another. The person that's making the photographs has a very narrow field of view, and will focus on features of interest, but loses the overall context of that feature."

Later, the subject pointed out that most geology involves looking at cross sections, as in highway cuts or along fault scarps, and that the scale of such features is on the order of tens of feet. He noted that at Amboy, one is more concerned with the planform, and that is why aerial reconnaissance is important. He also said that aerial reconnaissance is important for channels, paraglacial features, and other features that are planform.

3.2 Second Subject

The second subject took as a point of departure the question, "What if I were here for the first time?" He initially addressed the question from a perspective of scientific goals, and later revised his priorities based on scientific process. His first priority would be, he said, to identify the materials in the region, to determine how they got there, and their relationships to the other materials in the area. While noting that he could determine "in about half a second" that the basic materials in the area were sand and basalt, he addressed the question as if he had no prior knowledge, and demonstrated the approach he would take.

3.2.1 Sampling Demonstration. Given the revealing interplay of locomotion, manipulation, perception, and cognition observed in the subject's sampling demonstration, the brief activity is discussed here in detail. Surveying the surrounding environment, the subject observed in mock innocence of the place, "Well, there's light stuff and there's dark stuff." That immediately prompted the subject to walk swiftly in about 12 paces to the nearest outcrop saying, "Let's look at what the dark stuff is." Arriving at the low margin of the outcrop, he crouched for a better look and commented that he was looking for an unweathered surface. Seeing a likely sampling site, he then stood up, pulled out his hammer, and took four steps through the low rocky margin of the outcrop to position himself to break off a rock. Taking the hammer in both hands, he bent to hit a low rock three times, shattering pieces free. He identified one of the pieces that flew off to a distance of about 18 inches, picked it up, and inspected it.

To inspect the rock, he brought it to within about 12–15 inches of his eyes, having rotated his forearm above the elbow, and his wrist, in a right to left rotation of about 180° from the picking-up orientation. He then rotated his forearm and wrist an additional approximately 30° to the right, then rapidly rotated left to right 90°, then back right to left 90°. Finally, he rotated the sample from the bottom to the top, about a quarter rotation, in his fingers. Throughout the manipulation, the sun was above and to the left relative to his view of the sample. The subject then rejected the sample as being weathered, commenting, "Pretty cruddy stuff!" He then hit the low, partly shattered rock an additional seven times, slightly shifting his left foot to the left to gain better leverage as the hammer blows came from right to left.

He then crouched to inspect the fresh rock face revealed by the hammering. His body cast a shadow on the fresh rock face so he shifted his position for a better sun angle. He positioned his eye close to the fresh rock face, straight above it, at a distance of about 15 inches, while rubbing it with his fingers to feel its texture. At

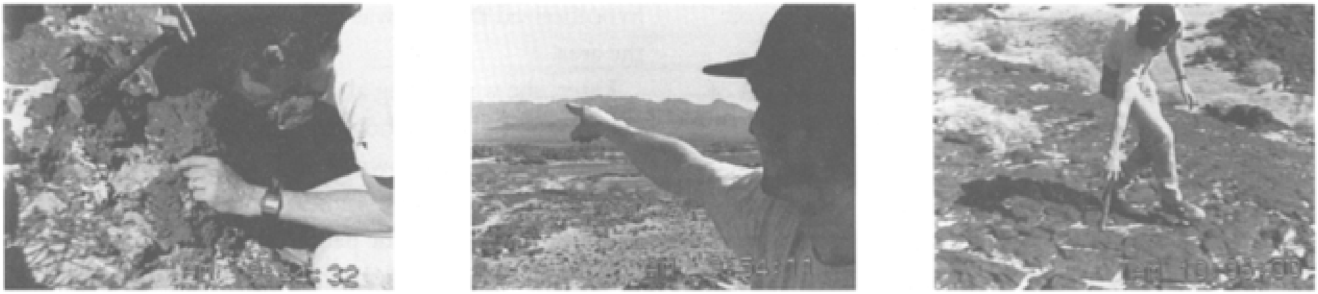

Figure 4. *Stills from videotaped interview with, and demonstrations by, the second geologist. (Left) The geologist closely views a fresh rock face in order to observe glints of embedded crystals. (Center) A view from a local maximum of elevation provides information at the regional scale. (Right) The geologist traces parallel arcuate forms in the basalt.*

this point, he declared that it was a fresh surface, that it was dark, mafic rock (igneous rock rich in magnesium and iron and comparatively low in silica), and proceeded to describe the weathering process that had prompted his efforts.

The subject then looked very closely, from about 12 inches, at the fresh face, at an oblique angle of about 45° relative to the roughly horizontal rock face (Fig. 4a). He then moved his body so as to move his eyes around in an elliptical trace, such that the rock face was positioned at the apex of a cone with an elliptical base. The eyes moved as far as 2–3 inches to the left, 2–3 inches to the right, and plus or minus 1 inch in the vertical direction. He explained that he was looking for the glints of sunlight off the individual crystals embedded in the rock. The crystals were phenocrysts, he explained, crystals larger than the surrounding rock matrix, that were formed prior to the eruption that carried them to the surface. Regarding the phenocrysts, he commented, "The easiest way to pick them up is by moving your head around and looking for the glints that come off the individual crystals."

It is highly instructive to compare the eye-hand-terrain relationships shown in Figure 4a with those of the conceptual rover design in Figure 1. This comparison makes it vividly obvious that the realities of field geology must be made clear to rover designers.

Turning his attention to the outcrop in general, he commented on the surface of the rocks, which were covered with small pit-like features called vesicles. Then his attention to texture moved to an even larger scale, and he commented on the structures of lava extrusion. The canonical extrusion patterns on land being aa ("ah ah") and pahoehoe ("pa HOee HOee"). This led the subject to try to find a ropy texture in the outcrops to illustrate the likely pahoehoe pattern of the Amboy flow. (Aa is a very blocky flow.) He commented that deep erosion makes such textures hard to find.

3.2.2 Overviews and Context. The subject then spontaneously set out to find a locally elevated location. "One of the first things that you're going to do at a site like this, and probably the first thing I really would have done if I had never been here before would have been to get up as high as I can and just look around, and see what it is I see. Because you can always characterize things better by looking down on them and getting a broad view. If you were going out here and doing geology the first time you would do everything you could to get your hands on some air photos."

This would enable the explorer to understand where he is, and to understand the regional context, according to the subject. If there were no air photos, he would climb to the highest point, much as he had just done, he said, to obtain the necessary overview of the regional context (Fig. 4b).

The scale at which one worked, he said, might depend on one's questions of the moment, or one's approach, so that at times attention would be focused on: microscopic details in a rock, or a whole outcrop, or the lava field and cinder cone taken together, or a region kilometers on a side, or larger areas at the scale of plate tectonics, or even global scales. "To really understand the geology, you have to work at all those scales."

Returning to the use of air photos, in the context of scale, he said, "you're going to rely heavily on remote sensing to establish the regional context and select carefully from that regional context the places where you can get the most science from local intensive field study." Commenting later on related uses of aerial photos in geological field work, the subject commented that local investigation of such features as sand-filled pressure ridges, combined with a recognition of their appearance from the air, allows one to extrapolate to the rest of the field. This information yields clues about the directions of the lava flow, the process that created the local terrain.

3.3 An Unanticipated Result: Observation of Chance Discoveries

One of the Amboy subjects as well as one of the geologists on the JPL Death Valley field trip were observed as they made chance discoveries. This is important because it is commonly argued that machine intelligence lacks the ability to take advantage of surprises, while humans excel at this. It is worthwhile to make note of how such an event transpires. During an interview the study team conducted on the Death Valley trip, a geologist had commented that science is "observing and reacting to the unexpected" and that no preprogrammed rover could do that. Rather than being completely unexpected, however, the two observed cases of chance discoveries were examples of what might be called *primed* chance discoveries. Accumulated observations during the traversals, coupled with prior knowledge and previous field experience, were brought to bear on unexpected, unconscious observations.

In the first case, the geologist had earlier been discussing her belief that green epidote, a medium-high temperature metamorphic mineral, could be found in the area. She based this on her knowledge that metamorphic rocks are common in the area, and the fact that she had even seen green glints on rocks from the car as it approached the Avawatz fan, the site of the interview. So, based on her knowledge, and a chance observation, she hypothesized that she was likely to find such a rock in the area.

Later, she was talking about the fact that an alluvial fan is a good place to look for rocks because many sorts of rocks are washed down from the mountains. As she said this, she gestured to indicate the sweeping vista of the mountains. Then she paused, as if reflecting on something. She then looked in a particular direction as if to confirm an observation, and said, "Now there's a great face of green epidote way over there. That's one of the best ones I've seen." She then walked over to the rock, protruding from the ground, bent down to touch the rock surface, saying, "This is a case where you can actually see the crystals picking up the sunlight."

Thus, the geologist had been primed to find green epidote, and had, in the back of her mind, as a background process, so to speak, some part of her interpretive skills assigned to look for green epidote. Later, though consciously attending to another topic, she had chanced to observe the flash of the green crystals in the sun. She then paused to mentally review the event, determined the direction to look to repeat the observation, and consciously saw the epidote.

In the other observed case of primed chance discovery, the second subject in the Amboy study, who had earlier not been able to find an example of the ropy texture associated with a pahoehoe lava flow, was standing on an outcrop discussing the appearance of pressure ridges in aerial photos. Suddenly, he hesitated, resumed speaking on his topic, then halted in mid-sentence. He scanned the surface of the outcrop in front of him, and said that he just noticed something interesting. After completing his point about the pressure ridges, he pointed out the subtle but undeniable pattern in the surface of the outcrop. It was better appreciated by standing back, he noted, as the pattern covered a large area, several feet on a side. Light colored sand partially filled the low grooves between multiple, parallel, rounded ridges of dark basalt, enhancing the three dimensional pattern. The pattern traced arcuate, parallel curves in the surface of the outcrop, which the subject indicated with sweeping gestures of his rock hammer (Fig. 4c). Thus, in a situation similar to the observation of the green epidote, the subject's foreground activity had been interrupted by

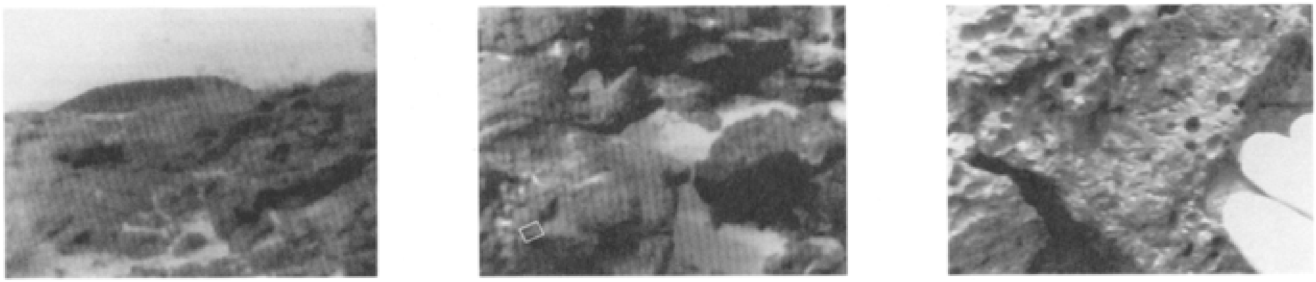

Figure 5. *Geologist's HMD view as he discussed loss of context (see text).*

a background process which had found the pattern he had continued to seek.

3.4 Results Using the Head-Mounted Camera/Display

While wearing the head-mounted camera/display system (Fig. 2a), both subjects attempted to identify materials, attempted to differentiate weathered from unweathered surfaces, used rock hammers to achieve fresh surfaces, and made interpretations based on recall of similar environments. The first subject spontaneously concentrated on sampling issues, including interpretation of fine visual detail (e.g., Fig. 2b). The second subject spontaneously concentrated on locomotion, particularly the notion of building up a mental model of the terrain. (Significantly, this subject was also in Amboy testing a device to digitize the terrain with a laser imaging system.)

As soon as each subject donned the head-camera/display, he commented immediately and negatively about the poor resolution of the head-mounted display/camera relative to natural vision. (Each was reminded that he was to do the best he could, as if the system were the only means available to explore the environment, and to comment on his difficulties.) The monitors provided approximately 200 lines of video over the vertical field of view of 20°. The lack of stereo vision provided in the head-mounted display prompted both subjects to use alternative cues to make spatial judgments. Both subjects found that by adjusting the manual iris controls of the video cameras, contrast and detail could be dramatically improved when looking at the very dark basalt or very bright sand.

3.4.1 Effects of Narrow Field of View. The subjects both commented that the narrow field of view of the visual system (20° vertical by 25° horizontal) reduced context. The subject who focused on sampling issues found that the narrow field of view reduced the information needed to understand the environment of a sampling site: "The narrow field of view is a real constraint. I lose the context of where I am. And even scanning, panning, I don't have the feeling for where I am. That's a real constraint."

Relating fine detail, such as the orientation of fluted vesicles, to the region as a whole was especially difficult with the narrow field of view, even though the imagery was correlated with head-movements. This is illustrated in Figure 5a–c, three views of the environment surrounding the subject as he noted the loss of context. The view in Figure 5a, which is up and to the left relative to the view in Figure 5b, includes the cinder cone in the distance, and a portion of the outcrop. Figure 5b shows a small area of the outcrop as the geologist approached it. Figure 5c is a close-up view of the outcrop seen in 5b. The inset box in Figure 5b is the approximate outline of 5c. In the close-up view (Fig. 5c), the subject was able to see the details of the vesicles well enough to judge whether they had been eroded by wind-driven sand ("fluted").

Later, the subject backed off from an outcrop of basalt to see more of the surrounding area of the outcrop, in

Figure 6. *Scenes from the HMD traverses of the second geologist. (Left) A relatively easy path between the outcrops, as seen by the geologist. (Center) Geologist's view as he indicates a traversal goal beyond a geometrically complex jumble of broken basalt. (Right) The geologist steps across a deep pressure ridge at the top of an outcrop.*

order to compensate for the narrow field of view, but found it unsatisfactory.

The other subject was particularly descriptive of his experience in dealing with the narrow field of view, saying that he felt, "significantly hindered by the narrow field of view. The thing that bothers me about that is that what I try to do with my eyes as a geologist when I'm out in the field is I use my eyes to establish my frame of reference. In other words, I use my eyes to get the big picture, to get the context. If I look down and I find a rock and pick that rock up, I know where it came from. . . . The problem is, what I have to do with this [video vision system] on, it's like I have to build up a virtual model in my brain. . . I can only scan a very small segment of what I see and so I have to remember what was immediately off to the side of it. And it makes it a lot harder for me to get a feel for the geological context."

Traversal was also significantly affected by the narrow field of view. While walking on sand and low protruding rocks between the large basalt outcrops (Fig. 6a), the geologist commented that his strategy was to look ahead, note key features, and try to keep track of those features as he moved through the terrain. At one point, he arrived at the base of a large outcrop and knelt to inspect the surface, but hit his knee on a rock. He hadn't built up a good enough "virtual terrain model" he said. Later, trying to traverse a difficult, rocky area (Fig. 6b), the subject used the head camera to watch each placement of each footstep, saying that the environment was "too geometrically complex for me to build up a simple model in my brain of what's where." The subject was sufficiently confident to climb to the top of a six foot high basalt outcrop, to step across the deep pressure ridge (Fig. 6c), and to walk briskly down the other side.

After a lengthy traverse, the subject found himself unsure of the direction back to the starting point, saying he felt that his sense of direction was impaired. He felt that his mental model of the terrain was inadequate to support his sense of direction because of having "poor data," that is, information accumulated while walking with a limited field of view, modest visual resolution, black and white imagery, and no stereo vision. He had a generally correct idea of the route back, and was able to sight familiar landmarks from high ground. But soon, the subject got slightly confused again regarding the direction back, and had to again reorient with a visual scan. It should be noted that to view the tape of the imagery seen by this subject is even more disorienting, since correlated head movement information is unavailable.

3.4.2 Other Self Motion and Positioning Used to Interpret Space. Both subjects adopted strategies involving self motion and position to make spatial judgments. To understand the configuration of nearby outcrops, one subject commented: "I have a poor sense of depth perception without moving around a bit," as he rocked left and right, shifting his weight from foot to foot. Review of the head-camera tape confirms that he achieved motion parallax so that the nearby outcrop looked very three-dimensional and stood out clearly from the outcrop behind it.

Traversal and interpretation of slope also required spatial judgments based on body-referenced perspective cues. Where the sandy traversal path sloped, and no rocks appeared in the visual scene, the subject could not judge the slope. Reviewing the head-camera tapes, it is evident that the resolution and contrast of the displays were insufficient to communicate the texture cues associated with sloping sand. (During an earlier demonstration of the system, a user had experienced similar difficulty judging slope in a bright, sandy, rock-free area, even with stereo.) A different sandy slope had a rock-sand interface at the top, and the slope was interpretable: "For the sand and rock contact to be where it is, either it would have to be up and close or very much farther away than I know it to be based on textural cues that I can see in the rock. . . . I'm using head angle plus my perception of range [to judge the slope]."

As described in the previous section, one subject experimented with his perception of distance by walking. He picked out a feature some 20 to 30 feet ahead and slightly to the side of his path, walked that distance without looking at the feature, then looked down and to his right to see if the feature was where he expected it to be. It was.

This calibration of space via locomotion was not limited to the use of biocular vision. During a brief demonstration of the head-cam for an astronomer/manager during the Death Valley trip, the user spontaneously commented on his need to calibrate his sense of distance. After discussing his perception of the spatial arrangement of nearby rocks, the user said: "Now, the next question is 'Do I have it calibrated?' That is, [he points about 10° below the horizontal] I can tell that there is a point of rock sticking out here and there is another rock behind [he points about 5° higher]. What I don't have a good sense of at the moment is how close I am to that point of rock, so I'm going to try walking over there." He walked, knelt, touched the rock, and stood up. "Okay, I find that with a small amount of locomotion, knowing how long my strides are approximately, I begin to get a sense of how far things are away. So after doing this for a while I think I would be able to look around in stereo and have some idea of how far something is from me. . . . So I think you can get this calibrated fairly well by moving around."

3.4.3 Sampling and Judgments. Both subjects attempted to make judgments regarding the nature and condition of outcrops, and the utility of samples taken from those outcrops. Since the camera and display system lacked color capability, the brown weathering rind was impossible to distinguish from unweathered dark gray basalt unless the brown surface was also lighter, which it sometimes was. Without color imagery one subject confused small clay filled vesicles with phenocrysts (crystals imbedded in the matrix of the basalt), which made a poor sampling location appear to be a good one. Both subjects said that color imaging is absolutely necessary for a geological telepresence system.

Wielding the rock hammers while wearing the head-cam, the subjects were somewhat tentative. This appeared to be mostly due to the limited field of view, but also due to the fact that the cameras were slightly offset from the positions of the subject's eyes. The first subject made increasingly large swings of the hammer as he gained confidence with the system. It appears that positioning the left hand near the target for the hammer blows was a helpful compensatory gesture (Fig. 7a–c). The subject found the system adequate for guiding the action of breaking off a rock sample (exhibiting a high degree of dexterity that was clearly driven by subtle strategy), and to enable him to observe weathering of the sample so as to reject it from a petrologic point of view. He did so on the basis of seeing weathering phenomena, including white material lining a vesicle, that contrasted well with the dark basalt. The second subject tended to inspect the fresh face revealed by the hammering that remained part of the outcrop, rather than the piece that broke off, when wearing the head-mounted camera/display. This may have been due to the difficulty of keeping track of the piece knocked off by the hammering.

The limited resolution of the video vision system made it difficult for the subjects to adequately survey sandy areas when walking or standing, though the first subject was able to repeat the trickle test of sand. Moving the head-mounted video camera much closer to the sandy accumulation between the basalt outcrops, and rubbing the material between his fingers, he was also able to differentiate tiny eroded basalt particles from sand, silt and clay.

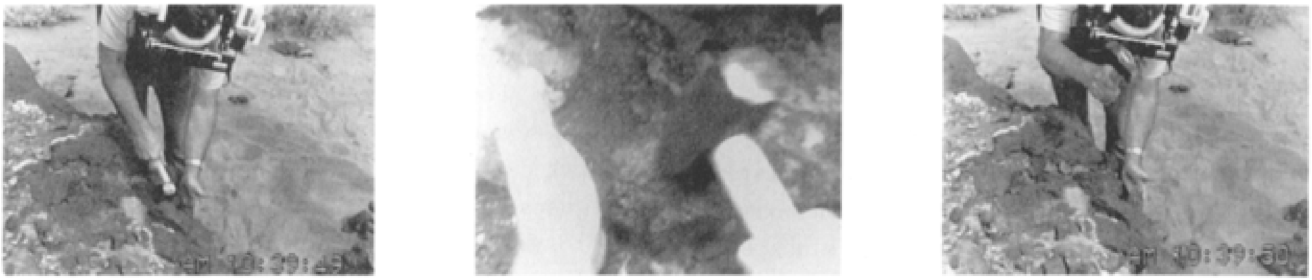

Figure 7. *Scenes from HMD sampling activity of the first geologist. (Left) The hammer is positioned at the point to be struck, as the left hand is positioned to both locate the point and to catch the freed sample. (Center) The same event shown in a, but from the point of view of the geologist. (Right) The geologist takes a large backswing with the sledge hammer, well outside his field of view.*

4 Discussion

4.1 From Ethnography to Design

In a fascinating and seminal paper, Forsythe and Buchanan (1989) made a substantial contribution to the promotion of ethnographic techniques for the development of user-based computer tools. They propose that as a minimum, designers should be willing to gather "knowledge" data via well designed interviews with users. They assert (p. 437) that it might be preferable to do a thorough ethnographic observation and analysis except that "under pressure of time and money, most [knowledge engineers] appear to want to spend less rather than more time with their experts." Perhaps if the connection between ethnography and design were more clear, more precise, the ideas of Forsythe and Buchanan might yet catch on.

One path from the field to the system can be seen in the fact that the methodology of ethnographic observation and analysis is strikingly related to object-oriented analysis and design. Ethnographers have decades of experience in the analysis of culture and component behaviors via field observations, and a rich diversity of literature on methodology and criticism. [See Fetterman (1989), Hammersley & Atkinson (1983), Spradley (1979), Clifford & Marcus (1986), and Jacobson (1991) for useful access points to the literature.] They have developed many ways to observe, query and analyze behaviors, as well as valuable insights regarding methodological issues and the relative contributions of observing and theorizing. Ethnographers do not, of course, move beyond observation and analysis to design.

In his book, *Object Oriented Design* (1991), Booch describes a methodology which clearly maps, although he does not say so, from the output of ethnographic analysis to the design of systems. In addition, Booch presents his analytical strategies in a manner that motivates—more systematically than appears to be done in ethnographic circles—the underlying issues about why one must, and how one can, identify redundancies, divide and conquer, categorize, identify hierarchies, etc., basing his arguments solidly on the nature of complexity and how to understand complex systems.

According to Booch (1991, p. 37), "Object oriented analysis is a method of analysis that examines requirements from the perspective of the classes and objects found in the vocabulary of the problem domain." This kind of analysis provides an access point to introduce ethnographic analysis to object oriented design, if one interprets "vocabulary of the problem domain" in its broadest sense, and one inclusive of the notion of the "vocabulary" of terrain (McPhee, 1982, p. 19). Thus, there is a clear path from field research (observing explorers or other users in the field) to design of virtual planetary exploration systems (and other user interactivity systems), via ethnographic observations and analysis coupled with object oriented analysis and design.

Among the methods of decomposition of complex systems is the identification of hierarchies. "The two most important hierarchies in a complex system," Booch writes (1991, p. 54), "are its class structure (the 'kind of' hierarchy) and its object structure (the 'part of' hierarchy)." One can and should develop the more obvious class structures for kinds of terrain morphologies, kinds of rocks, kinds of minerals. These, however, could readily come from textbooks and would not really be much improved by ethnographic field observations, except to identify the focus of a particular geologic field study. Similarly, the more obvious object structures, such as the "part of" (class) structure of a landscape, from the mineral constituents and embedded crystals to the constituent parts of a lava field, might be better obtained from textbooks than from ethnographic field studies.

What the ethnographic approach can more usefully bring to object-oriented analysis and design are the more subtle and less obvious redundancies, and object and class hierarchies, and the relationships among them. Some of these are elaborated in the following analysis of field geology and presence. The path from field work to design guidelines may well be cleared by such joint applications of ethnographic and object-oriented methods.

4.2 Field Geology and Presence

Field geology and presence can be viewed as complex systems, and methods for understanding such systems may well apply. The essential approach is to divide and conquer, which depends on the existence of redundancies, providing the potential for decomposibility into kinds and parts, and identification of hierarchies. Thus, as a minimum requirement, field geology and presence must each have some redundancy or they cannot be simplified. According to Simon (1969, p. 221), "If a complex structure is completely unredundant—if no aspect of its structure can be inferred from any other—then it is its own simplest description. We can exhibit it, but we cannot describe it by a simpler structure."

On what basis can it be said that a person is present in an environment? Is it just a matter of obvious bodily presence, and thus not redundant? What, if any, are the redundancies of field geology and of presence? A candidate for redundancy in field geology is the common purpose in widely disparate field behaviors of recognizing and emphasizing continuities. With presence, a candidate for redundancy is the diversity of forms of continuity that together seem to account for its character. In both cases, the central notion is continuity. This fundamental similarity is reasonable given the evident fact that the essential purpose of field geology is to exploit presence.

For the purposes of this discussion, a few definitions are helpful. A terrain is a terrain *environment*. An environment is the context of its constituent locations, objects and features. Objects, locations and features are identifiable chunks of environments, such as landmarks and samples. Objects, locations and features can be environments. An environment contains one or more referents (constituents), that are the locations, objects and/or features whose context is the environment. Humans are actors which are objects. Another definition is also useful in the following discussion: Gesture is purposeful bodily movement, which includes locomotion and manipulation, as well as movement which can express or emphasize ideas, emotions, etc., or convey a state of mind or intention. [Definitions derived from Guralnik (1970).] A virtual planetary exploration (VPE) system is a virtual presence system that can operate in one of two modes: (1) The virtual environment serves as a telepresence buffer enabling the field geologist to explore a remote planetary location via a remote rover, or (2) the virtual environment is decoupled, if only temporarily, from action at a distance, for planning and other purposes.

4.2.1 Continuity. Ethnographic observations at Amboy, research into the nature of field geology, and experience with virtual presence systems strongly suggest that a synergistic organizing principle involving recognition, reinforcement, and exploitation of continuities is fundamental to field geology and to presence. Continuity is the state or quality of continuousness, and is synonymous with connectedness and coherence, an unbroken flow or series, the whole cloth. There are, as will be argued below, several major classes of continuity in field geology and presence: the continuities of continuous existence, that is, the persistence of governed engagement; context-constituent continuities, the primary ones of interest to field geologists being related to geologic context and its constituents; and state-process continuities, linking the flow of observations to more stable representations, geologic processes to the configuration of terrain, and the process of exploration to the structure of planets.

In general, the analysis is based on the notion that the essence of presence in field geology is to recognize, reinforce, and exploit continuities in the environment. If this idea is valid, then it would follow that the degree of presence varies directly with the extent that continuities in the environment are recognized, reinforced and exploited. A hypothetical situation that could test this is the following: If group A is subjected to a preponderance of continuity relations in an environment, and group B is subjected to a preponderance of discontinuity relations in an environment, group A will have a greater sense of presence within the environment. If this is found to be true, then virtual planetary exploration systems should promote the recognition, reinforcement, and exploitation of continuity relations in virtual planetary environments. The following discussion further analyzes the continuities of presence and their implications.

4.2.2 Continuities of Continuous Existence. There are several kinds of continuity in field geology and presence. Probably the most compelling of these is the constraint that objects (including the self) and environments have continuous spatial and temporal existence. Objects are irrevocably held in relation to environments (and, by definition, to other objects that comprise environments). They persist in relation to one another without even momentary lapses in the continuity of their continuous existence. In addition to acquiescing to this fundamental *persistence of engagement,* they must acquiesce to the persistence and continuity of physical laws that govern physical relations among the existers. They cannot, for example, instantaneously translate, rotate, change scale, skip about in the stream of time, or change form. They cannot violate the gross integrity of space, time, matter, or energy. The continuity of continuous existence is the *persistence of governed engagement.*

The continuity of continuous existence also applies to the connection of thought and action in objects that are sentient and animate. Thought and action persist in governed engagement. For example, the continuity between the will and the motor functions that provide locomotion and manipulation can produce translations and rotations of oneself relative to objects and within environments, or of objects relative to oneself. Built on this foundation are continuity of translation (persistent and governed translation of objects relative to the visual system, or of the visual system within environments) and continuity of rotation (persistent and governed rotation of objects relative to the visual system, or of the visual system within environments). Because of these continuities of continuous existence in natural presence, one's views of, and interactions with, objects and environments cannot instantaneously change, but *must* flow, evolve, and transform. This continuity prevails without fanfare under conditions of ordinary presence in natural environments, and is in fact difficult to defeat. Indeed, it is precisely this tenacious preservation of continuity, of governed engagement, that is the essential condition of presence.

The continuity of continuous existence is the glue that binds the will, via locomotion and manipulation, to predictable translation and rotation relative to objects within a relatively predictable environment. Thus, the explorer has the opportunity to correlate willed action with the resulting sensory input so as to enhance his or her understanding of the spatial arrangement of the environment and its constituent objects. The field geologists observed at Amboy exhibited and described exactly such behaviors. They moved themselves relative to the environment, and moved objects relative to themselves, in order to understand them. They observed the environment from orbit and high ground, spiraled down from high altitudes in light planes to obtain dynamic oblique perspectives, measured terrain with their paces, claimed to accumulate mental models of the environment by visual scanning as they walked, oscillated slightly about a point in space to observe the glint of sunlight from crystals in rock faces, and turned rock samples over in their hands. They used all of the perspective cues to advantage. They relied heavily on various modes of locomotion and manipulation to aid visual exploration.

These exploration behaviors indicate that field geologists depend on the persistence of governed engagement, on continuous and predictable results of willed action, in the exploration of terrain. It can be expected that the conduct of field geology, and the sense of presence, would be degraded by engagement between the geologist and the terrain which is ungoverned and intermittent. Further, the sense of presence experienced by the geologist relative to the terrain environment can be expected to vary directly with the extent to which the continuities of continuous existence are recognized, reinforced, and exploited. These assertions could be tested with the following situations: (1) If group A experiences a high degree of continuity between visual experience and locomotion/manipulation, and group B does not, then group A will have a greater sense of presence. (2) If group A interacts with a virtual world that enforces continuity of translation and continuity of rotation, and group B interacts with a world that allows neither, then group A will have a greater sense of presence. (3) If group A interacts with a world based on the persistence of governed engagement, and group B interacts with a world based on transitory and arbitrary discontinuities, then group A will have a greater sense of presence.

If a virtual planetary exploration system is to provide a sense of presence, it must support the continuities of continuous existence, that is, the persistence of governed engagement. While these continuities are very difficult to violate in actual presence, they are readily violated in computer-generated environments. In fact, the evolutionary improvement of virtual presence systems is centered on the systematic pursuit of such continuities. While design elements such as head-tracked, head-mounted displays and hand gesture tracking devices have already been applied to virtual presence systems based on an intuition of appropriateness, the notion of persistence of governed engagement provides a more solid theoretical underpinning, and provides a framework for additional improvements. Even designs which are intended to radically warp and manipulate presence, rather than slavishly replicating everyday presence, can benefit from the conceptual notion of persistence of governed engagement.

4.2.3 Gesture, Measurement, and Iconification.

The continuities of continuous existence, described above, enable the linkage between the intellect and the environment via bodily gesture. Gesture at Amboy was used to measure and iconify terrain and terrain-related processes. Gesture, in the form of paces, was used to measure terrain by both formal subjects, as well as one of the informal subjects. This measuring was done in concert with their predictions regarding the result of the gesture relative to the result achieved. Gesture measurements also included, but were not limited to: the "taste" (fine texture) test to differentiate between silt and clay, the trickle test of sandy material to measure the relative amounts of its components, hardness testing of outcrops by hammer blows, mass testing of samples by hefting, measurements of tactile texture with finger rubs, and measuring the terrain by climbing hummocky outcrops, stepping over jumbled blocks of broken basalt and across pressure ridges, and traversing the field a number of paces and checking resulting locations against local features as seen in an aerial photo.

Gesture was also used to characterize (in more abstract ways than measuring as above) and identify terrain features and processes, in a manner that amounts to iconification, as when the first geologist/subject made simple but characteristic gestures that were dynamic icons representing key features and processes at Amboy. These included the cinder cone, dark streak, and wind, as well as the transport of sand and the turbulent scouring of the surface downwind of the cone. The creation (or at least reinforcement) of a gestural icon was observed when one geologist repeatedly swung his rock hammer in sweeping arcs to indicate a diagnostic pahoehoe texture in a basalt outcrop (Fig. 4c). During the interviews, both geologists frequently used a combination of hand, arm, and head gestures, and occasionally more animated ones, to illustrate and embellish their discussion points. For example, one geologist made very descriptive gestures regarding overflights of the terrain in small planes and the resulting visual implications (e.g., Fig. 3c).

Presence provides the opportunity for bodily interaction with the terrain. This interaction appears to be iconified and later used as a descriptive device, a communication aid, and a mnemonic tool. It would appear that without presence, the formation of such gesture-based icons would be greatly impeded, to the detriment of understanding. It seems likely that gesture-based iconic representations are continually congealed, dissipated, revised, applied, and reinforced during field activity (not to be construed as excluding additional derivations from the interpretation of maps, air photos, theoretical processes, etc.) and that the operation of this process of iconification via gesture is an important component of the sense of presence.

The key assertion here is that a significant benefit of presence to geologists in the field is their opportunity to measure and iconify terrain with gesture (though not necessarily doing so consciously). This would suggest that the degree of presence varies directly with the extent that the terrain can be measured and iconified with gestures. A hypothetical situation to test this suggestion might be as follows: If group A is able to measure and iconify terrain with gestures and group B is not, then group A will have a greater sense of presence in the terrain. Design implications for virtual planetary exploration systems would include enabling field geologists to measure and iconify terrain with gesture, and deriving gestures for the operation of virtual planetary exploration systems from natural field gestures.

4.2.4 Context-Constituent Continuities. Context is the circumstance, environment, or situation that is relevant to a particular event or object. It is the fabric in which a thread resides. The referent of the context, the thread in the fabric, might be called the constituent of the context. Thus, a hierarchy built of continuity relations between contexts and constituents is called a context-constituent hierarchy. In the specific application of field geology, the context of interest is the geologic context, so the focus is the *geologic context*-constituent hierarchy. Field geologists traverse this hierarchy of relations in a very distinct and orderly way during the process of planetary exploration.

As synonymous expressions for geologic context, the Amboy geologists used phrases such as "the feeling for where I am," "where a rock came from," "frame of reference," and "the big picture," that is, the geologically relevant environment. This includes proximal objects and events as well as less than obvious influences on emplacement and modification (such as an ancient, distant impact event whose ejecta altered the nearby terrain). This contextual information is used to feed the generative imagination of the geologist so as to aid in the interpretation and visualization of the configurations, events, processes, and forces that together created the terrain, thereby constructing the "Big Picture" (McPhee, 1980, pp. 78–82; also see McPhee, 1986, pp. 43–61 and 143–154, and Compton, 1985, pp. 25–27).

The essential structure that imposes the context-constituent hierarchy on the process of exploration is the complex system that constitutes a planet and its unrelenting processes of alteration. Unlike complex technological systems, however, there is a less discrete nature to this hierarchy. There are no black boxes connected by wires. There exists, however, the potential to exhibit levels of abstraction, where each level is based on lower ones, but is also interpretable to some extent in its own terms without requiring a probe into the complexity of other levels. Thus, crystals compare to crystals, rocks to rocks, outcrops to outcrops, sites to sites, regions to regions, and planets to planets. Traversing down the hierarchy, the strategy of divide and conquer applicable to all complex systems enables the explorer to meaningfully subdivide planets into regions, regions into sites, sites into outcrops, etc., and thus cope with the enormous complexity of the total system one chunk at a time, at the appropriate level of detail. Aided by the "information hiding" provided by levels of abstraction, the field geologist must nevertheless traverse and relate all of the levels of the hierarchy in order to construct the big picture.

In a concrete example, the geologist/subject who had previously done scientific field work at Amboy had started with Mars, found features of interest (the dark streaks), and located comparable features on Earth. The streak on Earth at Amboy led to identification of the Amboy lava field and the encompassing desert as the next contexts in the hierarchy to be explored. An air photo of the lava field was obtained, followed by overflights in small planes to develop an understanding of the site and its context. Based on aerial views, the lava field could be conceptually subdivided into chunks such as the basalt lava outcrops, the cinder cone, the dark streak, and the areas filled in with sandy material that had been brought in by the wind. To closely investigate the nature of these regions, surface exploration was necessary. The wind turbulence created by the cinder cone was found to account for the jostling of desert pavements into place (especially with the aid of very occasional rain), and for the continual scouring of its surface. Thus, a relationship was recognized to exist between the fine structure of the desert pavement, observed during surface exploration, and the dark streaks seen in the aerial and orbital photos. These streaks, previously understood only at the higher, less detailed levels of the context-constituent hierarchy, could now be related down, via intermediate levels of abstraction including the lava field and its sandy desert environment, the cinder cone, the eroded basalt outcrops, and the sand blown onto and between them, to the very rocks and sand of the desert pavement that comprise the streaks.

In another example of traversing the context-constituent hierarchy, the surface environment at Amboy was observed by one of the geologists to consist of "light stuff" and "dark stuff." The dark stuff was differentiated into parts likely to yield unweathered samples, and parts unlikely to yield such samples. By breaking off a piece with a hammer, the dark stuff was differentiated into a sample and the rest of the outcrop. The sample was categorized as either having an unweathered surface, or not. Those with unweathered surfaces revealed that the rock could be differentiated into a fine grained matrix and inclusions. The inclusions were phenocrysts, that is, imbedded crystals, one of several kinds of possible inclusions. Individual crystal faces reflected sunlight to the eyes of the geologist, and were seen as glints. Under 10× magnification, the facets themselves could be seen. At this point, after several "kind of" and "part of" subdivisions, the geologist had subdivided the originally undifferentiated environment down to the level of the crystal facets in a phenocryst, while maintaining knowledge of the hierarchical relations that connect the environment to the facets.

The ability to traverse the hierarchy of context-constituent continuity relations during the course of surface exploration is among the most essential capabilities that field geologists bring to planetary exploration and that autonomous rovers cannot. The field geologist takes full advantage of presence by pondering field relations *in situ*, at the place of their realization, and by directly investigating the implications of those ponderings while they are fresh, in the locations where they are most relevant, with the greatest freedom to discover confirming or disconfirming evidence.

Orderly traversal of the context-constituent hierarchy during the process of planetary exploration is a formalization that has most likely been arrived at through the evolution of professional technique. If this process of building up a model of context relationships is fundamental to presence, and not just to field geology, then creation, modification, and traversal of a context-constituent hierarchy, though perhaps in a disjointed and undisciplined manner, is likely to be a general process that occurs in all who interact with unfamiliar environments. This might be tested in the following situation: If group A has a well-developed context-constituent hierarchy and group B does not, then group A will have a greater sense of presence. It is useful to note that the existence and robustness of the hierarchy can likely be tested one context-constituent relation at a time.

Implications for the design of virtual planetary exploration systems include the importance of supporting traversal of the context-constituent hierarchy, rather than imposing a contrary structure on user-environment or user-system interactions. Further, since development and traversal of this hierarchy is one of the key purposes of geologic field work, sufficient resources must be provided to support that work during actual planetary exploration via virtual presence. In particular, the rigidity of the operational time line that was characteristic of Apollo mission lunar field work must yield during future explorations to the intellectual character of the exploration task.

Because the field geologist experiences the environment at varying levels of abstraction, and variously attends to chunks within those levels, and because computational power will always be inadequate relative to the complexity of reality, the virtual planetary environment system should not represent the environment with a uniform level of detail. Instead, the available complexity should be managed in a fashion that correlates with the dynamic requirements of the explorer by allocating it to the currently activated levels, and currently attended chunks, of the context-constituent hierarchy. The benefit of such a strategy could be tested in the following situation: If group A conducts field geology in a virtual terrain using a virtual planetary exploration system that allocates complexity according to the needs of the user, and group B conducts field geology in the same terrain using the same VPE system, but distributing the same amount of complexity uniformly throughout the virtual environment, then group A will experience a greater sense of presence in the terrain, and will perform its geological tasks more effectively.

4.2.5 State-Process Continuities. In general, state-process continuities are relations between the static and the dynamic, the invariant and the variant, the form and the flow. Such continuities relate state representations to process representations. As Simon (1969, p. 229) asserts in his seminal work on complex systems, "The correlation between state description and process description is basic to the functioning of any adaptive organism, to its capacity for acting purposefully upon its environment." This correlation is essential to the conduct of effective field geology since emplacement and alteration processes are generally inferred from the state of terrain, and because the overriding objective of field geology is to transform the flow of on-site observations and interpretations into more concrete, lasting, and communicable forms. With respect to presence, state-process continuities are the relations between continuous existence and real or abstract objects derived from that flow which then stand relatively unchanged in the stream of time.

The flow of observations, the coin of field presence, is mandated by the continuities of continuous existence and exploited by the field geologist, but to be analyzed and understood, this flow must be correlated with state representations. To accumulate and profit from the treasure of observations, they must be banked in a stable form. In field geology, these include descriptions of the state of the terrain and its previous states, the state of existing knowledge about the terrain, the state of a geologist's understanding of the terrain, and any descriptions of the terrain that may be useful for its interpretation (e.g., scientific papers, maps, plan-view orbital or air photos, oblique orbital or air photos, surface photos, or sketches).

A map, orthophotomap, or oblique aerial view or photo enhances the understanding of geologic context, a fact appreciated quite early in the era of aerial photography by Lee (1922). Views from local maxima of terrain elevation also enhance this understanding. These overviews provide a stable, integrated frame of reference relative to which further observations can be arrayed. It is for this reason that field geologists greatly value the opportunity to view terrain from above. In the opinion of the U.S. Geological Survey field geologist David Love, the subject of McPhee's book *Rising from the Plains* (1986), it is valuable and *satisfying* to "put the geologic scene into a broad perspective." As Love offered this idea (p. 149), McPhee reports, "we were sitting on an outcrop at ninety-two hundred feet and looking at a two-hundred-and-seventy-degree view" of the Rocky Mountains. "[Love] also said, reflectively, 'I guess I've been on every summit I can see from here.' "

The transition from overviews to surface traversal and sampling changes the emphasis of a geologic field investigation from one of working primarily with state descriptions to one of working primarily with process descriptions so as to convert them or relate them to state descriptions. The flow of observations has to be constantly filtered, codified, and accumulated to create the abstract and comprehensive description that comprises a scientific understanding of the terrain. This necessity manifests itself in the compilation and annotation of maps, the making of photographs and sketches, the summarization of key points in field notes, and the iconification of salient features and processes. Thus, state descriptions are created and modified by conversion from, or the establishment of stable relationships with, salient elements in the flow of observations.

Overviews of terrain are connected step by step to the flow of field observations. At some point early in the exploration of the field, the geologist obtains or creates one or more overview representations, such as maps or orbital or aerial photographs. Where possible, aerial reconnaissance provides dynamic, oblique viewing of terrain which helps to bring out, through relative motion, salient features of terrain in ways that maps and still photographs cannot. In the field, views from local maxima of terrain elevation help to relate the overviews to views from the surface. Also, alignment of a planview aerial photo or map of the terrain with the terrain itself enables the overview to be brought into greater correspondence and continuity with the terrain it represents. First, the axes are aligned. Then, features are brought into correspondence by recognizing them in both the map and the surrounding scene. Once the connection is made between the features on the map, and those in the surrounding scene, the surrounding scene becomes a readily accessible extension of the global state description.

This progressive extension of connections between the overviews and the surface views, spanning the conceptual chasm between a global state representation and the flow of observations, is an essential process in establishing an informed sense of presence in the terrain. This sense enables the field geologist to readily bring the stream of observations, via the surrounding scene, into correspondence and continuity with the global state description, the global geologic context. At a surface location on the terrain where the surrounding scene has been made conceptually continuous with the global state description, each instantaneous view can be related to that larger context by relating it to the surrounding scene. A narrow field of view, such as that imposed by the head-mounted display used at Amboy, inhibits this acquisition of a working awareness of geologic context. With a wide field of view, the "what" and the "where" can be apprehended simultaneously and with the appropriate division of labor for the visual system, since the parafoveal region is more functional for object discrimination, while the peripheral visual field is more functional for self-localization and interpretation of self-motion in the world (Haber, 1982). Another factor is that a narrow field of view requires the geologist to correlate a smaller solid angle of terrain, one having fewer salient features than a naturally wide field of view, with the totality of the encompassing scene. In short, a narrow field of view reduces the continuity between the immediate flow of observations and the developing hierarchy of state-process relations.

If these assertions are correct, then it follows that the degree of presence in terrain varies directly with the quality of the apprehended state descriptions of that terrain, and to the extent that they can be correlated with observations made within that terrain. This relation can be tested by the following situation: If group A has a well-developed state description that can be readily correlated with observations made within terrain occupied by group A, and group B has a poorly developed state description or a diminished ability to relate observations to state descriptions of the environment, then group A will have a greater sense of presence in the terrain. It also follows from the foregoing arguments that the degree of presence varies directly with the instantaneous field of view. This can be tested with the following hypothetical situation: If group A has a wide field of view within an environment and group B has a narrow field of view, then group A will have a greater sense of presence.

Design implications for virtual planetary exploration systems are that state-process continuity relations should be supported. Field geologists should be provided with available relevant state descriptions, such as maps and images, and support for understanding the continuities between the images and ad hoc virtual views. For example, on a map of the local terrain, available within the virtual environment, a cursor should indicate the current location, direction, and field of view. As another example, photographs from traverses should be related to the locations at which they were made. The virtual presence system should also support creation, development, and elaboration of state descriptions, such as the sketching of features, the collection and annotation of snapshots, and the taking of notes. Finally, it would also be helpful to provide field geologists with a wide field of view display of the virtual terrain, such that the field of view of the camera or projection matches that of the display with respect to the field geologist. In addition, it would be useful to provide a capability for viewing panoramas from local maxima of elevation.

4.2.6 Discontinuity and Dissociation. Just as these diverse kinds of continuity relations are the foundations of presence and at the service of field geology, they can also reveal their character as discontinuities, with the result that presence is diminished and field geology suffers. Not knowing one's position on the map, and getting turned around and lost with respect to landmarks, are typical examples of momentary or lasting discontinuities in field geology. In the natural world, a sense of presence fluctuates with the ebb and flow of its component continuities, but certain of them cannot be readily eliminated, such as the correlation of head motion and visual experience, or physical exposure to the elements. Thus, one can feel a sense of distance but still be irrevocably present to a large degree. In a virtual world, however, certain continuities are difficult to maintain, some of the most fundamental are readily violated, and the redundancy of continuities must be worked in concert to maintain anything like a genuine sense of presence.

While gross violations of continuity do not generally occur in the ordinary experience of presence, they are commonly experienced in dreams, in virtual environment systems, and by watchers of movies and television. The film and advertising industries in particular have elevated discontinuities to an art form. In fact, Music Television (MTV) with its so-call "rock videos" has influenced the visual style of high tech media in recent years with a radical increase in the number and kind of discontinuities. These include discontinuities of visual and auditory flow, the flow of events, and logical juxtaposition, to name just a few. As a result of this style, viewers may enter a state approaching suspended presence.

A more serious and telling example of loss of presence through discontinuity is the dissociation induced by disaster and life-threatening accidents. Victims of these events routinely report a sense of detachment from their bodies, a sense of remoteness, feelings of unreality, a sense of psychological distance and of functioning like robots ("Strange feelings," 1991; "Scientific achievements and discoveries: 1991, Dissociative disorder," 1992). Evidently, when the discontinuity of disaster or accident strikes, negatively altering the environment in a surprising, out of context and disruptive manner, against one's will, one's usual or habitual relationships with the environment are greatly disrupted. (This evidence seems to confirm the hypothesis that if group A interacts with a world based on the persistence of governed engagement, and group B interacts with a world based on transitory and arbitrary discontinuities, then group A will have a greater sense of presence.) Given the role of continuity relations in the sense of presence, one would expect a diminution of the sense of presence when disaster or accident strikes, and that is precisely what is experienced. Further, social discontinuities seem likely to lead to a loss of the sense of social presence, accounting for such phenomena as alienation and anomie.

4.2.7 Summary. From the above discussion, it should be clear that presence and field geology (which is fundamentally premised upon presence) exhibit exploitable redundancies. This makes it possible to decompose presence and field geology into simpler structures by applying the methods of analysis of complex systems. The redundancy in field geology is the common purpose in widely disparate field behaviors of recognizing, reinforcing, and exploiting continuities. With presence, the redundancy is the diversity of forms of continuity that together seem to account for its character. In both cases, the central notion is continuity. This fundamental similarity is reasonable given the evident fact that the essential purpose of field geology is to exploit presence in terrain environments. There are several major classes of continuity: the continuities of continuous existence, that is, the persistence of governed engagement; context-constituent continuities, the primary ones of interest to field geologists being related to geologic context and its constituents; and state-process continuities, linking the flow of observations to more stable representations, geologic processes to the configuration of terrain, and the process of exploration to the structure of planets.

By observing and analyzing presence in field geology, a domain where it is essential, subtle aspects of presence, such as the characteristic continuities, can be made explicit, whereas they might be less pronounced, and so less observable, in more mundane and everyday experiences of presence. By understanding the nature of presence, and its specific applicability to field geology, it is possible to develop theory-based and user-based guidelines for the design of virtual presence systems for planetary exploration. It seems likely that the continuities that characterize the presence of field geologists in planetary terrain also operate, though perhaps with less intensity, within the sense of presence experienced in other domains, and indeed among all who experience presence.

4.3 Methodological Issues

4.3.1 Observation of Field Behaviors. While it is clear that geologic field work has a very significant component that is unobservable directly, that is, the mental activity of the explorer, the behaviorist approach enables the actions prompted by that thought to be observed directly. By prompting explanations, introspection, and comment, it is possible to supplement observations of behavior with annotations obtained directly from the subject, which helps to draw attention to the most relevant aspects of the overt behaviors.

The approach of having the subjects perform "typical" tasks was instructive. Rather than obtain a mere description of field activities, the goal was to observe them closely and in the context of the task environment. This task environment was initially viewed as the physical environment, but it became clear during the Amboy study that equally relevant is the structural context of the motivating scientific field study. This nonphysical context was missing at Amboy, but is now recognized as being of substantial importance.

While instructive, the observation of "typical" tasks was also ultimately unsatisfying. The context of any given task within the motivating structure of actual geological field research was either artificial or missing. Since one of the subjects had spent a considerable amount of time at the site for previous scientific research, the tasks he selected were essentially reenactments. This previous experience provided a globally motivating framework and rationale for the behaviors, and clearly indicated the links between actions and ideas. It did not, however, provide a coherent or comprehensive view of the fabric of field activity, the emergence of ideas and actions, or the specific context and motivation, the antecedents and consequents, of a given behavior.

The other subject, having done no previous field work at the site, performed a more disconnected set of generic tasks including orientation, overview, traversal, rock sampling, and rock identification.

The engagement of the subjects with the terrain, and, therefore, their degree of presence, was attenuated because of overmodulation by the observers. This resulted in rather discontinuous, out of context exploration behaviors. As a result, the author resolved to change the approach for the next studies, so that the subjects would be far more engaged, and the observers would exert far less influence on behavior.

4.3.2 On-Site Interviews and Queries. For the Amboy study, it was expected that presence in the environment would be conducive to a rich interview response from the subjects, as that presence would likely stimulate the user into a frame of mind comparable to that experienced during actual field work. While no proof of the validity of this conjecture is here offered, as might be obtained by interviewing a control group in the lab, based on the results of the interviews conducted in the field, it appears to be a valid and useful approach. Evidence of this is that references to the terrain during the interviews were frequent and detailed. Thus, while the interviews were "unstructured" in the classic sense, they were structured quite appropriately and usefully by presence in the task environment. This would seem to be a notion that would generalize well to other subject and task domains.

4.3.3 Use of the Head-Mounted Camera/Display. Use of the head-mounted camera/display prompted the subjects to introspect and verbalize concretely on their use of vision, visual information, and mental models of the environment, relative to their tasks. This provided valuable information that may not have otherwise emerged. In particular, the limited field of view of the system prompted one of the subjects to say that it was his top priority for improvement. He also called for (in priority order) better resolution, color, stereo, and having the camera/manipulator configuration better match his eye/hand configuration. There was never a thought that the video vision system was better than presence, of course, but experiencing the effects of limited vision in a realistic exploration environment has likely provided the geologists with a more specific and focused understanding of the importance of these visual parameters relative to their work. This kind of experience should improve the utility of the telepresence requirements these users generate.

It was expected that loss of the peripheral visual field due to the limited field of view of the head-camera/display would have a detrimental impact on the subjects' general sense of position and orientation (Haber, 1982). The specific impact of this on geological field work, however, needed to be demonstrated concretely. Otherwise, it would be too easy in the heat of engineering tradeoffs to limit the field of view of a teleoperated system and the visual display of the control system. The personal experience of the ultimate user with the potential limitations on successful field work, like that which was provided at Amboy, will be a decisive factor in getting such theory-based considerations applied to real systems. Without that experience, it is doubtful that the role of field of view in field geology would have been so vividly appreciated. It is particularly significant that the both geologists decried the loss of context resulting from the loss of a wide field of view. Without the intervention imposed by the use of the HMD, such potentially valuable evidence for a theory of presence would have been far less likely to emerge.

Even so, given how very disruptive the use of the HMD turned out to be, it would be difficult to convince a geologist to use the system in the field to do professionally important work, on the usual limited budget of time and money. The system was intended as a device to take a small step back from presence, and the step is too large to be acceptable. That in itself is an interesting result, given the complete lack of time delay, the match between the gesture input and "end effector" output, and the match between head-motion and "image update." Clearly, the virtual presence systems to be designed for exploration of the moon and Mars must take such matters into consideration.

Another negative factor about the headset was the fact that it was front heavy, and tended to slip relative to the face and/or weigh too heavily on the nose. Comfort of head-mounted displays must get careful attention for any long-term use, particularly for use in the field.

To test whether field of view is indeed the key factor in loss of context, it would be reasonable to go into the field with goggles that merely limit field of view but have no effect on resolution, color, stereo, or camera-eye position mismatch. This, however, is also likely to be resisted by a geologist conducting a professionally important study for the very reason that it might well impact negatively on his or her sense of presence in the field.

4.3.4 Recording Observations with Video. The use of videotape to record the field activities and interviews, as well as the subject's view through the head-camera/viewer system, serve as "experiential field notes," recording complex field behaviors for later review. Video allows the behaviors to be repeatedly observed, applying a variety of criteria and attending to different details. The video record captured the rich environment of the terrain and the details of the actions taken by the field scientists in that terrain. Since the subjects were instructed to introspect and talk about their activities, the video/audio recorder also captured this information, and did so in the precise context in which it emerged.

Beyond stepping back from presence, the other two purposes of the HMD video recorder system were to capture the *total* visual experience of the subject and to record the geologist's point of view and his comments as he went about his work. Recording the video vision system imagery as it was presented to the subjects in the field provided an exact record of the total visual input to the subjects. Viewing the recording while wearing the head-set itself is very comparable to the visual experience of the subject, with the important exception that the imagery changes independently of the passive reviewer's head motion. As a result, it is an unpleasant experience. Playback on a small monitor reduces the unpleasantness, but the spatial disorientation remains. This further indicates the importance of head-tracked imagery for capturing the experience of presence, with the caveat that the geologists felt a loss of context, even with head-tracked imagery, when the field of view was small.

The goal of recording the total visual experience may not be worth the decrement in on-site visual performance, but the recording of scenes from the point of view of the geologist could be obtained by other means. Specifically, a tiny video camera with a wide angle lens could be mounted very near to one eye at the side of the head, and the imagery recorded on a VCR in a fanny pack. A further elaboration would be to add a narrow field of view video camera to the other side (for balance) of the head, judiciously pointed, to capture detail in the center 25° or so (the "pseudofovea") of the total field of view, in a manner analogous to the use of high-resolution insets in high-performance military head-mounted displays. The addition of a boom-mounted microphone, such as the one used at Amboy, would be unobtrusive and would provide valuable in-context verbalizations from the geologist.

4.3.5 Stepping Back Farther from Presence. Additional trips to exploration environments would be useful for experimenting with further increments back from presence using video vision and other telepresence techniques. In fact, such a trip was conducted by McKay and Stoker of NASA ARC in 1992. The researchers remotely controlled an underwater rover using a head-mounted display and separate console control system. The system was used in the conduct of scientific exploration of lakes in the dry valleys of Antarctica.

Another approach might be to allow a student in geology to wear a head-mounted camera system and to have the field geologist, sited nearby at a control facility, in communication with the surrogate. The communication between the two, the recorded imagery, and post-field trip interviews might be quite revealing. If the project was done as part of the training of a student field geologist, and the controlling field geologist was the mentor, it seems likely that the intellectual context would be sufficiently rich to be a contribution to the study of presence in the field. By using the unobtrusive camera system of the sort described above, and providing a large, high-resolution color monitor for the controlling geologist, the difficulties of degraded visual performance could be largely reduced to a level comparable to likely future planetary mission capabilities.

4.3.6 Toward Greater Ecological Validity. The ethnographic approach to knowledge engineering applied at Amboy, observing geoscientists as they conducted tasks common in field work, was instructive but limited. Focused studies in analog environments like the Amboy lava field provide an opportunity for exploration technologists to observe and analyze exploration behavior in the field, but, as noted above, the approach taken of observing "typical tasks" was found to introduce a large element of discontinuity. Yet continuity in many forms was found to be essential to the character of presence. Thus, it is evident that it would be valuable as a next step to accompany geologists on purely geoscientific field trips, conducted for the purposes of the geologists in their own way. The structure imposed by professionally meaningful geologic field work would provide a significant contribution to the organization and purpose of observable field activities. This would enable the observation of a full spectrum of exploration behaviors in a far richer context than was done at Amboy.

In fact, the first phase of such a plan has already been implemented with completion of an ethnographic study trip by the author to the 1801 Kaupulehu lava flow of the Hualalai volcano on the island of Hawaii with a different group of field geologists. These scientists were conducting the first phase of a multitrip geologic field study, which is still in progress. The Hualalai site is particularly relevant to planetary exploration as it is considered by the geologists to be an analog for comparable sites on the moon and Mars.

5 Conclusion

The ethnographic study of field geologists can yield information that is not only useful for the development of planetary exploration technologies, but is also applicable to the development of a theory of presence. As a means to these ends, a potentially useful linkage has been established between ethnographic observation and analysis, and object-oriented analysis and design, via methods for understanding complex systems, particularly the identification of redundancies. As a result of this study, the enterprise of field geology has been characterized in a new and potentially useful manner. Further, some testable ideas about the nature of presence, especially the presence of field geologists in planetary terrain, have been offered. Finally, a more solid basis in application and theory has been provided for some of the basic approaches to the design of virtual presence systems, and some new design concepts have been introduced.

One of the reasons for systems designers to learn about the needs of particular users is to gain an understanding that will yield design guidelines to make systems that are structured, and that function, in a way that is inherently familiar to those users. Thus, the operation of the system is metaphorically related to the real-world, non-computer-based application, and the user's knowledge about the task domain is applicable, to a valuable extent, to the operation of the system. For paperwork, the desktop metaphor suffices. For planetary exploration, including field geology, an exploration metaphor is required. The results of this ethnographic field study offer some concrete and specific concepts to develop this metaphor, which could well apply to a broad range of virtual presence systems.

Beyond suggesting improvements in equipment and systems, a better understanding of the subtle and powerful role of presence in field geology will enhance appreciation and utilization of the unique qualities and capabilities that humans can apply to planetary surface exploration.

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References

Akin, D. L., Howard, R. D., & Oliveira, J. S. (1983a). *Human factors in space telepresence.* NASA CR-173420. Washington, DC: National Aeronautics and Space Administration.

Akin, D. L., Minsky, M. L., Thiel, E. D., & Kurtzman, C. R. (1983b). *Automation, Robotics and Machine Intelligence Systems (ARAMIS), Vol. 1: Telepresence technology base development.* NASA CR-3734. Washington, DC: National Aeronautics and Space Administration.

Akin, D. L., Minsky, M. L., Thiel, E. D., & Kurtzman, C. R. (1983c). *Automation, Robotics and Machine Intelligence Systems (ARAMIS), Vol. 2: Telepresence project applications.* NASA CR-3735. Washington, DC: National Aeronautics and Space Administration.

Berelson, B., & Steiner, G. A. (1964). *Human behavior.* New York: Harcourt, Brace & World.

Booch, G. (1991). *Object oriented design.* Redwood City, CA: Benjamin/Cummings.

Clifford, J., & Marcus, G. E. (Eds.). (1986). *Writing culture.* Berkeley: University of California Press.

Compton, R. R. (1985). *Geology in the field.* New York: John Wiley.

Computerized reality comes of age. (1990, August). *NASA Tech Briefs, 14*(8), 10–12. New York: Associated Business Publications.

Conway, L., Volz, R. A., & Walker, M. W. (1990). Teleautonomous systems: Projecting and coordinating intelligent action at a distance. *IEEE Transactions on Robotics and Automation, 6*(2), 146–158.

David, L. (1990). Robots must precede humans to moon, Mars. *Space News, 1*(44), 12, 14.

Daviss, B. (1990, June). Grand Illusions. *Discover, 11*(6), 36–41.

De Jong, E., Saunders, S., Hall, J., & McAuley, M. (1991, October). Magellan scientists use computer-simulated flights to explore Venus. *Information Systems Newsletter,* Issue 23, 1–4.

Fetterman, D. M. (1989). *Ethnography, step by step.* Newbury Park, CA: Sage.

Forsythe, D. E., & Buchanan, B. G. (1989). Knowledge acquisition for expert systems: Some pitfalls and suggestions. *IEEE Transactions on Systems, Man, and Cybernetics, 19*(3), 435–442.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Guralnik, D. B. (Ed.). *Webster's new world dictionary* (2nd ed.). New York: World.

Haber, R. N. (1982). Locomotion through visual space: Optic flow and peripheral vision. Appendix D. In R. Whitman & K. Dismukes (Eds.), *Vision research for flight simulation.* AFHRL-TR-82-6. Brooks AFB, TX: US Air Force Systems Command.

Hammersley, M., & Atkinson, P. (1983). *Ethnography, principles in practice.* London: Routledge.

Held, R., & Durlach, N. (1991). Telepresence, time delay and adaptation. In S. Ellis (Ed.), *Pictorial communication in virtual and real environments* (pp. 232–245). London: Taylor and Francis.

Jacobson, D. (1991). *Reading ethnography.* New York: State University of New York.

Lee, W. T. (1922). *The face of the earth as seen from the air.* New York: American Geographical Society.

Loomis, J. M. (1992). Distal attribution and presence. *Presence*(1), 1, 113–119.

McGovern, D. E. (1991). Teleoperation of land vehicles. In S. Ellis (Ed.), *Pictorial communication in virtual and real environments* (pp. 182–195). London: Taylor and Francis.

McGreevy, M. W. (1984). *NASA Ames Virtual Environment Display: Applications and requirements.* Unpublished internally distributed technical document, Aerospace Human Factors Research Division. Moffett Field, CA: NASA Ames Research Center.

McGreevy, M. W. (1988). Personal simulators and divergence from realism. Plenary address, SIGGRAPH Symposium on User Interface Software, Banff, Alberta, Canada.

McGreevy, M. W. (1989). Personal simulators and planetary exploration. Plenary address, CHI '89, Association for Computing Machinery conference on Computer-Human Interaction.

McGreevy, M. W. (1990). The exploration metaphor. Invited technical presentation, Engineering Foundation Conference on Human-Machine Interfaces for Teleoperators and Virtual Environments.

McGreevy, M. W. (1991). Virtual reality and planetary exploration. *On Line* 13(8), 1,3,8.

McGreevy, M. W. (1993). Virtual reality and planetary exploration. In A. Wexelblat (Ed.), *Virtual reality: Applications and explorations.* Cambridge, MA: Academic Press.

McPhee, J. (1980). *Basin and range.* New York: Farrar Straus Giroux.

McPhee, J. (1982). *In suspect terrain.* New York: Farrar Straus Giroux.

McPhee, J. (1986). *Rising from the plains.* New York: Noonday Press.

NASA, 1973. *Apollo 17 preliminary science report.* NASA SP-330. Washington, D.C.: National Aeronautics and Space Administration.

NASA, 1989. *Report of the 90-day study of human exploration of the Moon and Mars.* Washington, D.C.: National Aeronautics and Space Administration.

Philbin-Ziv, P. (1991, March). Weltraumforschung am computer. *MACup,* 8–17.

Pivirotto, D. S., & Dias, W. C. (1989). *United States planetary rover status—1989,* p. 21. JPL Publication 90-6. Pasadena, CA: Jet Propulsion Laboratory.

Planets of the mind's eye. (1991, November 9–15). *Economist,* 153–154.

Rayl, S. (1991, July 21). The new, improved reality. *Los Angeles Times Magazine,* 17–20, 30.

Scientific achievements and discoveries: 1991, Dissociative disorder. In M. S. Hoffman (Ed.), *World Almanac* (p. 198). New York: Pharos.

Sheridan, T. B. (1992). Musings on telepresence and virtual presence. *Presence,* 1(1), 120–125.

Sheridan, T. B., Kruser, D. S., & Deutsch, S., (Eds.) (1987). *Human factors in automated and robotic space systems: Proceeding of a symposium,* p. 324. Washington, D.C.: National Research Council. (Note: Exact quote obtained from official recording of speakers and commentators.)

Simon, H. A. (1969). *The sciences of the artificial.* Cambridge, MA: MIT Press.

Spradley, J. P. (1979). *The ethnographic interview.* Fort Worth: Holt, Rinehart & Winston.

Stewart, D. (1991). Artificial reality: Don't stay home without it. *Smithsonian, 21*(10), 36–45.

Stoker, C. R., McKay, C. P., Haberle, R. M., & Andersen, D. T. (Eds.) (1989). *Mars human exploration science strategy.* Report of the Ames Space Science Division Mars Study Project and Report of the Mars Science Workshop. Moffett Field, CA: NASA Ames Research Center.

Strange feelings show as result of '89 quake. (1991, May 17). *San Jose Mercury News,* p. 5b.

Swann, G. A., Bailey, N. G., & Regan, R. D. (1967). *Apollo applications program field test 5.* Technical Letter: Astrogeology 27. Flagstaff, AZ: United States Geological Survey.

Taylor, G. J., & Spudis, P. D. (1991). A teleoperated robotic field geologist. In S. W. Johnson & J. P. Wetzel (Eds.), *Proceedings of space '90: Engineering, construction, and operations in space II* (pp. 246–255). New York: American Society of Civil Engineers.