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The Ground-up Design, Deployment and Educational Evaluation of an Educational Robot for Unmediated Informal Learning Sites

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Robotics brings together learning across mechanism, computation and interaction using the compelling model of real-time interaction with a physically instantiated intelligent device. 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. Here we describe the robot hardware and software designed for this task, the exhibits developed, and the results of formal evaluation of the exhibits' educational impact on museum visitors.

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 [9, 10]. Through the Personal Rover Project, we have focused specifically on the application of interactive, physically embodied robotic technology to informal learning environments [8]. This agenda has been motivated by our and others' 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, 7, 12, 15, 16, 18, 19, 20, 21].

The educational goals of the Personal Rover Project are:

- Inspire children to explore boundaries of knowledge and creativity through the use of science and technology and to pursue careers in math, science and engineering.
- Stimulate the public's awareness of the NASA mission and the challenge of using robotic devices to perform science and exploration.
- Teach children the critical skills of teamwork, collaboration, problem-solving and inquiry-based science - skills that are important for all walks of life.

Previous Personal Rover Project results include the design, implementation and formal educational evaluation of a seven week summer robot programming course for secondary level students [16]. 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 Stayton 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) and the Institute for Learning Innovation (ILI) 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).

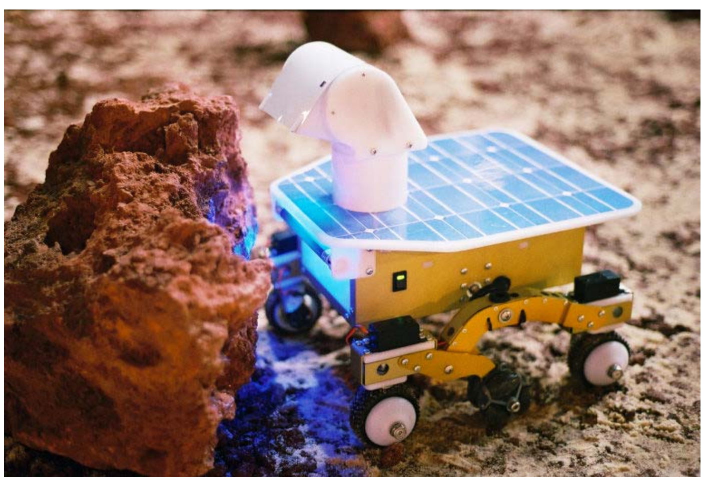

Fig. 1. A PER tests a rock for signs of life at the National Science Center.

Significant research results span physical robot design, robot software architecture and human-robot interaction design. In just the first two months, Personal Exploration Rovers effected more than 20,000 autonomous science target approaches, achieving Mean Time Between Failure performance exceeding one week of use. Greater than 30 miles of rover travel were completed, with idle times approaching 0% of museum operating hours at the Exploratorium. The total number of robotic failures in this span of time was only 9 failures, all of which were straightforward servomotor failures, easily repaired by the replacement of a hobby servo. Key enabling advances include the areas of power management, terrain inference and science target approach and software architecture. Installations have operated at five national science centers in early 2004, including the Smithsonian National Air & Space Museum and the San Francisco Exploratorium. Preliminary educational analyses of these and our preceding educational robotics programs suggest broad learning across lifelong themes as well as statistically significant results with respect to closing the perceived gender gap in engineering and technology [16].

This technical report describes all aspects of the Personal Exploration Rover project, including goals, approach and results for each of the five key research thrusts comprising the PER project:

1. Rover mechanical design
2. Embedded electronics architecture
3. Software architecture
4. Interaction design and iterative implementation
5. PER exhibit installations
6. Exhibit educational analysis and statistical results

The sections below provide details regarding each PER research thrust

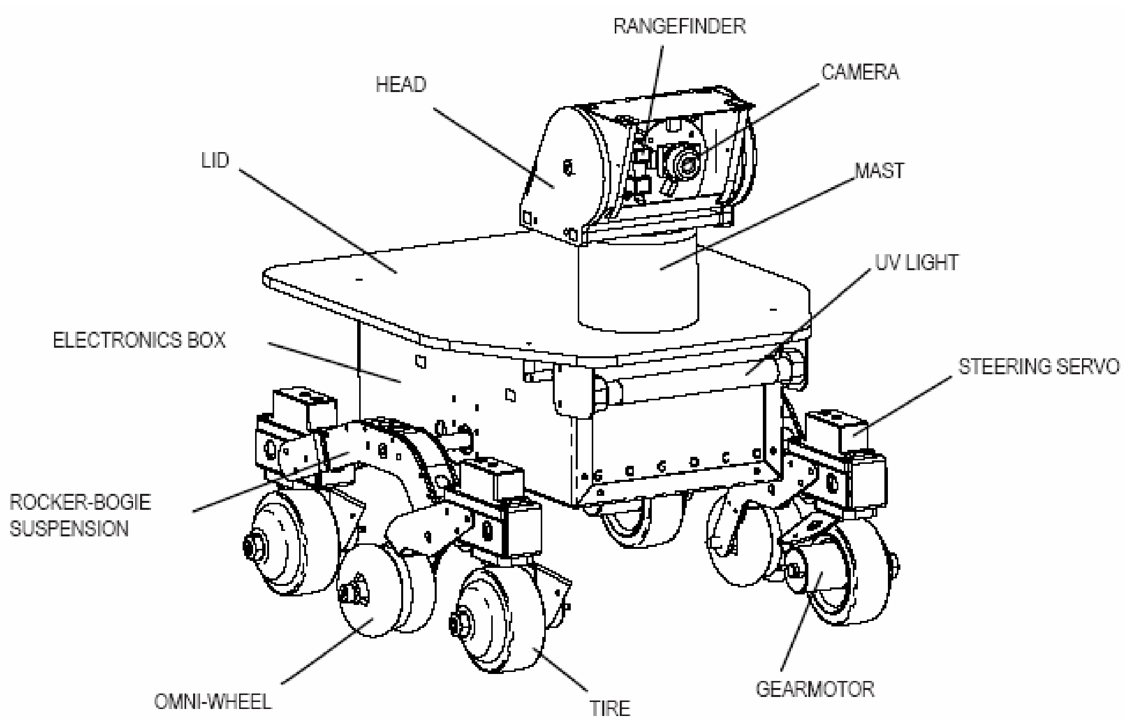

Fig. 2. PER chassis.

ROBOT DETAILS

Mechanical summary

Physical Description. 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 wheeled suspension supporting a rectilinear body/electronics box. Above the electronics box is a camera head atop a short mast. Overall, the height of the PER is approximately 36cm, the length is 33cm and the width is 34cm. (Fig. 3) The approximate weight, fully loaded, is 15 lbs.

Objectives and construction. First and foremost, the PER is a mobile camera platform. Like the MER, the PER needs to be able to traverse unstructured terrain while capturing images both for navigation and science study. 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 [11]. To this end the PER design process embraced the use of off-the-shelf electromechanical components whenever feasible (e.g. stock RC hobby type servos, batteries, gearmotors, etc.). 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. The final size of the PER was ultimately determined by the size of the electronics box required to house the electronics boards (i.e. microprocessor board, motor controller, power board) and batteries.

The majority of custom-made parts are either laser cut plastic or formed sheet metal. Minimizing the number of machined parts minimizes parts costs while the anodized aluminum sheet metal construction helps to lend the PER a space hardware aesthetic.

Suspension and drivetrain. The PER rolls on six wheels using a rocker-bogie suspension system similar to that used by the MERs. There are three wheels in line on each side. The four corner wheels are powered by DC gearmotors and are independently steered by standard RC hobby-type servos through a total range of approximately 180 degrees. The tires are stock rubber 6.8cm diameter RC car tires. The two center wheels are omni-directional, freely spinning, Swedish 90 wheels, which means that they allow free motion in any direction. The overall wheelbase (distance between the center of the front and rear wheels) is 25cm, and the wheel width (distance between the center of the left and right wheel treads) is 26cm. (Fig. 3)

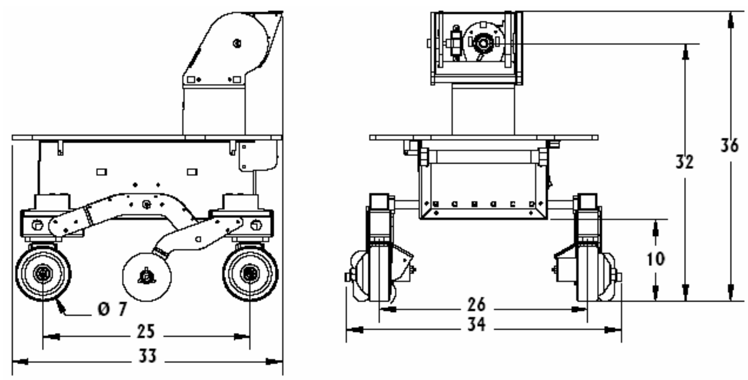

Fig. 3. PER dimensions in centimeters.

The rocker-bogie-type suspension was used in both the Sojourner rover and the recent MERs. Developed by JPL, it allows all six wheels to maintain full contact with an uneven surface without the use of springs or powered actuators. It also averages out the displacement of all six wheels, minimizing the resulting tilt of the rover's main body as the suspension negotiates bumps and rocks. Such main chassis stability is particularly important to the MERs and the PERs because it yields a more stable camera platform.

As a compromise to minimize power and control requirements, only the corner wheels of PER are driven, unlike the MERs which have six driven wheels. This is detrimental to the PER's ultimate ability to traverse tough terrain, but is adequate for the artificial Mars Yard terrains and helps to mitigate cost and control complexity.

Having four independently steerable corner drivewheels along with omni-directional center wheels gives the PER great directional freedom. It can turn in place, translate sideways, or drive at an angle independent of orientation. While not technically *holonomic* because the pairs of motors on each leg always turn at the same speeds, this geometry enables omnidirectional and Ackermann-style motion.

Electronics box. The suspension system carries the enclosed electronics box where the batteries and electronics are mounted. The lid of this box is hinged to allow easy access to the batteries for battery swapping. The power switch and a UV fluorescent light are also mounted to the exterior of this box. The box is fully enclosed to protect the electronics from dust and damage. For strength, the bottom and sides are metal while the ends and lid are made of plastic for radio transparency to allow the WiFi link in the electronics board to operate. The lid is shaped to be reminiscent of the "winged" solar panels on the MER deck.

Camera and camera mast. The lid supports the PER's camera and optical 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 pan axis can rotate ±180°, allowing 360° picture scans to be made with the camera. This is achieved using an off-the-shelf R/C hobby servo intended to serve as a multi-turn sailboat winch. The tilt axis mechanical range is +90°/-45°. The camera lens axis intersects the pan axis to help simplify the interpretation of imagery; panning does not also cause translation of the point of view. Based on prior results regarding diagnostic transparency, great care was taken to design the PER's pan/tilt head so that it demonstrates a clear 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. Physical design, combined with the appropriate motion dynamics, plays a large role in guiding robotics novices to draw appropriate conclusions regarding a robot's level of awareness of its surroundings.

Electronics

Processors. Fig. 4 shows a schematic of the PER's electronic system. For low-level control of motors and for reading sensors we use a Cerebellum control board. This PIC microprocessor-based board was designed by the Robotics Institute (Carnegie Mellon University) and Botrics, LLC. It can command two pairs of DC motors and 8 R/C style servos. It can also read 8 analog inputs and additional digital inputs. Communication between Cerebellum and Stayton is via RS232 serial running at 115200 baud.

The PER's main processor, the Stayton board, is an embedded computer designed by Intel Corp. for robotics applications. This single-board computer runs the Linux operating system on a 400 MHz ARM processor. On-board memory consists of 32 MB Flash ROM and 64 MB RAM. This board communicates with the rover's camera, the Cerebellum, and via 802.11b wireless Ethernet it communicates with the mission control interface running on a PC.

Power. The rover is powered by four 7.2 volt nickel metal hydride (NiMH) batteries connected in series. Their total capacity is 3 Amp-hours at 28.8 volts. A power board was designed by Botrics, LLC exclusively for the Personal Exploration Rover. This board distributes the power from the 28.8 volt battery pack to all the on-board electronic devices. Its total power output is 4 Amps at 5 volts (to processors), 5 volts (to servos), and 16 volts (to motors). A fully charged pack powers the rover for about 10 hours during typical museum usage.

Output. The four rover drive motors have a 332:1 gear ratio that allows them to spin at a near constant velocity whether or not they are under load. The rover drives each motor at 16 volts giving the PER a top speed of 4 cm/second. The motors are also small enough to fit inside of the rover's custom wheels. Because the Cerebellum is only able to drive 2 independent motors, the motors on the left side use one channel and the motors on the right side use the other.

The PER's steering and head angles are all driven by standard R/C-type hobby servos. The steering servos are low-profile, high-torque servos with brass shafts. The pan servo is designed for use in R/C sailboats as a winch and is capable of turning more than 360 degrees. A UV-fluorescent bulb and driver electronics enable the PER to illuminate target rocks in order to test for organofluorescence. The parts for the light come from a Chauvet handheld UV flashlight used for identifying security features on currency.

Sensors. The rover has a USB camera and an IR rangefinder mounted in its pan-tilt head. The camera, a Creative WebCam Pro, is used for panoramic imaging and close-up target imaging. It has a maximum frame rate of 15 frames / second and maximum resolution of 640 x 480. For finding distances, an infrared triangulation-based rangefinder is used. The Sharp model 2Y0A02 rangefinder returns point distance readings accurate between 20 cm and 150 cm. The rover uses this rangefinder to scan for obstacles in its path during traverses and to identify the exact distance and bearing to target rocks. A connection between the power board and the Cerebellum allows the rover to monitor battery voltage.

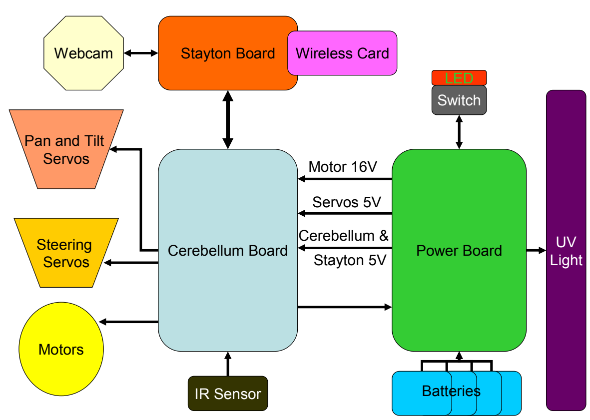

Fig. 4. PER electronics schematic.

Software architecture

Cerebellum. The software on the Cerebellum was designed to be as simple as possible. Following that principle, it only accepts a single type of command that specifies the positions for the 6 servos, the motor velocities, and the state of the UV bulb. It always returns the same type of response containing a status byte along with the IR range and battery voltage. The Cerebellum limits the speed at which the servos move to put less stress on the motors. To ensure safe operation of the robot, if no valid command has been received in the last 120ms, the servos and drive motors are turned off.

Stayton. The Stayton only makes decisions that are too time-critical to be sent over a wireless link. When the robot is commanded to turn a specified number of degrees or drive a certain distance, the Stayton makes the decision as to when to stop the robot. While driving, the Stayton moves the head to scan for obstacles using the IR rangefinder and makes the decision to stop if an obstacle is detected.

While scanning for a rock, the rover sweeps the rangefinder through 270 degrees generating 91 range readings. In order to complete the scan quickly, the head cannot be allowed to come to a stop to record each distance. Complicating the action is the fact that the servos do not provide any position feedback. Every 50ms, the pan servo is commanded to a new position and the range reading is sent back. Through experimentation, it was determined that while scanning, the servo's actual position lags the commanded position by about 100ms. In this application, timing is critical to make sure that the scan readings are as accurate as possible; therefore, the scanning action is controlled on board the Stayton.

The other main function of the Stayton is to create an abstraction to a user controlling the robot. The drive motors all turn at slightly different speeds. The servo motors all have different center positions and different ranges of motion. For example, changing the pulse with from 1ms to 2ms may cause one servo to move 90 degrees and another to move 95 degrees. For this reason, every robot has a calibration file which is loaded when the Stayton program starts running. It tells the Stayton how to convert an angle into a servo position that the Cerebellum understands and stores the characteristics of the motors so that the rover can turn and drive accurately, despite inherent motor speeds that can vary as much as 25%.

The Stayton keeps track of the positions of all 6 servo motors, which allows it to wait just the right amount of time for the servo motors to get to the commanded angle. This feature simplifies taking a picture so that the user can simply command that a picture be taken at a specific pan and tilt. The Stayton moves the head to that position and takes a picture when the head is in place. Requests for pictures can be queued up, so that right after a picture is taken, the head is moved to the position for the next picture before the image is compressed and sent. These features are used to create panoramic images without blur in as little time as possible.

Intel has licensed the Stayton technology to Crossbow Technology, Inc. The resulting Stargate board replaces the Stayton in subsequent builds of the PER with no noticeable differences.

PC. The software on the PC makes all decisions related to high-level mission execution. A mission starts off with the Java program on the PC calculating the angles at which to take images in order to compile a panoramic image. The user selects a rock (providing angle information) and locates the rover and target rock on a satellite map (providing distance information). After the rover has turned and driven the distances specified, the software on the PC makes its first decision: how to scan for the target rock. If the rover stopped early because it detected an obstacle, the short-range scan only looks in front of the robot because it knows that there is something there. If the rover did not detect an obstacle, the short-range scan will be broader. If the first scan fails, a long-range scan is done. A short-range scan differs from a long-range one in that the head is tilted down farther to look for close rocks and range readings are only taken every 5 degrees during the short-range scan. A long range scan needs to have the head at a higher angle to see farther and takes samples every 3 degrees to ensure good resolution on rocks as far away as one meter. If a rock is found, the rover will turn and drive up to the rock. After it is very close to the rock, another scan is done to find the exact distance to the rock. The mission concludes with the rover approaching the target rock, analyzing it with the UV light, and returning pictures to the user for scientific analysis.

EXHIBIT INTERACTION DESIGN

Fig. 5. A volunteer uses a prototype vehicle to test an early version of the exhibit interaction.

The PER project required an effective and efficient design approach that could encompass an evolving legacy system while exploring new interaction and interface concepts to maximize users' learning experiences. A multidisciplinary team consisting of two interaction designers, roboticists, and programmers was assembled as the first step in this approach.

The team followed an iterative design process and used several methods to understand the scope, goals, and technical requirements of the project. An initial assessment of the existing interface and results from preliminary informal user tests (Fig. 5) revealed some areas for improvement. Specifically, three goals were set:

- Each user should be able to complete a mission easily in less than three minutes.
- Communicate that robots are tools for science, and through teamwork with the rover, a user can work to complete a successful mission.
- Demonstrate that the rover is semi-autonomous—while a user gives the rover high level commands, the rover makes some smart decisions during mission execution.

Scenarios were also an essential tool in the design process and were created based on the informal testing to illustrate a good and a bad experience with the rover exhibit from a user's perspective. In several brainstorming sessions, members of the team used affinity diagramming to determine areas of focus. Based on the emergent clusters, 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 another 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. 6), 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.

Real-Time Feedback. A "Mission Builder" screen display (Fig. 7) 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" sub-window 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 [3].

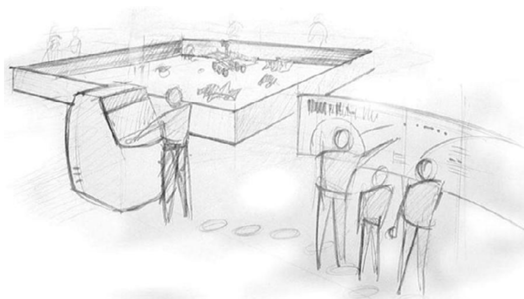

Fig. 6. The ability to see the yard and kiosk screen simultaneously aids users in orienting themselves within the exhibit.

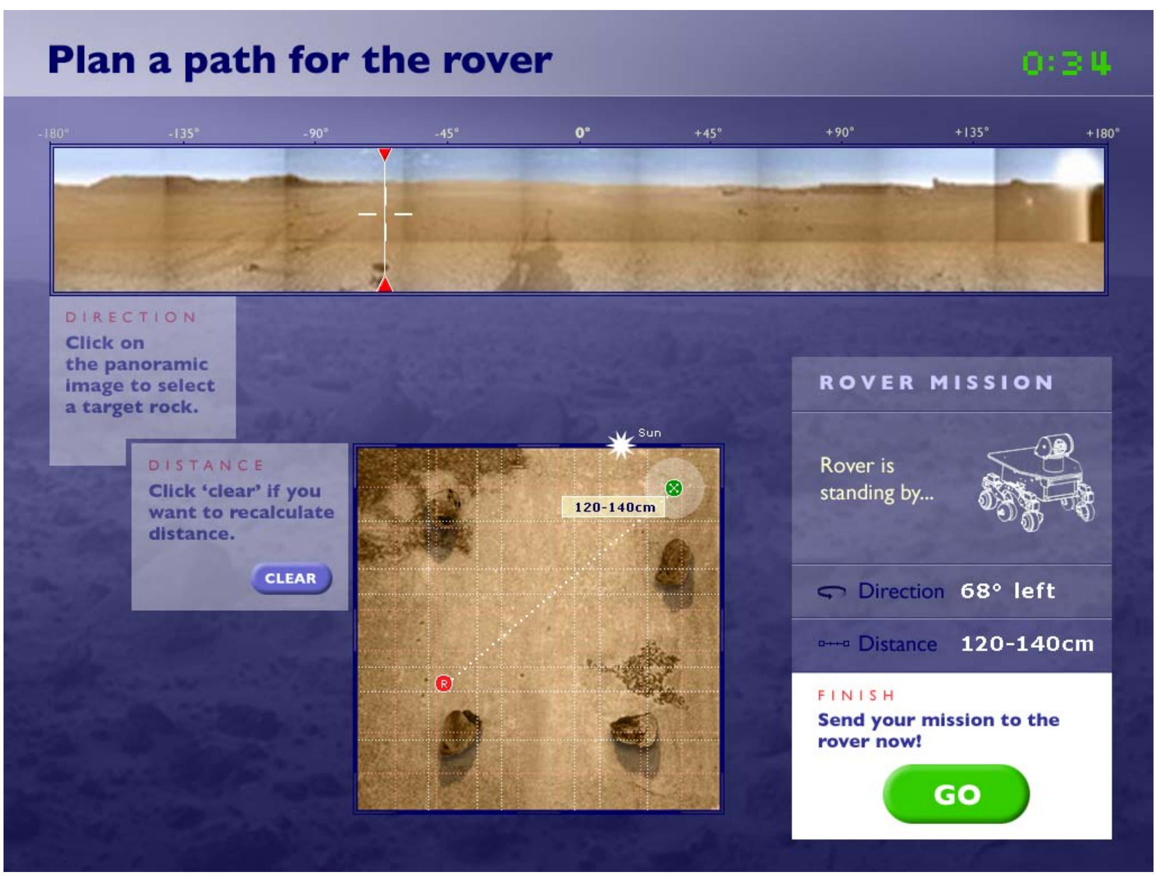

Fig. 7. The "Mission Builder" screen display.

MUSEUM INSTALLATIONS

The PER exhibit has been deployed at five main locations across the country: the Smithsonian 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).

Interaction format

The format of the exhibit is left up to the individual museum. As a result we have observed three different styles of interaction. At the Smithsonian Air and Space Museum, interaction with the exhibit is completely mediated by a dedicated docent. At the 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 unmediated.

Mars yards

Each museum designed and produced its own Mars yard or yards for the exhibit. 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 except for four or five large rocks which serve as scientific targets. The yards are surrounded by walls decorated with Martian landscapes and horizons from NASA's Pathfinder mission. Each yard also displays a sun on one wall designed to help the visitors orient themselves when using the exhibit. The hip height walls are high enough to be viewed as obstacles by the rover but low enough to allow visitors a view of the yard.

The National Science Center and Exploratorium each have two yards, while the other locations each have a single yard. Sizes and shapes vary based on the space available at each location. The largest yard is a single yard at the NASA Ames Mars Center which measures 16 feet square. The smallest yard is approximately 8 feet by 9 feet. At the National Science center, the yards are polygons designed to maximize available space (Fig. 8). The yards are constructed from spray painted Styrofoam; layered paint, glue, sand, wood and plaster; small lava rocks and sand; and layered Styrofoam, polymesh and dryvit compound.

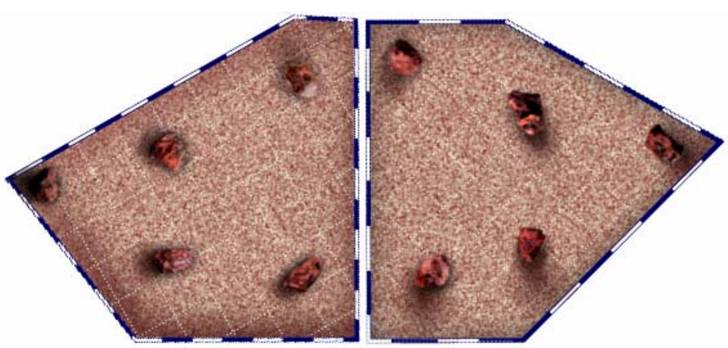

Fig. 8. The two yards at the National Science Center are built from lava rocks and sand and designed to maximize available space. The yards fill the available portions of a 15' x 30' rectangle.

Both the Smithsonian Air and Space Museum and Hazy Center yards were built by local high school students. Using data from the Pathfinder mission, Earth Science classes designed the yard topography from cut Styrofoam to be an exact scale model of real Martian terrain. Art classes covered the foam with dryvit, painted the yard, and built realistic looking Styrofoam rocks. The end result is a realistic Martian terrain for the PERs to explore (Fig. 9).

Fig. 9. 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 ANALYSIS

Rover reliability

The rovers have proven to be very reliable, and, as we can see from this museum staff person's comment, often more reliable than the museums had expected:

> *"Unlike most of our exhibits these [PERs] get slammed constantly, opening to closing, with no rest. I think they're holding up surprisingly well. Better than I thought they would."*

Most failures are due to broken servos or motors which are easily serviceable by museum staff. When the exhibits opened, the first robot failures we saw were in the tilt servos, drive motors, and steering servos. For all of these parts we made modifications to the robots to make them more robust. To help keep the drive motors from breaking, we reduced the speed of the motors from 100% to 80% with a firmware update first introduced Jan 12th. The steering servo speed was also reduced in this firmware update, and beginning Jan 27th, we modified the power board to send 5V rather than 6V to the steering servos. The original tilt servos had plastic gear teeth. Beginning Jan 27th, we replaced these servos with a metal-geared servo. After these modifications were made, rover reliability was much improved (Fig. 10).

	Before Modifications ~38 operating days/robot for Tilt & Steering Servos. ~13 operating days/robot for Motors.	**After Modifications** ~80 operating days/robot for Tilt & Steering Servos. ~105 operating days/robot for Motors.
Tilt Servos	6	4
Steering Servos	8	16
Motors	5	6

Fig. 10. Number of broken rover components before and after rover modifications were implemented.

Although the robots have been in operation roughly 8 times longer after the motor modification than before, the number of broken motors after modification is only slightly higher than the number broken before modification.

The robots have been in operation roughly twice as long after the steering servo and tilt servo modifications as before the modifications. The number of broken tilt servos has decreased slightly. The number of broken steering servos has doubled, as would be expected. However 13 out of the 16 post-modification servos that broke were located at the National Science Center. We believe that the high proportion of broken servos at that location is due in part to the rough surfaces of the National Science Center yards. Beginning June 1st, a new and hopefully more robust steering servo will be substituted as the old steering servos break.

The other rover components all seem to be quite reliable. In the roughly five months between Dec 29th and June 1st, a single pan servo was broken due to an accident, four IR wires and three camera wires broke but were easily repaired, one camera broke, and one robot developed communication problems.

Robots ran an average of 8 days between failures before modifications and an average of 19 days between failures after the modifications. Looking at the total operating time between Dec 29th and June 1st, robots ran on average 15 days before a failure.

In conclusion, the rovers last roughly two weeks before encountering a failure, and most failures can be easily serviced by the museum staff.

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 [6].

About half of the missions (52.7%) ended with the rover successfully locating a rock (Fig. 11). 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.

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

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.

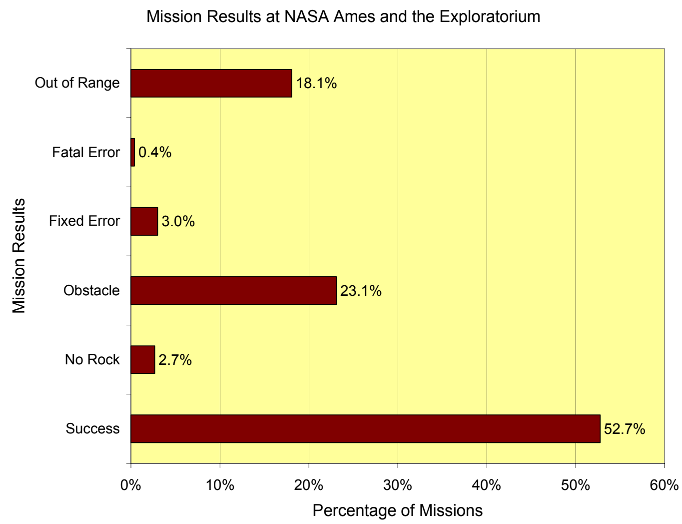

Fig. 11. Mission results from NASA Ames and the Exploratorium between December 29th, 2003 and April 14th, 2004.

EXHIBIT ANALYSIS

Traditional school-based assessments of learning are often inappropriate for use in informal learning environments [1]. As groups of visitors use and talk about exhibits, they are constructing a shared understanding of the content. Following recent theoretical and empirical work in museum learning [5,14], our analyses focus on this naturally occurring talk as the best indicator of whether the exhibit is successful in terms of its educational goals.

The PER exhibit is interesting to a wide range of visitors, but we focus here upon impact for one of the most common user groups: Children visiting the museum with families. In this article we first analyze videotapes of families using the exhibit in order to describe the extent to which their conversations reflect the intended educational themes. Second, we analyze post-exhibit interviews with children in order to describe the extent to which they understood those same themes after having used the exhibit.

Method

Research was conducted at the Exploratorium during February 2004 and at the Smithsonian National Air and Space Museum (NASM) in April 2004. At the Exploratorium families interacted with the exhibit on their own, although staff were generally available to answer visitor questions. At NASM 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. Thus, the sites provide a contrast in how the exhibit functioned in stand-alone vs. supported environments.

We analyze the activity of 43 families recruited at the two target sites: Twenty-nine at the Exploratorium and 14 at NASM. For recruiting purposes, a ‘family’ was defined as a parent or guardian (over age 18) and at least one child between the ages of 4 and 14. The average age of children 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.

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 MER missions: Parents were asked to describe what they knew about the MER; their family's level of interest in the MER missions; and what they thought their child learned from the PER exhibit.

Results

In this article, we focus on the question of how the exhibit supported its two stated educational objectives: 1) allowing visitors to explore the role of robots in mission science; and 2) enabling visitors to appreciate the nature of robot autonomy. We will describe conversational coding schemes we created and applied to the interaction and interview data. Unless otherwise specified, comments about the MER and the PER were given equal weight in coding. Reliability was assessed by comparing codes from two independent raters on 20% of data. Inter-rater reliability for each coding scheme exceeded 85%.

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. We developed four coding categories to capture exhibit talk related to the role of robots in mission science.

The first coding category, 'About the Mars Mission', captured exhibit talk about the two Mars Exploration Rovers and the goals of their mission. An example of this type of talk is:

> *Now that is what they sent to Mars… I heard last night they were running one of the wheels so they could make a trench (Parent, Exploratorium)*

A second category included direct comparisons made between the design and capabilities of the PER and MER.

> *The real ones on Mars don't go much quicker than this (Docent, NASM)*
>
> *… you noticed this one had a light in front of it to do its science? The real one actually has an arm that reaches out and checks out the rock (Docent, NASM)*

The next two categories were created to capture talk about robots as part of a collaborative team. The third category focused on communication, specifically the mediating nature of programming and telecommunications:

So you're going to pretend that you're gonna be one of those computer guys, okay, and you're going to do some signals so that the rover can move around like it was on Mars. (Parent, Exploratorium)

A fourth category, 'Collaborating with Robots', captured talk about how robots and people can work together and exchange information.

If you look on the computer screen, it shows you what the camera on the rover is seeing (Parent, Exploratorium)

So did you have to give it an exact directional… or do you just say there's a rock over here and it locks on the rock? (Parent, Exploratorium)

So now it's going to ask you to make a map for it (Parent, Exploratorium)

Conversations at the PER Exhibit. Fig. 12 presents the percentage of conversational groups[3] 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, conversational 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. 12. Percentages of conversation groups at each museum discussing themes related to the role of robots in mission science.

Further analysis revealed that parents generally initiated the same amount of thematic talk at both the Exploratorium and NASM exhibits[5], and that the additional talk observed at NASM was coming from the docents. As one might expect, this additional docent talk was often general and driven by the script docents used. In contrast, parent comments, particularly in the Exploratorium, were more often specific and targeted to child experience. For example, a mother and 4-year old boy were getting ready to initiate a new mission at the Exploratorium. After setting up the mission, mom turned to her son to encourage him to push the "Go" button and begin the mission: "OK, now look, you want to tell him to go?" The child nods, leans

[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), 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.

[5] 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.

over to the Mars Yard, looks straight at the PER, and shouts: "Go!" Even though they just used the interface together, mom realized that her son did not really understand that the computer was mediating the human-robot interaction. Thus, she slowed down, took a step back, and addressed the misconception: "*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.*"

Child Interviews. We used the same four coding categories for children's post-exhibit interviews. Regardless of site, children came away from the exhibit demonstrating fairly high levels of thematic knowledge. Almost all children demonstrated basic knowledge of the MER mission (Exploratorium, 93%; NASM, 100%) and of collaborating with robots (Exploratorium, 97%; NASM, 100%). Most children (Exploratorium, 72%; NASM, 69%) were also able to describe devices people can use to communicate with robots (e.g., computers and, in the case of rovers in space, satellites). Although we never directly asked children to compare MER and PER, 21% of Exploratorium children and 38% of NASM children made spontaneous comparisons between the two. None of these differences were statistically significant.

In conjunction with the conversational analysis, these findings suggest that the mission-based exhibit format was successful in encouraging visitors to engage with the idea of robots as partners in scientific exploration. Because we did not pretest children, we cannot make strong causal claims about learning from the PER. However, we do not think that learning, as it is traditionally measured, is the point of exhibits such as the PER. We can make strong claims about the exhibit being successful in supporting specific connections to the MER missions, suggesting that the PER was a catalyst for conversations that were probably based on news accounts of the ongoing MER missions. From the perspective of the museum community, where exhibitions take years to develop and are rarely linked to current events, the PER exhibit demonstrates an innovative strategy for informal science education.

The Nature of Robot Autonomy

The second main objective of the exhibit was to help visitors explore rover autonomy. Although all museum visitors will come to the exhibit with some prior knowledge about robots, most have probably not interacted with a robot that possessed true autonomous properties [13]. Thus, the exhibit provides a unique opportunity for visitors to re-evaluate concepts of robots that have perhaps been built largely upon fictional autonomous robots such (e.g. R2D2 and C3PO) or non-autonomous robots (e.g., manufacturing or telepresence).

We developed three coding categories relevant to the goal of appreciating rover autonomy. The first category, rover design, included talk about the technology used to build rovers, rover size, and the importance of rover autonomy. For example:

> *See it [PER] has two motors. One is at the wheels… to move it forward, and the other is the other on the top, which is to turn the wheel. You see – it has two motors. The design is very simple, actually (Parent, NASM)*

The second coding category captured talk about the types of activities rovers could perform, such as taking pictures and examining rocks.

> *There's some pictures that it's taking (Parent, Exploratorium)*

> *Now the rover's starting his mission, so what he's doing is taking pictures all the way around himself to create a 360 degree panorama (Docent, NASM)*

The final category captured 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.

> *This rover also has a great deal of autonomy, meaning he can think for himself…he's going to go the distance you gave him. When he's done following your commands, then he does the thinking by himself to find the rock (Docent, NASM)*

Conversations at the PER Exhibit. As shown in Fig. 13, visitors at both museums were coded as addressing all three themes, although each was 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 for talk about robots and mission science, the presence of docents was responsible for the increased frequency of thematic talk about autonomy 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. 13. Percentage of conversation groups at each museum discussing themes related to rover autonomy.

Child Interviews. Children's interview transcripts were first coded using the first two of the categories described above: rover design and rover activities. Children were able to speak knowledgably about rover design at both the Exploratorium (52%) and NASM (77%) and to speak about rover activities at both Exploratorium (55%) and NASM (85%). Although there was a suggestion that children at NASM were more likely to demonstrate knowledge in these two categories, neither of these differences proved significant.

In constructing a measure to assess children's ideas about the third theme--rover autonomy—we needed to account for the fact that children were often inconsistent and uncertain when deciding whether a robot would be capable of particular autonomous behaviors. To do this, we constructed an autonomy score. For each statement indicating comprehension of the autonomous operations of the rover, a child was given one positive point[6]. For each statement indicating the opposite belief, namely that the rovers were incapable of independent action and operated via remote control, a child was given one negative point. These points were summed independently for statements about the MER and PER, thus each child was assigned two autonomy scores.

Examples of statements from different children that were coded as indicating rover autonomy, and thus receiving a positive point, included:

> *I clicked it and it didn't go far enough and it [PER] looked around and it found the rock anyway (10 yo boy, Exploratorium)*

> *It has a smarter capability to say, and its able to move around those. It can detect an obstruction and it will go around it instead of going straight through it. (10 yo boy, Exploratorium)*

> *I think they [MERs] might need to do things for themselves because if the computer crashes they have no way of contacting it. So it must have a boot up or something that will make it go by itself and know what to do (10 yo boy, Exploratorium)*

Examples of statements that received a negative autonomy point were:

> *He [PER] can move when we tell him to do and when we don't tell him to he doesn't move (8yo girl, Exploratorium)*

> *People probably have to tell it [MER] how much to, how many degrees to turn and how much more to go, and maybe control the instruments (10 yo boy, NASM)*

[6] 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

Because it [MER] doesn't know which rock because it doesn't have any eyes. It only has a camera that the humans are controlling so only they'll know where it is (9 yo boy, NASM)

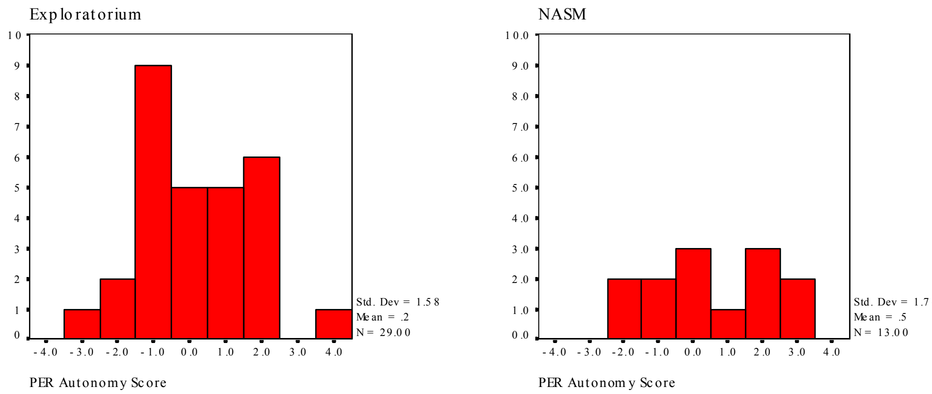

Fig. 14. PER autonomy scores. Positive scores indicate an understanding of robot autonomy. Higher scores indicate more consistent beliefs about the concept.

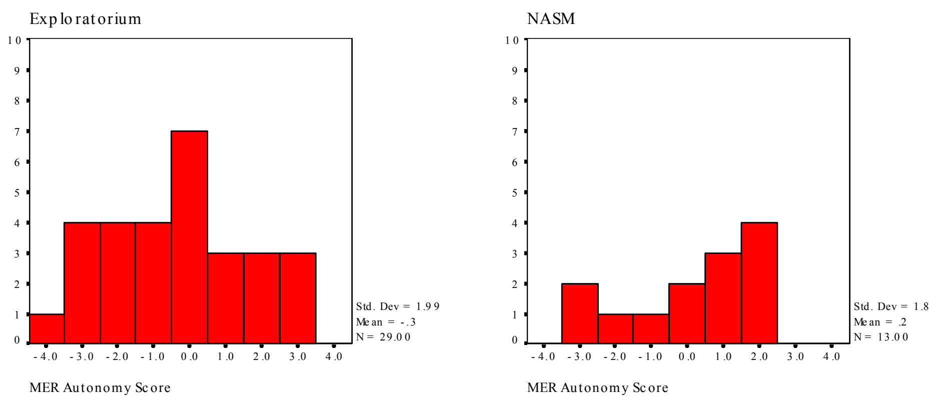

Fig. 15. MER autonomy scores. Positive scores indicate an understanding of robot autonomy. Higher scores indicate more consistent beliefs about the concept.

As shown in Figures 14 and 15, between about a third to a half of the children came away from the exhibit with a positive autonomy score for PER (Exploratorium, 41%; NASM; 46%) and MER (Exploratorium, 31%; NASM, 54%). As one might expect, PER and MER scores were significantly correlated (r=0.48, n=42, p=.001). The differences in scores between museums were not significant.

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 positive autonomy scores (i.e., children who described the rovers as capable of some autonomous action) were more likely to make comparisons between the MER and the PER. This was true for children with high PER autonomy scores, X2 (1)=5.02, p=.025, as well as high MER autonomy scores, X2 (1)=7.34, p=.007. 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. Children with positive PER autonomy scores were also somewhat more knowledgeable about rover design, X2 (1)=4.14, p=.042. 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.

How Parents and Docents Talked About Autonomy

Research in the field of museum learning suggests that parents can serve an important bridging function between what a museum intended for children to understand about an exhibit and what children actually do understand [4]. Of course, that bridging function is also the primary job description of museum docents. But while docents and parents may find themselves in similar roles in a museum, each group brings unique skills to the task. Museum docents are often trained in the content of the exhibit, while that is rarely the case for parents. On the other hand, parents are much more familiar with their child's interests, knowledge, and learning history than are docents. The goal of the current analysis is to determine if these differences led parents and docents to approach exhibit content in different ways.

In this section we report our analysis of how adults (parents and docents) talked to children about autonomy. Robotic autonomy statements were chosen to undergo additional coding for two reasons: (1) autonomy is a difficult concept, and parents and docents used a variety of strategies to explain it to children; and (2) an understanding of robotic autonomy is an important learning outcome for the PER exhibit. Each statement was coded in terms of two dimensions. Statements were categorized as either referencing a specific instance of rover activity (**targeted**), or as a general statement about the rover (**general**). Statements were also categorized as pointing out an autonomous feature of the rover (**feature-level autonomy**) or introducing the concept of autonomy at a higher conceptual level (**high-level autonomy**). Examples of these different types of statements are given below:

> *He just looked around to see if he could find the rock that you wanted him to go to (Targeted, feature-level autonomy statement by an Exploratorium parent)*
>
> *There it goes. Oh, it does the thinking itself* (Targeted, high-level autonomy statement by an Exploratorium parent)
>
> *So you have to tell the rover where to go, and it has to be smart enough to go find it on its own* (General, high-level autonomy statement by a NASM docent)
>
> *It won't run into the wall, because it's got sensors that will tell it… that will stop it before it gets to the wall* (General, feature-level autonomy statement by a NASM docent)

Eleven parents (10 from the Exploratorium, 1 from NASM) and 13 docents (1 from the Exploratorium, 12 from NASM) made statements about autonomy during exhibit interactions. The 11 parents produced a total of 14 autonomy statements, while the 13 docents produced a total of 37. Eighty-six percent of parent autonomy statements and 59% of docent autonomy statements were targeted to a specific instance of rover activity. Seventy-nine percent of parent statements addressed autonomy at the feature level, as did 57% of docent statements.

It would seem that the training docents received allowed them to generate more high-level autonomy statements at the exhibit. However, the finding that parents are more likely to target their statements about autonomy to specific instances of rover activity is consistent with previous research that parents provide 'just-in-time' explanations for scientific phenomenon [4]. Such explanations allow parents to provide children with information at the moment it is needed and to shape children's interpretation of what they are doing and seeing in the museum. Additionally, these explanations build upon the shared experience between parent and child, leaving open the possibility of the families following-up on the information at a later date.

Parent Interviews

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

Fifty-nine percent of parents from the Exploratorium, and 86% from NASM indicated a general interest in science and astronomy. When asked if they had previously attended a Mars exhibit or event, 24% of Exploratorium parents and 7% of NASM parents had done so.

The top three ways of gathering information about the MER missions for Exploratorium parents was newspapers or magazines (34%), television (34%) and the Internet (28%). Similarly, NASM parents collected their information through newspapers or magazines (64%), television (36%) and the Internet (29%). Parents were asked to indicate all of the ways they obtained information about the missions, so percents will sum to more than 100. Between one-quarter and one-third of parents at both museums indicated that they usually followed the progress of the MER whenever they saw information about it on a frequently viewed source (i.e., the Internet, television, or newspaper).

The frequency with which parents spoke to their children about the MER missions varied greatly. At the Exploratorium, 48% of parents reported that they had spoken to their children about the MER missions prior to coming to the museum. At NASM, 57% of parents reported having spoken to their children about the MER missions prior to their museum visit.

In order to determine if exhibit interaction patterns were affected by a family's level of interest in the MER missions, an 'interest score' was calculated for each family. This score was calculated by assigning one point for each of the following: following the progress of the MER missions; talking to children about the MER missions prior to the museum visit; indicating an interest in space and astronomy. The resulting scores ranged from 0 (no interest) to 4 (high interest), with an average interest score from the Exploratorium of 2.0, and an average interest score from NASM of 2.4.

Using this composite interest score, we examined the relationships between family interest and exhibit talk in the seven categories presented in figures 12 and 13. 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, X2 (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.

When asked specifically about the PER exhibit, the majority of parents believed the exhibit was a positive educational experience. 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 (50%) and helped their child learn how rovers worked (50%). Twenty-one 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.

Analysis Conclusions

This assessment suggests that the exhibit was an effective forum for involving visitors in explorations of the role of robots in mission science and of robots as autonomous agents. Analysis of family conversation suggests that visitors were expanding on relevant themes as they used the exhibit. Families 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 MER missions and that many of them also were able to connect the exhibit experience in specific ways to the mission. This finding suggests that the format of the exhibit, with children conducting their own missions, was effective both in holding visitor attention and communicating educational content.

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 did not necessarily believe that a single exhibit experience would be a sufficient base for children to develop fully correct theories of autonomy. Rather, 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. It may be the case that making the autonomous functions of the rover more explicit, either by providing signage to direct visitor's attention to the rover's autonomous capabilities, or by providing a direct explanation of robotic autonomy, would help families explore this concept more effectively.

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 PERs 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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