LUCI

"The Social Life of Spacecraft: The Organization of Interplanetary Socio-Technical Systems"

by

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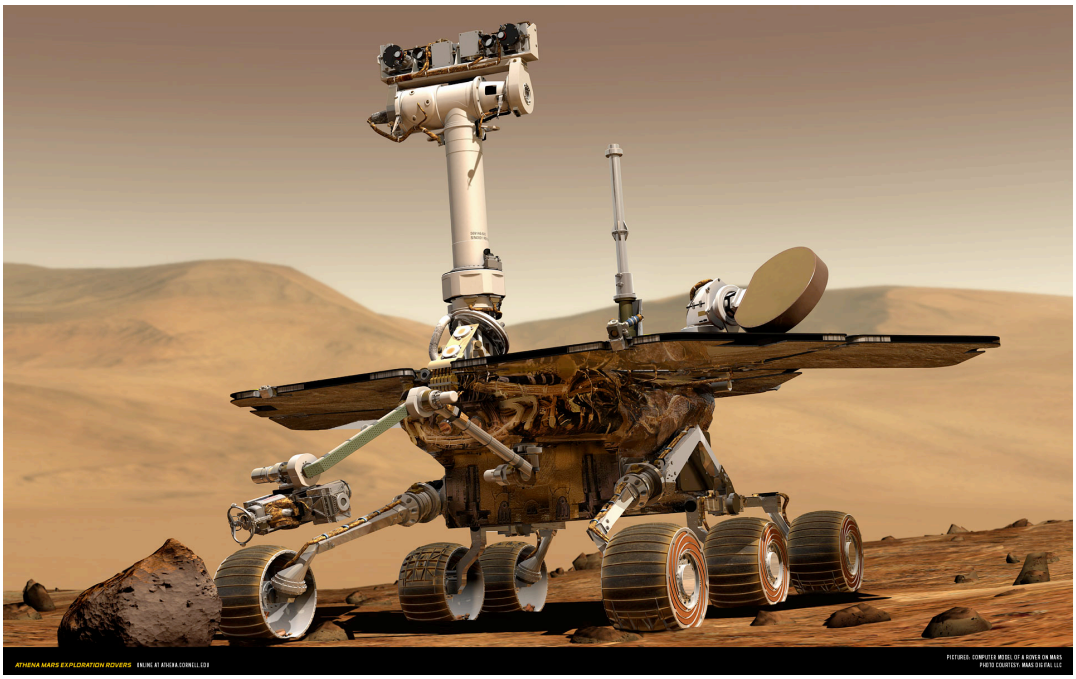
L U C I T E C H N I C A L R E P O R T
LUCI - 2008- 03

THE SOCIAL LIFE OF SPACECRAFT

THE ORGANIZATION OF INTERPLANETARY SOCIOTECHNICAL SYSTEMS



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Project Summary

Theorists in the social and historical studies of science and technology have long explored how technologies are constructed alongside assumptions about the organization of (scientific) labour and ideologies of the human and the machine. Building on existing engagements, our project will explore these interconnections in detail through ethnography, interviews, and archival work on NASA's Mars Exploration Rover mission and comparative case studies. Through our ethnographic and archival work, this research will offer a detailed, grounded case study of high-visibility scientific work conducted under extreme conditions of distribution and virtuality, in a complex organizational setting; through our comparative work, we will draw out the particular importance of, and relationship between, organizational culture and structure in these cases of "interplanetary sociotechnical systems."

Mars Rover team members consistently characterize their mission as uniquely successful and harmonious among NASA-funded unmanned missions. In their accounts, previous missions are characterized by hierarchies and fragmentation – both among members of competing science teams tied to different instruments, and between scientists and engineers – leading to antagonistic relationships between members of the spacecrafts' science and operations teams. In contrast, they claim, the Rover mission is purposefully organized so as to espouse different principles. They cite such innovations as acute attention to improved communication between scientists and engineers, the fostering of clear roles but within a flattened hierarchy, adherence to a consensus-driven decision-making model, open access to scientific data such as images on the internet upon their downlink from Mars, and the organization of a single Science Team into thematic groups around a holistically-designed Rover instead of into instrument-specific teams who otherwise vie for precious spacecraft time, power and bytes. Is the Rover project as unique as members believe? What factors distinguish this project, as a sociotechnical system, from others? What characterizes the role of cyberinfrastructure as an element of their work?

Intellectual Merit

The *intellectual merit* of our proposal lies in its melding of two areas of investigation – the history and sociology of science from the STS tradition, and the study of virtual organizations from the CSCW and Organization Sciences traditions – to generate a holistic picture of the institutional realities of large-scale technoscience in a radically distributed context. In particular, the NASA teams' dual perspectives on cyberinfrastructure – as an object that they create and as a means through which they work – offers unique insights into sociotechnical systems practice.

Broader Impacts

The *broader impacts* of this work include design implications for the next generation of cyberinfrastructure tools, and, in particular, ways of understanding scientific practice alongside the tools through which it is conducted, a truly sociotechnical approach. This is particularly relevant in cases such as space science, which is a critical site which scientific research reaches public consciousness; the very public nature of scientific success and failure associated with projects such as the Mars Exploration Rover make it an exemplary case study of contemporary scientific practice.

Project Description

It is a busy day on Mars. As the sun rises over the equatorial plains, NASA's Mars Exploration Rover *Opportunity* begins a painstaking descent into the large impact crater known as Victoria Crater. On the other side of the planet the sun is setting on her twin Rover, *Spirit*, also in a crater, who is racing against the clock at the speed of fifteen meters per day towards a place at the edge of an ancient hotspring where she[1] can survive the Martian winter.

It is a busy day on Earth too. At 8am Pacific time, a team of scientists associated with the Mars Exploration Rover (MER) team phone in to a teleconferenced meeting from their homes, offices, cafes and cars across the United States and some of Western Europe. A team of engineers at NASA's Jet Propulsion Laboratory in Pasadena, California are clustered at the back of the sizeable Science and Operations Working Group Meeting room, seated behind blue tent cards that spell out their roles for the day. Some of their scientist and instrument operator colleagues are visible on a commercial videoconference link, some are merely voices on the line; many of them have never met each other face to face and many more never saw the Rovers before take-off four years ago. As the voices on the line state their names and roles for the day, the empty chairs behind abandoned blue tent cards in the room at JPL slowly fill with virtual participants.

At the meeting, the group of scientists and engineers discuss a map generated the previous evening and distributed by a group of participating Geographical Information Systems scientists and their graduate students in Ohio, who have extracted elevation data from the Rover images to build a slope and terrain map upon which to plan the drive into Victoria. They circulate this file to the scientists and engineers through the group's internal "docushare" site (a web-based document repository). As the group analyzes the map and available image data together, an engineer at JPL traces her cursor across a screen linked to the internet so that everyone on the line can follow along. Collectively parsing the map, they decide to change the route to avoid a newly-discovered driving hazard ahead, and team members follow along with the changes on a dynamically shared plan developed on the command software.

When the teleconference ends, the engineers move downstairs to their workspace, dial into another teleconference line to connect to the Rovers' instrument operators across the country, and enter the commands that will allow *Opportunity* to descend into the crater: to do so, they must import images taken by the Rover into their command software, and manipulate a digital Rover in the resulting three-dimensional virtual space. A few hours later, the same team meets again by teleconference, but this time for a more heated discussion about *Spirit*'s race to a winter haven. One group of scientists argues that Spirit should go South, and has prepared Powerpoint slides laden with images and distributed them across the network; another group has prepared a counter argument for the northern edge and has hefty Powerpoint files of their own. As the team settles in to listen to the debate between the two sides, each member of the virtual group of scientists and engineers knows that at the end of the day, they have to decide on a single course of action. After all, this team – and the Rovers they animate – operates by consensus.

Many layers of virtuality knit the Mars Exploration Rover team together across the United States, Europe, and two field sites on Mars. In terms of technical infrastructure, the team relies upon systems from password protected file networks to teleconference lines, from Polycom video links to in-house software. They also rely on a network of satellite dishes around Earth and orbiters around Mars to relay their commands, and on two Rovers on Mars to execute them. But in this activity, they also rely on their colleagues, and on the organization and continued goodwill of a col-

[1] Like naval officers talking about ships, NASA project scientists anthropomorphize the Rovers as female when speaking of them in the third person. Discussing mission operations, however, the team uses the first person plural pronoun, "we". (Vertesi, 2008b)

laborative virtual team comprised of distinguished scientists, experienced engineers and excited graduate students. The team operates almost exclusively by consensus. As one of the instrument operators put it, "Once those Rovers leave Earth, the team is all we've got."

The proposed project expands on existing research to take seriously the social organization and dynamic of the team of scientists and engineers who operate robotic spacecraft such as the Mars Exploration Rovers, the interactions between team members and their robots, and the politics governing these robots' operation in the context of 20th and 21st century space science. We draw on a range of studies conducted of distributed scientific and engineering enterprises, including studies of "collaboratories" (Finholt and Olson, 1997; Lee et al., 2006; Olson et al., 2006) and other distributed organizations (Olson and Olson, 2000; Hinds and Kiesler, 2002; Cummings and Kiesler, 2005).

The topic of space science is particularly interesting, for various reasons including, first, the scale of the problems and, second, the public nature of the enterprise. While manned missions have received much attention from historians and sociologists of aerospace history (e.g. Mindell, 2008; Siddiqi, 2003; Vaughn, 1996), unmanned missions tend to draw less analytical attention due, perhaps, to an assumed literal absence of a human component in their operations (see Clancey, 2006). These missions have been the subject of technical reports, publications by participants (e.g. Mishkin, 2003; Shirley, 1998; Squyres, 2005), and even organizational studies (i.e. McCurdy, 1993) but have elicited little analysis from the history of technology, prompting recent calls for studies of robotic mission operations to balance our rich accounts of the human space exploration program (Dick and Launius, 2006; Launius and McCurdy, 2008). Indeed, previous NSF-supported research suggests a rich connection between the social organization of the human team, the technologies that anchor and inspire their interactions, and the management of spacecraft operations at interplanetary distances. Our project aims to explore these interconnections in detail through ethnography, interviews, and archival work on the Mars Exploration Rover mission and comparative case studies. Through our ethnographic and archival work, this research will offer a detailed, grounded case study of high-visibility scientific work conducted under extreme conditions of distribution and virtuality, in a complex organizational setting; through our comparative work, we will draw out the particular importance of, and relationship between, organizational culture and structure in these cases of "interplanetary sociotechnical systems."

PREVIOUS WORK

Theorists in the social and historical studies of science and technology have long explored how technologies are constructed alongside assumptions about the organization of (scientific) labor and ideologies of the human and the machine (c.f. Akrich, 1992; Doing, 2007; Latour, 1987; Lynch, 1993; Pinch & Bijker, 1987; Schwartz-Cohen, 1983; Shapin and Schaffer, 1989; Suchman, 1987; Zuboff, 1984). The proposed project aims to apply this approach to the study of the robotic space exploration. To better characterize the human element of unmanned space flight, we recall Appadurai (1998) in the phrase "the social life of spacecraft".

Our previous work on the Mars Exploration Rover mission (NSF award no. 0645945) has emphasized the political and social organization of the human team that animates the spacecraft. This echoes earlier studies of the Rovers as robotic proxies for their human teammates (Clancey, 2006) and studies of the organization of labor on Mars-Time (i.e. Mars's 24.5 hour-a-day clock) in the first 90 days of the MER mission (Mirmalek, 2008). Indeed Mars Exploration Rover team members consistently characterize their mission as uniquely successful and harmonious among NASA-funded unmanned missions. In their accounts, previous missions are characterized by hierarchies and fragmentation – both among members of competing science teams tied to different instruments, and between scientists and engineers – leading to antagonistic relationships between members of the spacecrafts' science and operations teams. This speaks to the deeply sociotechnical nature of their organization: recalling a previous mission in which thirteen differ-

ent Principal Investigators managed thirteen different instruments, one Rover team member exclaimed it was a miracle the spacecraft, "didn't tear itself apart into thirteen pieces!"

In contrast, team members claim, the Mars Exploration Rover mission is purposefully organized so as to espouse different principles. It is these claims of uniqueness and difference from conventional practice as sources of the project's success that motivate our research. Team members cite such innovations as acute attention to improved communication between scientists and engineers, the fostering of clear roles but within a flattened hierarchy, adherence to a consensus-driven decision-making model, open access to scientific data such as images on the internet upon their downlink from Mars, and the organization of a single Science Team into thematic groups around a holistically-designed Rover, instead of into instrument-specific teams who otherwise vie for precious spacecraft time, power and bytes.

On the other hand, this organization of the team is enacted in the operation of their robotic vehicle on another planet. This process requires managing not only elements of a distributed cyberinfrastructure but also a variety of sociotechnical resources to sustain the culture of consensus. For example, previous studies have shown how, using visualization software and Rover-mimicking gestures, team members not only embody the Rovers' interactions with Mars but even come together in the body of the Rover to experience Mars at a distance (Vertesi, 2008b). Locating "where the action is" (Dourish, 2001) with such a team requires navigating the virtual spaces of teleconference lines, the images and imagined virtual spaces of the Martian terrain, and the phenomenological embodied practices that bring the Rovers to life, bring Mars to Earth, and bring the team together.

We also draw upon extensive research into distributed collaboration and virtual organizations. Although studies of computer-supported collaboration stretch back to the early 1980's (Greif, 1980), the last decade has seen increased interest in the use of information technologies to support "virtual organizations" – ad hoc coalitions of partners who operate as an organization although with little or none of the formal infrastructure that characterizes traditional organizations (Mowshowitz, 1997). The range here is vast. On the one hand, we find instances of "virtual teaming" within established organizations, where project teams involving distributed members are rapidly assembled to tackle specific problems and dissolved once more when those problems have been addressed, but which operate within a known organizational context (e.g. Mark and Poltrock, 2004; Chudoba et al., 2005). On the other hand, we find instances in which collaborations emerge with no formal institutional structure at all, such as the case of open source software development (O'Mahoney and Ferraro, 2004; West and O'Mahoney, 2005; Mockus et al., 2002), which, in its purest form, is an entirely voluntary form of collective activity.

Research into distributed collaborations like these has emphasized a number of important concerns. We know that both time and distance impose significant obstacles that collaborators must overcome, most especially in the informal aspects of group work that are much more easily achieved in collocated groups (Olson and Olson, 2000; Jarvenpaa and Leidner, 1998; Teasley et al., 2000). Perhaps the most challenging issue the development of shared norms (Mark, 2002a) and a shared organizational culture (Barley, 1983, Smircich, 1983) that spans the different groups who make up the larger team. Research into organizational culture – the sets of practices, conventions, and understandings that characterize an organization's world-view and the shared values of its members – suggests that culture plays as significant role in coordination as organizational processes and routines (Pentland and Feldman, 2005). Coordination occurs not only through a common understanding of ways to solve problems, but a common orientation towards the semiotics of organizational life (Barley, 1983).

Although the analysis of organizational culture has often been associated with questions of evolution and organizational learning (Cook and Yanow, 1993), it has also been proposed as a way of understanding the framing of problems

and solutions particularly relevant in engineering organizations (Kunda, 1992), where it begins to illuminate the value systems within which notions such as elegance, efficiency, and innovation are deployed to evaluate solutions. At the same time, the culture of scientific work and the notion of science's value system was one of the first topics in the sociological study of science and scientists (Merton, 1973). It seems appropriate, then, to examine the social life of spacecraft, and the distributed technoscientific contexts of their production, from the perspective of organizational culture, in order to examine the ways in which value systems and cultural conformance play a role in the "human infrastructure of cyberinfrastructure" (Lee et al., 2006).

Our research examines of the organization of robotic space exploration teams as virtual sociotechnical systems. Our central question is: how, and to what extent, is the design, history and evolving story of the technology of robotic exploration bound up with the social organization of its human team? Or, to put it another way, how can we explore the relationship between the social organization and the operation of robotic spacecraft, given the centrality of cyberinfrastructure and virtual presence to the spacecraft as a complex sociotechnical system?

CRITICAL QUESTIONS

To explore these questions, we propose three complementary research strands. The first places the Rover mission itself into deeper institutional and historical context by seeking to understand the origin and development of mission operations strategies; the second broadens this context by seeking comparative cases with other historical and contemporary missions; and the third connects these social and cultural contexts specifically to the development and use of cyberinfrastructure.

1. The Mars Exploration Rover mission in institutional and historical context

What are the origins of the practices that Rover team members identify as unique to their mission? Engaging in a historical study of the Mars Exploration Rover mission both in its own right, and set within the context of NASA's institutional history may help us to address this question. After all, the Rovers are deeply embedded in and shaped by NASA's institutional history and culture. Spirit and Opportunity were born out of NASA's troubled Mars Exploration Program in the 1990s, which included the loss of Mars Observer (1992), Mars Climate Orbiter (1998) and Mars Polar Lander (1999): these spacecraft were designed in the wake of a presidential directive (the Space Exploration Initiative, discussed by Hogan, 2007) and an aggressive (but failed) Russian Mars exploration program in the 1980's and early 1990's. This setting is complicated by inter-institutional relationships surrounding the history of the Jet Propulsion Laboratory as the center for NASA unmanned missions operations and research (see Westwick, 2007). For example, during the mission, a Presidential directive to send humans to Mars in the near future changed the landscape of robotic space exploration as many engineers at JPL were laid off in order to build capacity at "manned" centers like the Johnson Space Center. More recently, budget difficulties with the next generation Rovers – the Mars Science Laboratory mission, under development – led to a NASA directorate decision to cut funding to the Mars Exploration program altogether, threatening the survival of the Rovers and orbiters already on Mars; upon public and institutional outcry the funding was reinstated, following which the Associate Administrator for the Science Mission Directorate tendered his resignation. Such examples prompt us to inquire into the relationship between the human and robotic streams of the NASA program (as explored by Launius and McCurdy, 2008), and the tensions between existing robotic missions, including allocation of resources and sharing of knowledge around team and communications management. Finally, the Rovers' operation in post-9/11 America places the mission amid a complex backdrop of congressional funding cycles, international politics, and military regulations concerning the participation of foreign nationals in aerospace ventures (see ITAR; Devorkian, 1992; Sheehan, 2007). To situate the mission within this rich political and (inter-)institutional history, we must explore the origins, development and response to such space policy directives. We will conduct this exploration through archival work at NASA centers, at the National Archives and

Records Administration in Washington, D.C. and local Federal Records Centers, and through extensive oral history interviews with past mission participants.

2. Comparative case studies with other missions

In addition to this deepening historical understanding, we are concerned that our previous ethnographic experience on a single mission is biased to how Rover team members believe they compare to others. We therefore ask: how unique is the Rover's model of team organization, and what other arrangements of humans and machines have characterized unmanned spaceflight missions? Under the proposed project we hope to broaden our perspective with studies of the spacecraft that these actors most often cite as precedents or comparative cases.

Of especial interest in our examination of these field sites is whether or not issues raised in the history of manned spaceflight have parallels in robotic exploration. For example, Slava Gerovich's (2007) studies of the mechanization of the Russian cosmonauts in contrast with the American astronauts' self-fashioned rugged individuality (Launius, 2005; Mindell, 2008) raises questions with respect to the Rovers; i.e. what kind of ideology is invoked in the political arrangement of technologies and bodies governed by consensus management, especially as embedded in the post-Cold War and post-9/11 historical milieu? We believe that bringing a perspective from Science and Technology Studies, Human-Computer Interaction, Computer-Supported Co-operative Work, and studies of virtual organizations to bear on previous and contemporary robotic missions will generate a detailed study of robotic space exploration, contributing to the broader literature in the understanding of these interplanetary sociotechnical organizations.

Historical missions will no doubt prove to be critical to understanding the organization of the contemporary spacecraft teams, not the least because several members of current missions were participating scientists or graduate students on previous missions. Mariner 9 (1971-2) and Viking (1975-1980) are often recalled as missions with strict organizational hierarchies recalling military managerial styles, while Voyager 1 and 2 (1977-present) are described as a 'dream team' and closest thing to a strong precedent for Rover operations (note that Mars Exploration Rover Principal Investigator Steve Squyres was a graduate student on this mission in the 1980's under Carl Sagan and Eugene Shoemaker.) Galileo is recalled for conflicts among the Science Team over the interpretation of image data from Jupiter's moon Europa, as well as fractured infighting that took the spacecraft on and off the launchpad so often that its high-gain antenna ultimately failed in flight, providing one of the most vivid cases of sociotechnical failure in these missions (1989-2003). Mars Pathfinder (1996) is remembered as primarily an exploratory engineering mission in which tensions between scientists and engineers were felt and managed in earnest (see Shirley, 1998).

Contemporary missions also provide comparative cases for the Mars Rover example: these we propose to analyze in some detail through ethnographic observation of meetings and interviews of three related projects. The Cassini-Huygens mission (1997-present) sports twelve different Principal Investigators tied to twelve different instruments, many of which are operated by different countries. NASA's upcoming new generation of rovers, the Mars Science Laboratory, sports a return to the model of multiple PI's as well. In addition, fruitful points of contrast may be offered with the European Space Agency's planned ExoMars Rover mission, especially concerning intergovernmental relations and cross-cultural miscommunications (Zabusky, 1992). More information on these missions follows in the subsequent section; we have already set up meetings with contacts at each of these missions to explore the potential for longer-term observation.

3. The duality of cyberinfrastructure

The Mars Exploration Rover team is simultaneously embedded in two cyberinfrastructures – that of the global network of data and collaboration tools that support their distributed operation, and that of the Rover control system itself, in which their very operation, management and data distribution is embedded. Cyberinfrastucture, then, is not

simply, for them, a critical component in the operational aspects of their work; it is also their raison d'etre. By the same token, the team does not simply constitute a sociotechnical system; sociotechnical systems are also their products and objects of attention. It is this duality that motivates our third research question, what are the mutual influences of the Mars Rover team's two relationships to cyberinfrastructure, as users and as builders?

To some extent, of course, almost all cyberinfrastructure developments efforts to date have shared some of this duality, because most have been relatively "home-grown" efforts construed in the "roll-your-own" or "eat your own dog-food" modality (in the colorful language of engineering efforts.) Similarly, sociological studies of infrastructure development and use have emphasized the relational nature of infrastructure (Star, 1998; Star and Ruhleder, 1996). However, in the case of the Mars Rover team, large-scale infrastructure is a primary focus of their work. In the tradition of "Big Science" efforts such as those of high-energy physics, this is a team of scientists whose science depends primarily on the construction and deployment of instruments; indeed, the process of constructing and deploying those instruments frequently absorbs more time, effort, and money that the process of using them (Traweek, 1988; Galison and Hevly, 1992). We are interested, then, in how the Rover team's conception of themselves as tool builders and tool users figures in the development of strategies and approaches to the organization of the project as a sociotechnical system.

Further aspects of this iterative relationship are manifest in how tools such as software and spacecraft are managed as both technical and social resources, with an eye to the management of the social network that supports this infrastructure. For example, Rover "health," "injury," and "death" are often wielded as a way to support or undermine a decisions about which way to drive or what science observations to accomplish. In another vein, the Rover's command software is under continuing development by an internal team of software engineers who are committed to releasing open source versions to the public and to testing versions for future missions; thus developments made in the interest of a single mission are assumed to have implications beyond the mission itself. In this study we plan to more deeply articulate these tool-using and -building strategies as well as establish a base for comparative study with other missions.

METHODS

The study will rely on three kinds of sources: participant observation; interviews and oral histories; and archival work.

1. Ethnographic Study

Work with the Rover team remains ongoing, and at time of writing we request funding to support ethnographic work at three sites for further comparative study.

1. **The Mars Science Laboratory** (MSL), launching in 2009, is another NASA Rover mission. It involves much of the same personnel as the Mars Exploration Rover team, but in a different configuration using the multiple-PI approach. While in the pre-launch phase, the mission is currently under high stress as it is over-budget and behind in its preparations for launch: situations of stress that challenge a team to work together effectively, thus revealing the underlying organization of the group. Upon launch NASA plans to move almost immediately to remote operations as a cost-cutting measure, meaning that the face-to-face bonding period of the primary mission will be lost. Our research group has made plans to attend the Landing Site Selection meeting in September 2008.

2. **Cassini** has been orbiting and exploring the Saturn system since July of 2004. As a robotic orbiter whose maneuvers are planned in advance in evenly spaced teleconference calls, the spacecraft presents different challenges to that of a Rover. However, the team sports thirteen different PI's, and while team meetings are heavy on negotia-

tion, the team as a whole does not operate by consensus. We have met with members of the Cassini team, including the PI of the imaging team, and have been offered an opportunity to observe some of their work in progress. Much of the work of managing Cassini occurs at JPL, although meetings occur around the country and internationally (due to co-operation with the European Space Agency).

3. The **ExoMars Rover** mission, to be undertaken by the European Space Agency, is currently under active development for launch in 2011. In its development phase this mission provides a fruitful site of comparison as one not managed by NASA. In addition to the multiple-PI approach, the mission is complicated by the participation of different countries and national space agencies as sponsors of different science teams and their associated instruments. The ESA would provide a fascinating site at which to observe the challenges of managing such an intercultural arrangement of participants around a proposed technical system. Meetings are expected to be intermittent but access may prove extensive; we have meetings scheduled with the the ExoMars team lead in the Netherlands in August 2008.

At each of these sites we will study the human team's interaction around their technology, both current and proposed. This will primarily include attending planning and science meetings to the extent permitted by national security restrictions. It may also include observation of scientists or engineers at work on these projects, again to the extent permitted by security regulations. Consistent with previous work on distributed teams linked by cyberinfrastructure, such interviews and observations will require travel to the location of the scientists' place of work: many of these scientists are located close to our institutional home base but some are farther flung across the United States and abroad. Past study of the MER mission has also confirmed that site visits are necessary, regardless of the daily teleconference meetings, as participants' experiences of the meetings differ from place to place.

The study of virtual teams in meeting situations may prove challenging due to the use of video and teleconference software that can obscure observation. We are here informed by a number of strands of prior research (Nardi et al, 1993; Heath and Luff, 1992; Dourish et al., 1996; Mark, 2002b). First of all, the challenge involved in using such technology may be usefully construed as the object of study, as it may be important to observe how and where the infrastructure of virtual sociotechnical systems can itself prove to be a resource in the management of large, distributed teams. In the MER study, it became clear that such teams have tightly honed methods of communicating from precision in turn-taking, to mute-button management, to the use of roles and hierarchies for decision-making. Here the techniques of Conversation Analysis (Sacks et al. 1974) will prove particularly useful. Conversation Analysis aims to disentangle records of conversation to observe talk as an activity with practical consequences and effects. Exemplary studies of scientists' talk-in-interaction (Garfinkel et al., 1981; Lynch, 1985a; Knorr-Cetina and Amman, 1990; Ochs et al., 1996; Woolgar, 1990), have aptly demonstrated how scientific talk is not simply demonstrative, but also constitutive: as scientists attempt to make something of what they see, their talk is essential for identifying objects, aligning observations, and co-ordinating action. Following strands of conversation around images, sequences of observations, and plans, even as it occurs over telephone lines, will prove helpful to untangling the nuances of the co-ordination of work and action in these distributed, interplanetary sociotechnical systems.

2. Interviews and Oral History

Both formal and informal interviews will also provide key primary materials for this project. On the one hand, getting a subject to talk about what he or she does while in the process of doing it is an engaging way to gain understanding of the activity. On the other hand, several key members of the team possess the experience, knowledge, and 'living memory' of the missions under study that will prove essential to this project. Visiting them on location for an interview can not only build the kind of rapport that generates rich data, but also can provide immediate access to the artifacts and images that might be essential to their stories. As these subjects are located in different sites, al-

though mostly clustered around participating institutions, face-to-face interviews will require travel funding to access participants and material settings.

However, this project also aims to situate contemporary missions in historical context, including attention to the work practices and social organization of unmanned space exploration missions undertaken by NASA from the early 1970's to the present. This project will rely extensively on oral history interviews, for two reasons. First, many of the missions under examination, including the Mars Rover Project, are too recent (or may even be ongoing) for their records to yet be made available to public access. The only way to access information about what decisions were made and what the working environment was like on earlier missions is to locate mission personnel, whether participating scientists, engineers, or administrators, and interview them. Second, due to national security restrictions, several documents and technical details of these missions are unavailable to public scrutiny and access would not be permitted even for academic research purposes. Such restrictions can be avoided through the use of interviews and similar conversations are a preferred method that enables the researcher to explore complex social and historical questions while avoiding the exchange of technical information, as protected by the International Traffic in Arms Regulations (ITAR: Code of Federal Regulations, Section 22.1.M. 121-130. For another example of such a study, see Gusterson, 1996). Such interviews cannot be performed by telephone, but require site visits to build rapport, make lateral contacts and enable informants to share materials from their personal collections. Fortunately, several contacts on the Rover mission have generously ensured that this project begins from an advantageous position, providing access key players in the planetary science community, and assisting our team in establishing connections with notable informants, both in America and abroad.

3. Archival Work

This project will also draw from textual, video and audio documents that can richly illuminate the history of the Rover mission as well as its robotic predecessors. These include the mission-specific documents present in the Federal Archives and Records Center Accessing such as archived reports, proposals and publications; mission documents that are still in use or in recent storage in participants' desks and file folders; and the archive of recordings from the Mars Rover's primary mission at NASA Ames Research Center. We also expect that documentation of the early days of the Rover mission, from minutes of meetings for specific projects such as the planning software or the panoramic cameras, to records from previous operations and engineering meetings, will be a critical resource for this project, as will the maps, satellite images and slides of Mars from past missions that deeply informed the choice of landing sites. Connections with Ames as well as the NASA History Office in Washington, D.C. will greatly facilitate such archival work at these locations and at other NASA Centers. The researchers' past experience in the history and sociology of science and technology will no doubt prove useful in bringing archival work into conversation with interviewing techniques in this study of the recent past.

INTELLECTUAL MERIT AND BROADER IMPACT

Intellectual Merit

Apart from the specific research questions that we set out to answer, the **intellectual merit** of this proposal lies primarily in its harnessing of multiple disciplinary perspectives to create a unified perspective upon a significant example of a virtual organization. Our proposal combines work in Science and Technology Studies (STS) with research in Computer-Supported Cooperative Work (CSCW) to bring a broad-based approach to the study of virtual organizations. From STS, we bring a concern with institutional and cultural contexts and the materiality of scientific practice; from CSCW, we bring a concern with technological mediation of social relationships and the importance of the informal and social aspects of everyday work. Although there have been some tangential connections between STS,

CSCW, and Organizational Studies (e.g. Barley, 1986; Gerson and Star, 1984; Suchman, 1987; Star and Griesmer, 1989; Button and Sharrock, 1998; Kellogg et al.,2006), our goal here is to forge stronger ties between these clearly-related areas of research investigation.

Broader Impacts

This study of a virtual sociotechnical system is poised to make at least two wide-reaching contributions to the organization and management of virtual teams. The first concerns the structure of NASA mission organization and management, while the second has broader implications for virtual organizations more generally.

Largely informed by military operations studies, NASA has paid much attention to the organization and management of its human teams and resources on manned missions. For example, the spectacular failure of the Challenger mission in 1986 led to public inquests that specifically targeted not only the O-rings, but the role of organizational decisions about the management of technical resources – from private suppliers of parts to engineers encouraged to treat reviews as routine – as fatal flaws that doomed the mission (Vaughn, 1996). Spectacular failures have also animated the robotic side: on Mars alone these include the loss of NASA's Mars Observer, Mars Climate Orbiter and Mars Polar Lander (colloquially called "Mars Polar Crasher" by team members), or the ESA's Beagle 2. However, little has been learned about the social life of spacecraft, their human component, aside from accusations of "poor management" or "not enough testing". Instead, NASA seems to treat the robotic spacecraft as a collection of technical problems needing to be solved: which instruments can be flown, how they should be attached, what the communications protocols should be, and what knowledge of the planet they are visiting is required to plan entry, descent and landing.

If our intuition is correct, however, the success of the Mars Exploration Rover mission – which has lasted 1500 Martian days instead of the projected 90 – is not only due to its technical robustness but also and especially to the organization and management of the team. If this is the case, then NASA's decision to return to the multiple-PI model for flagship missions like Cassini or the next generation of Rovers, Mars Science Laboratory, may have significant consequences for the science and even the technical operation of these missions. After all, the strain of internal disputes about Galileo may have contributed to its high-gain antenna failure and significant infighting over the interpretation of its limited image returns; the Mars Climate Orbiter failed due to miscommunication among its international team of engineers involving Imperial versus Metric units; and while the loss of the Beagle 2 was eventually ascribed to miscalculation about the Martian atmosphere, the European Space Agency admitted that its approach to Beagle as a purely technical addition to the Mars Express mission resulted in poor prioritization and support of the mission in its development phase. As increasing national, international and public-private co-operative teams are taking to space exploration, this study of the social life of spacecraft hopes to offer insight into the arrangement of the human element of the operating team that is ultimately bound up in the technical operation of the space-faring machine.

But the insights gained from a study of robotic spacecraft are not limited to space exploration alone. Increasingly large, international and distributed teams are engaged in complex planning or the operation of technical resources under the rubric of cyberinfrastructure. In the Rover case, we have a clear example of people engaging in this work daily, on a shifting but demanding schedule, and performing at such a level that both their social and their technical resources (i.e. the Rovers and the team members) continue to function at a high level. Understanding what exactly drives the functionality and dysfunctionaltiy of such extreme examples will no doubt prove important to the organization and development of virtual sociotechnical systems in a variety of contexts.

In addition, the proposed research has a particular sort of impact, and which is especially significant for the public funding of science (Galison and Hevly, 1992). After all, it is extremely important to recognize that the science we are studying here is "public science". Not only is it publicly funded, but it is also reported on the nightly news, and avidly followed on official and unofficial websites by professionals and amateurs alike. The importance of new digital media extends the cyberinfrastructure web to the public as data is released on downlink to the public, the Mars Rovers have their own LiveJournal blogs, and the Phoenix mission to Mars (just landed at time of writing) has its own Twitter feed with hundreds of subscribers in which the spacecraft speaks to the public in the first person. Research into these programs can better elucidate how science is conducted in the public good and under public scrutiny, and in how scientific results are translated into terms that can be broadly communicated especially over new digital media It can also generate the kinds of results of deep interest to those involved in science communication and the public understanding of science.

Finally, we seek opportunities to use this research as a means of outreach beyond the traditional research community. Dourish (PI) teaches in UC Irvine's interdisciplinary program in Arts, Computation, and Engineering (ACE) which emphasizes exhibitionary practice and community engagement as a form of research output. Given NASA's role in "public science," we would like to explore the opportunities to engage in public outreach around not only the engineering achievements of space science, but also the social life of spacecraft, in order to engage with new and different publics.

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