The Personal Exploration Rover:
Educational assessment of a robotic exhibit for informal learning venues

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Robotics brings together learning across mechanism, computation and interaction using the compelling model of real-time interaction with physically instantiated intelligent devices. The project described here is the third stage of the Personal Rover Project, which aims to produce technology, curriculum and evaluation techniques for use with after-school, out-of-school and informal learning environments mediated by robotics. Our most recent work has resulted in the Personal Exploration Rover (PER), whose goal is to create and evaluate a robot interaction that will educate members of the general public in an informal learning environment and capitalize on the current enthusiasm and excitement produced by NASA's Mars Exploration Rovers (MERs). We have two specific goals of teaching about the role of rovers as tools for scientific exploration and teaching about the importance of robot autonomy. To this effect we have designed an interactive, robotic museum exhibit which has been deployed at six locations across the United States, including the San Francisco Exploratorium and the Smithsonian National Air and Space Museum. Here we introduce the robot hardware and software designed for this task and the exhibits developed, then detail the educational assessment methodology and results, which detail exhibit impact on museum visitors at two installation sites.

INTRODUCTION

Critical enabling technologies for long-term, high competence mobile robotics have made significant strides over the past few years. In conjunction with this greatly increased potential for mobile robots to interact intelligently with humans, the field of human-robot interaction is experiencing significant growth as a field of scholarly endeavor [15,16]. Through the Personal Rover Project, we have focused specifically on the application of interactive, physically embodied robotic technology to informal learning environments [14]. This agenda has been motivated by our and others' quantitative and anecdotal results which show that educational robotics can trigger significant learning across broad learning themes that extend well beyond STEM (science, technology, engineering and mathematics) and into associated lifelong skills of problem-solving and communication [2,13,18,23,24,26,27,28,31].

Educational robotics, while a fast-growing and important present-day endeavour, has concentrated primarily upon mediated, formal learning venues. Robot contests such as BotBall and US First provide mediated structure for students in classroom settings and after-school programs [30,31]. Formal integration of research robots and field robot prototypes into curriculum has also been quite successful, where time with the robot is rare and therefore valuable and carefully managed and structured [8,9,22]. Intensive, challenge-based curriculum has even been shown quantitatively to demonstrate statistically significant broad learning acquisition, as prior work in the Personal Rover Project has shown [24]. In the present project our focus was to explore the role of technology in learning in the context of shorter-term, unmediated interactions as can be found in the high-volume setting of science museums. The first challenge was to choose a specific application.

Motivated by the broad expected exposure of the Mars Exploration Rover (MER) missions targeted to land in January 2004, we elected to launch a technology-based educational experience that would be widespread in the informal learning venue of a number of science centers across the country. This ambitious level of implementation demands robotic technology that can survive robustly without expert roboticists on call.

Dubbed the Personal Exploration Rover (PER), our resulting interactive science rover experience is meant for prolonged use in unmediated settings, by novice users, without demonstrating the fragility and susceptibility to failure often seen in interactive robotics devices. The PER is designed to meet its specific educational objectives within the context of the NASA MER missions. These objectives are:

- Show that rovers are tools for doing science by enabling visitors to act as mission scientists, using the PER to conduct a science operation.
- Enable visitors to appreciate the role of autonomy on board rovers.

In the hope of evaluating these educational objectives, science centers offer a prime venue because these informal learning spaces offer both transient and long-term interaction opportunities over a sufficiently large body of visitors such that statistically meaningful conclusions regarding interaction and education can be drawn.

The PER exhibit was designed from the ground up by a team led by Carnegie Mellon University consisting of government, industry and academic partners. NASA/Ames and Intel Corp. provided funding; Intel also provided the Intel Stargate arm-based single board computer. Gogoco and LotterShelly provided professional mechanical design and graphic design. Botrics provided electronics engineering services. The Learning Research & Development Center (LRDC) provided formal educational evaluation.

The Personal Exploration Rover has been designed as a robotic introduction to the technologies that enable NASA's missions and as an immersive tool for experiencing the challenges faced by NASA mission scientists. The PER pilot installations, aimed specifically at the informal learning environment of science museums and tech museums, present museum visitors with the challenge of searching for signs of life on discrete rocks placed in a physically instantiated Mars yard. Using a carefully designed user interface to communicate with the rover, visitors interpret panoramic imagery and orthographic, overhead imagery to identify their science target, then observe as the PER approaches the rock, scans to find the target's exact position, maneuvers autonomously for a close approach, then conducts an ultraviolet test for organofluorescent signs of life (Fig. 1).

Fig. 1. A PER tests a rock for signs of life at the National Science Center.

Installations operated at five national science centers in early 2004, including the Smithsonian National Air and Space Museum (NASM) and the San Francisco Exploratorium. Operation continues at several sites, including NASM, and will spread further in future months. In the first two months of 2004, Personal Exploration Rovers effected more than 20,000 autonomous science target approaches as directed by museum visitors. Greater than 30 miles of rover travel were completed, with idle times approaching 0% of museum operating hours at the Exploratorium. Key enabling technology advances include the areas of power management, terrain inference and science target approach and software architecture. This paper describes the specific results of educational analysis of the PER exhibit. First, however, we present contextual information regarding robot design and interaction design, both completed *de novo* for the purposes of the PER exhibit.

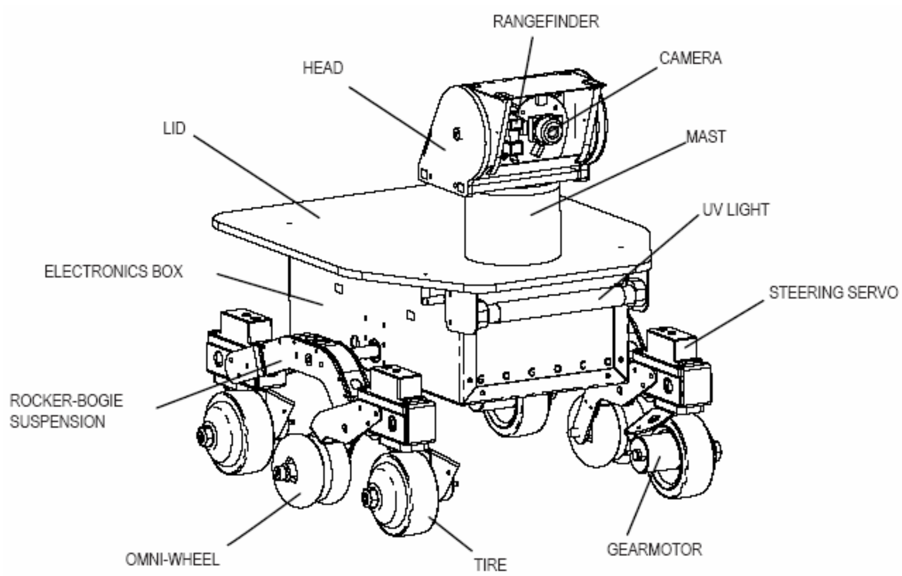

Fig. 2. PER chassis.

ROBOT DETAILS

The mechanical chassis of the PER (Fig. 2) loosely resembles the configuration of the two MER instances currently exploring Mars. Like MER, there is a six-wheel suspension supporting a rectilinear electronics box. A UV-fluorescent light mounted on the exterior of this box enables the PER to illuminate target rocks in order to test for organofluorescence. The lid of the electronics box is shaped to be reminiscent of the "winged" solar panels on the MER deck. The lid supports the PER's camera and optical infrared (IR) range-finder. These are mounted together on a pan and tilt head that is on a short mast at the front of the rover. The camera is used for panoramic imaging and close-up target imaging. The rover uses the rangefinder to scan for obstacles in its path during traverses and to identify the exact distance and bearing to target rocks. Based on prior results regarding diagnostic transparency, great care was taken to design the PER's pan/tilt head so that it clearly demonstrates the robot's direction of attention. This static design aesthetic, combined with appropriate dynamics as the head pans and tilts to search for obstacles and science targets, facilitates inferences made by museum visitors regarding the level of attention PER pays to its surroundings. For example, during forward motion of the PER, its head continuously scans left and right, aiming the rangefinder at the terrain the rover is about to traverse. Visitors easily recognize that PER is "looking for targets" or "looking for obstacles" even though they may be wholly unaware of the specific mechanisms used by PER. A catadioptric, parabolic mirror assembly would have enabled 360 degree vision and thus obviated the need for a pan/tilt mechanism, but such inferences of capability and internal robot processing would have been unacceptably sacrificed.

Unlike the MER, the PER was designed to be relatively inexpensive so that many PERs could be built for multiple simultaneous exhibitions at an affordable price point, as with previous Personal Rover Project robots [17]. Rather than designing the PER to have similar scale to the MER platforms, we chose to minimize the size of the PER, subject to off-the-shelf microprocessor, sensor and motor constraints, so that relatively small museum Mars yards would nevertheless yield rich interactions. Overall, the height of the PER is approximately 36cm, the length is 33cm and the width is 34cm. The approximate weight, fully loaded, is 15 lbs. All time-limited parts used on the PER were designed to be easily replaced. For instance, each position-controlled joint (of which there are six total) is powered by an unmodified, stock servomotor used by various hobby communities. These parts would prove to be the sole source of repeated repair and, due to their off-the-shelf nature, museums were able to replace servos in-house.

The PER's main processor, the Intel Stargate board (*www.xbow.com*), runs the Linux operating system and communicates via 802.11b wireless Ethernet with the Java-based mission control interface running on a PC. Wireless communication combined with a battery pack that can power the rover for approximately 10 hours enables the PER to operate without a tether, making it a more realistic emulation of the MER. For greater detail concerning PER hardware and software architecture refer to [25].

EXHIBIT INTERACTION

A multidisciplinary team consisting of interaction designers, roboticists, and programmers collaborated to design and implement the intended museum interaction. Three goals were set for the exhibit; as well as supporting the project goals of teaching about robot autonomy and robots as scientific tools, the interaction should be easily completed by visitors in less than three minutes in order to facilitate throughput in view of visitor flow requirements.

Although a series of static storyboards were used to identify candidate interaction trajectories, a critical aspect of the exhibit interaction design process involved real-world sparse testing. Before the final rover hardware was complete, a prototype four-steer robotic vehicle was fabricated for preliminary testing (Fig. 3). This prototype would serve multiple purposes simultaneously. First and foremost, this prototype used the candidate servomotors, drive gearmotors, rangefinder, USB camera device and microprocessors selected for the PER, serving as a burn-in test system for these off-the-shelf components. Second, this prototype exhibited the same kinematic motion capabilities of the final system, enabling high-fidelity testing of the interaction system even though the final PER instantiation would not be complete for several months. Several cycles of public usage of the prototype rover using candidate interfaces were completed, helpfully identifying the most critical adaptations of the interface required for smooth operation by untrained users. The interaction trajectory described below, together with the final design solutions, embody the conclusions drawn from this series of iterative test and refinement cycles [3,19].

Fig. 3. A volunteer uses a prototype vehicle to test an early version of the exhibit interaction.

Museum Interaction

A typical museum interaction begins when the visitor presses the button on the kiosk. The rover then takes a 360 degree panorama which is displayed on the kiosk screen (Fig. 4). The user selects a target rock by clicking on the panoramic image. This identifies the angle to the target. The user's next step is to select the location of the rover and the target rock on a "satellite" map in order to specify the distance from rover to target. When the user is satisfied with the mission specifications she sends the mission to the rover for autonomous execution.

The rover first turns to face the target, then drives the specified distance, all the while checking for obstacles in its path by panning and tilting its head as it moves forward. Upon reaching the end of the path, the rover scans the area in front of it to locate the rock. If it finds the rock, the rover will do a series of adjustments and scans to ensure that it is well aligned with the target. It then drives to within a few centimeters of the target and turns on its UV light to analyze the rock for organofluorescent signs of life. This is simulated with UV fluorescing paint which has been applied to a subset of the yard's rocks. The rover sends an image of the rock back to the user for scientific analysis, and the user makes the final determination of whether there is evidence for life on the rock.

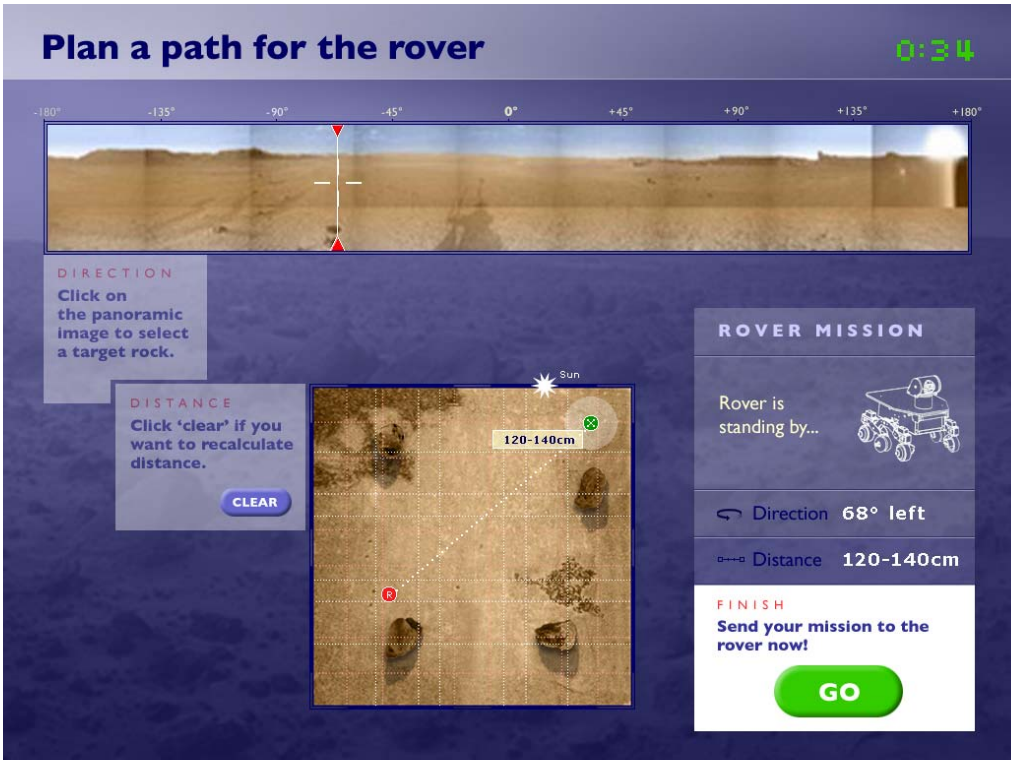

Fig. 4. The "Mission Builder" screen display.

Design Solutions

To maximize the users' learning experiences and create a fun and educational interaction, the designers focused on the interface language, interaction cues, physical orientation, real-time feedback, and the visual interface. Through rapid prototyping of the designs and a series of informal user tests, the team was able to quickly eliminate problematic concepts and arrive at the following sampling of solutions.

Interface language. The prospective audience can potentially cover a broad range of scientific expertise, so minimal formal scientific and technical terminology is used. Instead, a simple, inquisitive, game-like tone supports the interaction.

Interaction Cues. The default screen display in the kiosk is a loop that provides a visual overview of the impending mission and what the user might be expected to do. The kiosk itself has a track ball and a button, similar to an arcade game. The mission begins when the user presses the button. A linear interaction follows as the mission is progressively disclosed to the user.

Physical Orientation. To help the user orient between the Mars yard and the screen display (Fig. 5), a Martian sun is painted on the wall of the Mars yard and is visible from both the kiosk and in the panoramic view on screen. In addition, the rock positions, shapes, and the shape of the yard provide feedback and help users interpret the orthographic map. An animation is used to communicate the 360-degree nature of the panoramic image.

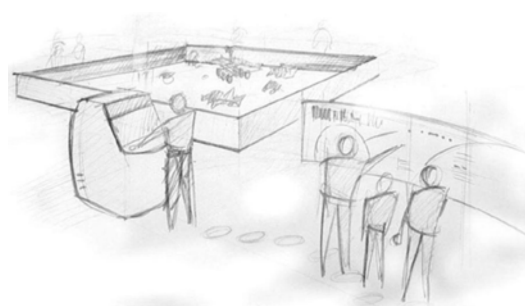

Fig. 5. The ability to see the yard and kiosk screen simultaneously aids users in orienting themselves within the exhibit.

Real-Time Feedback. A "Mission Builder" screen display (Fig. 4) was created to reinforce the educational aspects of mission building. The display tracks users' progress in real-time until they are ready to submit the mission to the rover. As the rover executes the mission, a rover's-eye view camera allows the visitor to experience the mission from the rover's perspective. The "Rover Mission" subwindow at bottom right remains during execution, providing data regarding rover operations, distance traveled and angles turned.

Visual Interface. A consistent color palette is used to unify the screens. Static and animated elements on the screen are designed to provide focal points for the users depending on the actions required. Consistent, clear typography provides visual hierarchy and improves readability [6].

MUSEUM INSTALLATIONS

The PER exhibit has been deployed at five museum locations across the country: the Smithsonian National Air and Space Museum, the Smithsonian Udvar-Hazy Center, the San Francisco Exploratorium, the National Science Center, and the NASA/Ames Mars Center. For a two week period the Exploratorium also shared their exhibit with the Randall Museum. The exhibits opened between December 29, 2003 and January 24, 2004 and ran for two months or more (at this time all but the Exploratorium exhibit are still operating). Although each museum was provided with guidance regarding exhibit construction (i.e. Mars yard fabrication, kiosk fabrication), variation in both exhibit design and execution has been significant across installations, leading to the potential for comparative analyses of the effectiveness of identical robotic technology as implemented in a variety of modes. The most distinct areas of variation are in interaction format and Mars yard design, summarized below.

Interaction format

The format of the exhibit in terms of docent activity is left up to the individual museum. As a result we have observed three different styles of interaction. At the NASM, interaction with the exhibit is fully mediated by a dedicated docent. At the Udvar-Hazy Center, the exhibit is used for structured teaching activities with school groups. The Exploratorium, National Science Center, and NASA/Ames allow visitors to explore the exhibit without mediation and in a freeform manner. This variation in the level of guidance, most extreme between the Smithsonian and the Exploratorium, justified joint educational analysis of these two installations, as described in the Exhibit Analysis section.

Mars yards

Each museum designed and produced its own Mars yard or yards for the exhibit, subject to yard design constraints expressed by the PER team to ensure exhibit success. The Mars yards are specifically designed with the PER's capabilities and the desired exhibit interaction in mind. The rocks and hills in the terrain are all traversable by the rover, demonstrating the animation of its rocker-bogie suspension system, except for four to five very large rocks which serve as the scientific targets. The yards are surrounded by hip-height walls decorated with Martian landscapes and horizons from NASA's Pathfinder mission. Each yard also displays a sun on one wall to help the visitors orient themselves when using the exhibit. This sun icon is apparent when viewing the physical yard, when viewing the rover-generated panorama and is iconically represented on the "satellite map" overhead view of each yard. Thus across all three representations of physical space the sun serves as a landmark for orientation and familiarity.

Museums have one to two yards ranging from 256 square feet to 72 square feet. The yards are constructed in a number of various ways, including spray painted Styrofoam; layered paint, glue, sand, wood and plaster; small lava rocks and sand; and layered Styrofoam, polymesh and dryvit compound (Fig. 6). Of particular interest is the fabrication methodology used by the Smithsonian NASM and Udvar-Hazy sites. Local high school students, working in teams, researched the topography of the Mars Pathfinder landing site, then recreated a portion of this landing site as a school project using shaped foam and stucco. Thus the Mars yard creation process itself was transformed into a learning experience and outreach opportunity by these museums.

Fig. 6. This picture of the Smithsonian Air and Space Museum yard was taken during installation of the exhibit, before the horizon images were added. The yard is built on casters and designed to split into four quarters so that it can be easily moved.

EXHIBIT USE PATTERNS

Quantitative statistics regarding exhibit use were collected automatically at installations by the exhibit software itself and by sampled passive observation. Both quantitative results and informal observations guided the more formal educational exhibit evaluation that followed. These statistics identify the demographics of the exhibit users and the manner in which the exhibit was used. Significantly, the statistics show that time on task is extremely close to the design target of 3 minutes, and more importantly virtually all exhibit users were able to successfully complete the entire mission. Together these statistics indicate that the distribution of time on task is not, as is often the case in museum exhibits, exponential but rather unimodal and narrow. Users who are engaged by the PER exhibit remain engaged through mission completion, then helpfully release control to the next museum visitor in queue. Details of both user demographics and mission use statistics follow.

Audience. Exhibit use observations were conducted at the Exploratorium and the National Air and Space Museum. At both locations, the exhibit was in nearly constant use. Over roughly 4.5 hours of observation, 184 people interacted with the exhibit. This included 71 adult users (36 females and 35 males), and 113 child users (28 females and 85 males). The majority of exhibit users were in groups, and the average group size was 3.06 (σ 1.22), with a total of 64 groups using the exhibit during this period. Group members often took turns conducting rover missions. Although more boys than girls were present at the exhibit, 61% of boys and 71% of girls attending the exhibit operated the rover.

Mission statistics. Based on logs automatically generated by the Exploratorium and NASA Ames kiosks between Dec 29th, 2003 and April 14th, 2004 we are able to report additional information about exhibit use[1]. The exhibits were in use 75.4% of the time while they were open (331 hours idle and 1017 hours in use). Out of 26,200 missions only 525 (2.0%) timed out before the end of the Mission Builder screen, meaning that 98% of users were able to successfully design a mission and send it to the rover. When a mission is unsuccessful, users are given the option to try again or quit. Only 499 (1.9%) of missions timed out at this stage, showing that users were highly engaged even when their mission failed to find the target rock. The average mission length was approximately 2 minutes 20 seconds (139.7 seconds σ 60.1 seconds). This is the length of time for a single set of instructions to be selected by the user, sent to the rover, and executed. On average each user engaged the PER in 1.6 missions (σ 0.94), thus the overall individual time on task is approximately 4 minutes, exceeding the 1.4 minute engagement time typically seen at interactive science exhibits [12].

About half of the missions (52.7%) ended with the rover successfully locating a rock (Fig. 7). The next most common outcome was the detection of an obstacle (23.1%), meaning that the rover encountered an obstacle more than 150 centimeters from the expected target distance. The rover went “out of range”, i.e. encountered a hip wall, only 18.1% of the time. In 3.4% of the missions, the mission ended due to a robot error such as failed communication. The rover was unable to locate any rock or hip wall 2.7% of the time.

In summary it is clear both from time on task values, time-out rarity and mission success rates that visitors are able to effectively make use of the PER exhibit, even in the unmediated cases of the Exploratorium and NASA/Ames installations. It is further clear that for children, there is no obvious statistical gender gap in terms of engagement with the PER exhibit. Both of the above conclusions are hopeful in that the PER exhibit attracts and engages the target population. The next question, addressed in the following section, is whether this exhibit uses technology in an educationally positive manner.

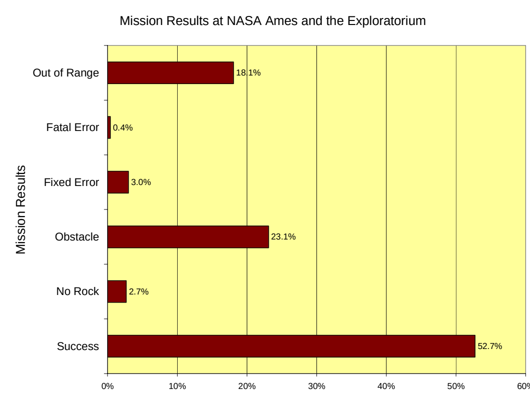

Fig. 7. Mission results from NASA/Ames and the Exploratorium between December 29th, 2003 and April 14th, 2004.

[1] All of the kiosks generate logs, but these results are based upon NASA/Ames and Exploratorium analyses only.

EXHIBIT ANALYSIS

In evaluating any interactive museum exhibit, there are two important questions: 1) Are people able to use the exhibit as the designers intended? and 2) Are people engaging with the intended content of the exhibit? The answer to the first question has already been provided in the section on exhibit use patterns. The current section will address the second question.

Traditional school-based assessments of learning are often inappropriate for use in informal learning environments [1]. A central purpose of interactive exhibits is to engage visitors in activity that is connected to authentic disciplinary processes. Visitors do learn pieces of declarative or conceptual knowledge as a result of this activity, but the accumulation of such knowledge is a secondary effect of the interaction. Thus, assessing the success of interactive exhibits involves documenting both the socio-cognitive activity of using the exhibit and then documenting individual understanding of visitors after they have used the exhibit.

Our target audience for the evaluation was visiting family groups. By exhibiting the PER in museums, science centers and other informal learning spaces, families are provided with opportunities to explore ideas about robots and the Mars mission together, and engage collaboratively in the process of making sense of the exhibit's content. To determine the extent to which families followed up on these opportunities, we analyzed family conversations as visitors used the exhibit. This fits with the framework of viewing conversations in museums as both the process and the outcome of visitor learning [21]. As visitors talk about a museum exhibit, they are both interpreting the exhibit and constructing an understanding of the content. By analyzing exhibit conversations, we can begin to understand what concepts families are taking away from the exhibit. Our analysis of conversation focuses particularly upon parent talk, reflecting recent findings suggesting that active parent participation in museum exploration encourages children to engage exhibits in ways that are more reflective and connected to the intended content of the exhibit [11]. Our analysis of individual understanding focused on children, as the promotion of children's understanding and interest in science and technology is a stated goal, both for this exhibit and for the larger Personal Rover initiative.

Method

In order to evaluate the educational impact of the PER exhibit, research was conducted at two of the PER installation sites – the San Francisco Exploratorium and the Smithsonian National Air and Space Museum (NASM). Data was gathered at the Exploratorium and NASM during February and April of 2004, respectively. These two museums were chosen as research sites in order to provide a full picture of how the exhibit functioned with different levels of museum mediation. In the Smithsonian installation, a docent was stationed next to the control kiosk, in order to provide information about the PER (and MER mission) and to assist visitors as they engaged with the exhibit. At the Exploratorium, families interacted with the exhibit on their own, although staff were generally available to answer visitor questions.

We analyze the activity of 43 families recruited at the two target sites. Twenty-nine of these families were recruited at the Exploratorium and 14 were recruited at the NASM. For recruiting purposes, a 'family' was defined as a parent or guardian (over age 18[2]) and at least one child between the ages of 4 and 14. The average age of child participants at the Exploratorium was 8.8 years (SD=2.1; range=4.8 to 12.1 years). This sample included 12 girls and 17 boys. The average age of child participants at NASM was 8.8 years (SD=1.1; range=6.9 to 10.3 years). This sample included 4 girls and 10 boys. Participants at the Exploratorium spent an average of 6 minutes, 38 seconds at the exhibit, of which 5 minutes, 1 second was spent at the kiosk, operating the rover. Exploratorium participants completed an average of 2.3 missions, of which 55% were successful. Participants at NASM spent an average of 15 minutes, 9 seconds at the exhibit, of which 4 minutes, 18 seconds were spent at the kiosk. NASM Participants completed an average of 1.4 missions, of which 88% were successful.

An additional four families agreed to participate in the study but then chose not to conduct any missions with the PER. These families gave a variety of reasons for not

[2] Under the Internal Review Board (IRB) guidelines followed by the research team, children are not permitted to participate in a research study without the written consent of a parent or guardian over the age of 18.

completing the exhibit, including not wanting to wait in line to use the PER. The data from these families has been excluded from this analysis.

Families were approached at the entrance to the exhibit in each museum, and invited to participate in the research study. Interested families were asked to sign a consent form. Participating families were videotaped as they used the exhibit (including while they waited in line to operate the PER). In order to record exhibit conversations, one child in each family was asked to wear a wireless microphone. Upon completion of exhibit use, one child and one parent from each family were interviewed separately.

The child interview consisted of a set of open-ended questions about the Mars mission, the Mars Exploration Rovers, and the Personal Exploration Rovers. At the beginning of each interview, children were shown pictures of Spirit and Opportunity, the Mars Exploration Rovers, and asked to identify the rovers and the goal of their mission. Children were then asked to explain how they thought the rovers worked. For example, children were asked to predict how action is initiated for the rovers, whether the rovers needed to be 'smart' to accomplish their goals, whether the rovers were capable of autonomous behavior, and why NASA would decide to send robots (instead of astronauts) to explore on Mars. Questions about autonomy and whether the rovers were 'smart' were repeated verbatim for the MER and PER. The question about initiating action was only asked of the MER. For the PER, children were asked to describe what they did in the exhibit, and whether or not the PER had a successful mission. When children reported that the PER did not have a successful mission, they were asked whether the rover or the person controlling the rover was responsible for the mistake. The average length of child interviews was 6 minutes, 23 seconds at the Exploratorium and 7 minutes, 50 seconds at NASM.

The parent interview also consisted of a set of open-ended questions regarding the Mars mission and the rovers. Parents were asked to describe what they knew about the Mars mission and the Mars Exploration Rovers, their family's level of interest in the Mars Exploration Rover mission, and what they thought their child learned from the Personal Exploration Rover exhibit.

Visitor experiences at the Exploratorium and NASM installations were compared through videotaped conversations and post-exhibit interviews. In this article, we present selected analyses focusing on the questions of how the exhibit supported the two educational objectives of allowing visitors to explore 1) the role of robots in mission science and 2) the nature of robot autonomy. For additional analyses see [25].

The Role of Robots in Mission Science

One of the goals of the PER exhibit was to provide a tangible connection to the unfolding story of the search for signs of life on Mars. This story includes both the possibility of finding life on Mars, and the excitement of using robots to conduct exploration. In this section, we evaluate the extent to which the exhibit supported visitor learning of the role of robots in scientific exploration.

Our first task was to address the question of what it means to learn about the role of robots in mission science. In response, we developed a set of coding categories designed to capture exhibit talk related to this theme. Our first two coding categories were specifically related to the Mars mission. We coded whether groups mentioned anything about the mission: Did they talk about the fact that were currently rovers on Mars that were examining rocks to find signs of life? We also coded whether the groups ever made specific comparisons between the design and capabilities of the PER and MER. The second two sets of categories were concerned with more general issues of using robots. We coded whether groups talked about how people communicate with robots; specifically whether they discussed the mediating nature of programming and telecommunications. We also coded talk about how robots and people work together to solve problems. These four general categories each contained multiple subcategories. However, for the purposes of this article we collapse up to the super-category level. Unless otherwise specified, comments about the MER and the PER were given equal weight in this coding scheme. Reliability was assessed by comparing codes from two independent coders on 20% of data. Inter-rater reliability for all exhibit interaction coding was 86%.

Conversations at the PER Exhibit. Fig. 8 presents the percentage of conversational groups[3]

[3] As a unit of analysis, the conversational group includes anyone present at the exhibit with the child. At the Exploratorium, the conversational group generally included the child, parent(s),

discussing each topic, broken down by museum. These data suggest that the PER exhibit supported conversations about the Mars mission and general robotics at both sites. However, conversation groups at NASM, which included a docent, were significantly more likely to talk about the Mars mission and to make explicit comparisons between the MER and the PER.

Themes	Exploratorium	NASM
About the Mars Mission*	55%	93%
Comparisons between MER and PER*	24%	79%
Communicating with Robots	45%	72%
Collaborating with Robots	86%	93%

*indicates a statistically significant difference between the Exploratorium and NASM groups, $p<.01$

Fig. 8. Percentages of conversation groups at each museum discussing themes related to the role of robots in mission science.

Further analysis of the conversation data revealed that parents generally initiated the same amount of thematic talk at both the Exploratorium and NASM exhibits[4], and that the docents seem to be responsible for the increase in the amount of thematic talk at NASM. However, even if docents are able to provide additional factual information to museum visitors, is it not necessarily the case that the PER exhibit is more successful when mediated by a docent. Anecdotal evidence suggests that parents are more sensitive to their children's understanding of the rover, and are more likely to tailor their comments at the exhibit to correct children's misperceptions. One example of this comes from the parent of a 4-year-old Exploratorium visitor. While the parent and child were using the exhibit, the child attempted to control the rover by leaning into the Mars yard and shouting, "Go!" Realizing that her child was misunderstanding how the robot worked, this mother went on to explain that they could only talk to the rover through the computer: "...Look at that, he's following directions (points towards yard). You communicated with him through the computer….you were able to give him accurate directions, just by moving and clicking." By emphasizing the role of the computer in mediating communication between robot and user, this parent was helping to correct her child's misperceptions about the way the rover received instructions.

Research in the field of museum learning suggests that parents can serve an important bridging function between children and museum exhibits, making the parent's role an important one [10]. However, further research is needed to quantify other differences between parent and docent mediation at museum exhibits.

Child Interviews. In order to assess the extent to which children left the exhibit with an understanding of the role of robots in mission science, we coded the children's post-exhibit interviews using the same categories as in conversational coding. Reliability for coding was assessed by comparing codes from two independent coders on 20% of data. Inter-rater reliability for child interview coding was 85%.

When interviewed after exhibit use, almost all children at both the Exploratorium and NASM possessed basic knowledge of the Mars rover mission (93% and 100% respectively). Additionally, 21% of children at the Exploratorium and 38% of children from NASM made spontaneous comparisons between the MER and the PER.

With regard to person-robot communication, 72% of children at the Exploratorium and 69% of children at NASM were able to describe the devices people can use to communicate with robots (e.g., computers and, in the case of rovers in space, satellites). There were no statistically significant differences between children from the Exploratorium and NASM for any of the categories reported here.

The Nature of Robot Autonomy

This exhibit was designed to provide museum visitors with the knowledge and information necessary to appreciate the importance of rover autonomy. Although all museum visitors will come to the exhibit with prior ideas of what robots are and what they can do, most have probably not interacted with a robot that possessed true autonomous properties [20]. Thus, the exhibit experience provides a unique opportunity for visitors to re-evaluate their

siblings and any other exhibit users with whom the child interacted. At the National Air and Space Museum, the conversational group included the child, parent(s), siblings, other exhibit users, and a docent.

[4] With the exception of talk about collaboration with robots (i.e., people and robots working together to solve problems), which was initiated more often by parents at the Exploratorium.

concepts of what a robot is and of what a robot is and is not capable of. We developed a coding scheme to capture exhibit talk about rover capabilities (including autonomy). An additional measure was developed to assess children's understanding of autonomous behavior in robots. Each of these measures are described below.

Conversations at the PER Exhibit. We developed three coding categories to capture exhibit talk relevant to the goal of appreciating rover autonomy. The first category, rover design, included talk about the technology used to build rovers, rover size, speed of travel, and the importance of rover autonomy. The second coding category included the types of activities rovers could perform, such as taking pictures and examining rocks. Finally, we coded for talk about the autonomous activities of the rovers. This category included discussions of rovers sensing things in the environment (e.g., looking for rocks), rovers avoiding obstacles, planning their own routes, and achieving goals with minimal user input. While each category included several sub-categories, current analyses were performed only at the super-categorical level. Unless otherwise specified, comments about the MER and the PER were given equal weight in this coding scheme.

Fig. 9 shows the percentage of conversational groups discussing each topic at the Exploratorium and NASM. Each topic was addressed by conversational groups at both museums, although all topics were addressed significantly more frequently at NASM. Analysis of the source of exhibit conversation revealed that parents at both the Exploratorium and NASM discussed these topics with similar frequency. As was the case in the previous set of exhibit conversation analyses, the docents seem to be responsible for the increase in frequency of thematic talk at NASM.

Themes	Exploratorium	NASM
Rover Design*	34%	93%
Rover Activities*	45%	100%
Rover Autonomy*	52%	93%

*indicates a statistically significant difference between the Exploratorium and NASM groups, p<.01

Fig. 9. Percentage of conversation groups at each museum discussing themes related to rover autonomy.

Child Interviews. In order to assess children's ideas about rover capabilities, children's interview transcripts were coded using two of the categories described above: rover design and rover activities. Children from both the Exploratorium and NASM were able to speak knowledgably about the technology on the rovers and the type of actions they were capable of performing. Fifty-two percent of children from the Exploratorium and 77% of children from NASM talked about rover design (e.g., the technology typically found in rovers, such as motors, cameras, range finders). Similarly, 55% of children at the Exploratorium and 85% of children at NASM were able to describe the types of activities a rover could perform (e.g., taking pictures, driving, exploring); this difference was marginally significant, $X^2(1, N = 42) = 3.39$, p=.06.

Assessing children's ideas about rover autonomy proved to be more challenging, as some children were inconsistent or unsure of whether a robot would be capable of autonomous behavior. In order to address this issue, we devised a separate system to measure both the adequacy and the strength (consistency) of children's ideas about robotic autonomy. For each statement indicating an understanding of the autonomous operations of the rover, children were given one positive point[5]. For each statement indicating the opposite belief, namely that the rovers were incapable of independent action and operated via remote control, children were given one negative point. This system was applied to children's answers to open-ended questions about how the rovers operate. Points for the PER and MER were summed separately.

[5] The following references were used in order to develop guidelines for coding statements as autonomous: Smithers, T. (1997); The Mars autonomy project: www.frc.ri.cmu.edu/projects/mars/; Wikipedia, online encyclopedia: http://en.wikipedia.org/wiki/Autonomous_robot; What is autonomy technology?: http://ic.arc.nasa.gov/projects/remote-agent/activities/pofo/docs/mission/1-whatis-autonomy-tech.html

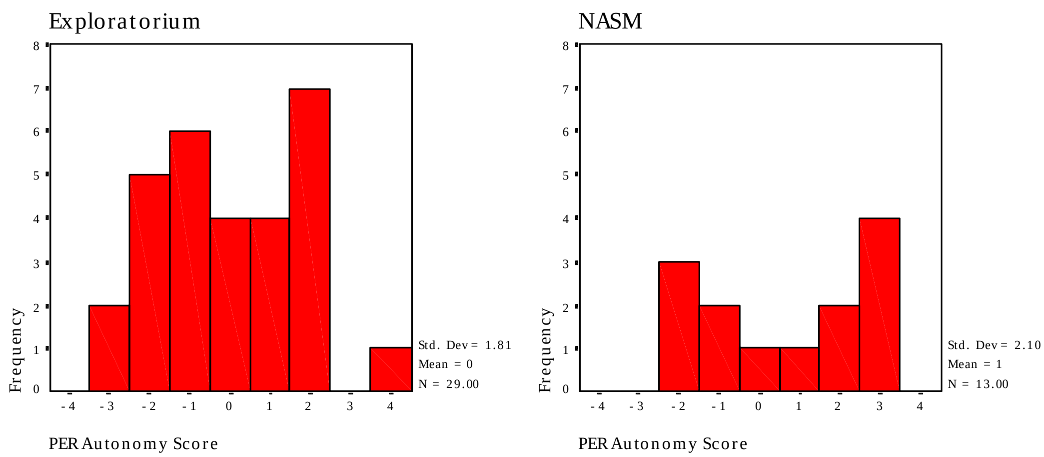

Fig. 10. PER autonomy scores. Positive scores indicate an understanding of robot autonomy. Higher scores indicate more consistent beliefs about the concept.

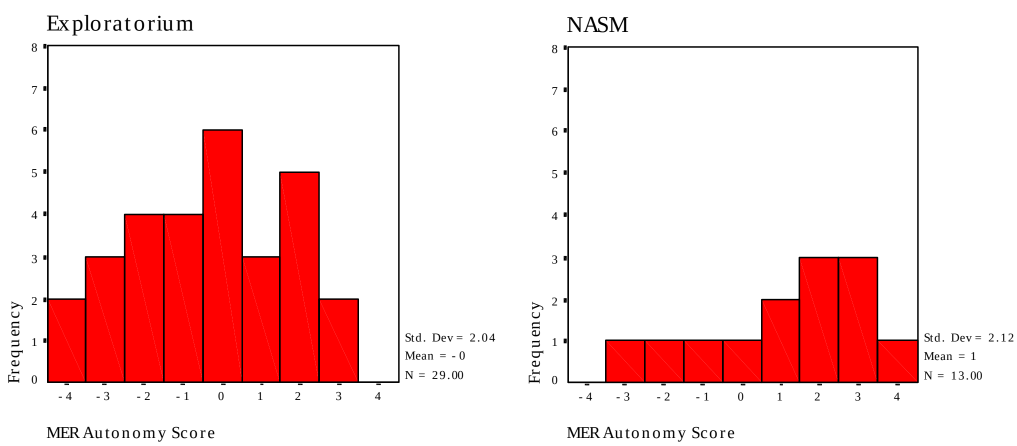

Fig. 11. MER autonomy scores. Positive scores indicate an understanding of robot autonomy. Higher scores indicate more consistent beliefs about the concept.

Fig. 10 and Fig. 11 illustrate the distribution of children's autonomy scores for the PER and the MER at each institution. Neither PER nor MER autonomy scores correlated significantly with age, although, as one might expect, PER and MER scores were significantly correlated with each other ($r=0.5$, $n=42$, $p=.001$). Across institutions, there was no significant difference in PER autonomy scores, but MER autonomy scores were significantly higher for children at NASM than at the Exploratorium, $t(40)=-2.18$, $p=.035$.

In order to assess whether children with high autonomy scores were simply more knowledgeable about robots, additional analyses were conducted to look for potential relationships between children's autonomy scores and the other categories of robot/Mars mission talk described above. This was only done with data from children at the Exploratorium, as there were too few children from NASM to allow a further breakdown of the data. Analysis revealed that children with high autonomy scores were more likely to make comparisons between the MER and the PER. This was true for children with high PER autonomy scores, $X^2(1)=4.78$, $p=.03$, as well as high MER autonomy scores, $X^2(1)=3.89$, $p=.05$. As autonomy is an important commonality between the MER and the PER, perhaps children were more likely to make comparisons between the rovers when they were aware of their autonomous attributes. However, it is important to note that there were no other significant relationships between children's autonomy scores and other topical categories. It would seem that an understanding of robot autonomy is potentially available for any child who comes to use the exhibit, regardless of their prior knowledge about the Mars mission or about robots in general

In total, over 40% of children at the Exploratorium and over 50% of children at NASM came away from the exhibit with some understanding of the autonomous capabilities of the PER. Similarly, 34% of children at the Exploratorium and over 50% of children at NASM came away understanding the autonomous capabilities of the MER[6]. The somewhat higher autonomy scores at NASM may be a function of the explicit conversation from docents regarding robot autonomy. Cognizant of the goals of the exhibit, docents were more likely to be explicit in their descriptions of the rover's autonomous behavior than were parents. It may be the case that for a concept as difficult as robotic autonomy, children benefit from explicit descriptions and definitions of autonomous behavior.

Parent Interviews

In this section, we will discuss selected data from post-exhibit interviews with parents, including assessments of family interest in the Mars rover mission, and parents' beliefs about what their child learned from using the PER exhibit.

In order to determine if families with strong interest in the Mars rover mission used the exhibit differently than less-interested families, we examined the relationships between family interest and exhibit talk in the seven categories presented in Fig. 8 and Fig. 9. This examination was only conducted for families from the Exploratorium, as the exhibit interaction at NASM was largely controlled by docents. In general, it would seem that the exhibit was equally accessible to families with low and high levels of interest in the Mars mission, and that parents were able to successfully navigate the exhibit with their children, regardless of prior knowledge. The only significant relationship was between family interest and discussion of robot autonomy at the Exploratorium, such that families with high levels of interest in the Mars mission discussed autonomy more often than those with low levels of interest, X^2 (1)=5.84, p=.02. It is possible that families with high levels of interest in the mission were more knowledgeable about rover autonomy, although there was no significant relationship between family interest and children's scores on the autonomy measure.

At both the Exploratorium and NASM, the majority of parents believed their children learned something from the exhibit. At the Exploratorium, 62% of parents believed that interacting with the PER exhibit increased their child's knowledge about the Mars mission and the rovers. Thirty-one percent of parents said the exhibit taught their child something about the process of operating robots remotely. Twenty-one percent of parents said their children learned how rovers work, and 17% believed that the exhibit would increase their child's interest in the Mars mission and the rovers. Parents from NASM also believed that the exhibit increased their child's knowledge of the Mars mission and the rovers (64%) and helped their child learn how rovers worked (57%). Twenty-nine percent of NASM parents said the exhibit taught their children about how rovers can be controlled remotely, and the same number of parents believe that the exhibit will encourage their child to take an interest in the Mars mission and the rovers in the future. A small percentage of parents from both the Exploratorium and NASM believed the exhibit taught their child how difficult it is to operate rovers.

Conclusions

This assessment suggests that the exhibit was successful in meeting its core goals of involving visitors in explorations of the role of robots in mission science and of robots as autonomous entities. Analysis of family conversation suggests that visitors were expanding on relevant themes as they used the exhibit. They talked about the ongoing Mars mission, they compared the MER and PER, they discussed communicating and collaborating with robots, and they talked about robot design, technology, and autonomy. Interviews with children following the exhibit suggested that almost all children were aware of the Mars mission and that many of them also were able to connect the exhibit experience in specific ways to the mission. Children did not end their experience with a uniformly robust view of autonomy. Although some recognized autonomous characteristics of the rovers, most children held inconsistent theories. More than half still held views that the rovers are primarily operated through direct remote-control. We do not necessarily believe that a single exhibit

[6] These percentages represent the number of children with positive autonomy scores for the MER and PER.

experience would be a sufficient base for children to develop fully correct theories of autonomy. The exhibit experience is probably best seen as a chance for families to work out some of these issues in the context of an authentic autonomous rover. Still, future versions of such exhibits should be designed to more explicitly challenge children's incorrect or inconsistent theories.

CONCLUSIONS

The Personal Exploration Rover has served as a rewarding demonstration of educational robotics applied to the informal learning space. Given concrete goals in relation to the NASA Mars Exploration Rover mission, this team designed a new educational rover from the ground up, tested and refined a graphical interaction system, engaged multiple high-traffic museums across the country, shepherded installation and maintenance of the resulting exhibit and performed quantitative and qualitative evaluation of the exhibit's efficacy. In summary this project demonstrates that robotic technology has compelling value in the museum setting, and that concrete educational results can be achieved and measured in such a setting. More than 40 PER's have been fabricated to date, with mean time between failure statistics often exceeding 2 weeks for full-time usage by non-roboticists. Exhibit statistics suggest that, among children, girls and boys are both engaged by this robotic exhibit, to such a degree that virtually all users succeed in the completion of an entire scientific rover mission. Educational evaluation suggests that the exhibit effectively serves as a platform for family discussions about the MER mission and robotics, and that children come away from the exhibit with measurable knowledge in these areas.

As robotic technology advances, such interdisciplinary teams of engineers, interaction designers and education specialists will be capable of inventing and executing ever more compelling exhibits and curricula for both formal and informal learning venues. We hope that this project can serve as a motivation for future teams to not only research, dream and invent, but also to harden, fabricate and install so that thousands can benefit from these educational technology ventures.

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Captions

Fig. 1. A PER tests a rock for signs of life at the National Science Center.
Fig. 2. PER chassis.
Fig. 3. A volunteer uses a prototype vehicle to test an early version of the exhibit interaction.
Fig. 4. The "Mission Builder" screen display.
Fig. 5. The ability to see the yard and kiosk screen simultaneously aids users in orienting themselves within the exhibit.
Fig. 6. This picture of the Smithsonian Air and Space Museum yard was taken during installation of the exhibit, before the horizon images were added. The yard is built on casters and designed to split into four quarters so that it can be easily moved.
Fig. 7. Mission results from NASA/Ames and the Exploratorium between December 29th, 2003 and April 14th, 2004.
Fig. 8. Percentages of conversation groups at each museum discussing themes related to the role of robots in mission science.
Fig. 9. Percentage of conversation groups at each museum discussing themes related to rover autonomy.
Fig. 10. PER autonomy scores. Positive scores indicate an understanding of robot autonomy. Higher scores indicate more consistent beliefs about the concept.
Fig. 11. MER autonomy scores. Positive scores indicate an understanding of robot autonomy. Higher scores indicate more consistent beliefs about the concept.

Scope of this paper:

This paper describes a new educational robot, the Personal Exploration Rover (PER), and the accompanying exhibit interaction designed for the informal learning environments of museums and technology centers. The exhibit has run at museums across the country including the Smithsonian National Air and Space Museum and the San Francisco Exploratorium. Results of educational analysis conducted on the exhibit are presented.