An Analysis of the Intelligent Robotics Group's Experience with the Mars Exploration Rover Mission

Kristen Stubbs Illah Nourbakhsh*

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School of Computer Science
Carnegie Mellon University

Intelligent Robotics Group*
NASA Ames Research Center

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Introduction

From December 2003 through March 2004, a number of members of the Intelligent Robotics Group (IRG) at NASA Ames traveled to Pasadena, California, to aid the Mars Exploration Rover (MER) mission at NASA's Jet Propulsion Laboratory (JPL).

During May 2004, Kristen Stubbs spent two weeks at NASA Ames with the IRG. During this time, she conducted two sets of interviews with seven of the IRG team members who spent time working at JPL on the MER mission. The first set of interviews focused on the work that the team did for the MER mission, whereas the second set of interviews focused on the lessons that the team members learned while working on the mission. This study is the result of an analysis of all of the thirteen interviews that were conducted.

The primary goal of the IRG team was to assist the MER mission scientists by providing a variety of services and data products, as outlined below (adapted from a report by Randy Sargent and Illah Nourbakhsh):

Viz

- Browser for finding 3D models, helps scientists find and later return to 3D models, a daunting task in view of the information overload that is otherwise a major barrier.
- Helping scientists look for evidence of ripples and crossbedding in layered rocks.
- Predict shadows caused by terrain or rover geometry at various times of the day to help with science activity scheduling.
- Convert and import models from USGS and MSSS for viewing under Viz.
- Predict visibility conditions of various rover cameras for a set of candidate traverse locations, helping with decision-making for rover trajectory planning.
- General 3D scene understanding in order to enable scientists to better comprehend scale, distance, etc.
- Generate false-color elevation maps based on 3D Pancam models.

Microscopic imager

- Focal section merge with parallax correction, enabling at-a-glance investigation of multiple frames of data by the scientist, merged into one.
- Data dropout correction tools that make the resulting processed products of focal section merge more complete than the original data.
- Registered sequences of microscopic images, enabling a series of "rectified" snapshots so that scientists can look at change over the image series.
- 3D models of microscopic stereo pairs, providing relief and texture that enables scientists to truly study the 3D micro-terrain.
- Registered 2D and 3D mosaic models of microscopic images, provide broader visualizations of the area of interest than is possible with any single image pair, and with far more detail than Pancam. This was critical for looking for crossbedding at the Last Chance rock (Opportunity).
- Microscopic image browser, enables scientists to quickly find original images and matched processed products far more quickly than before.

Stereo and registered products

- Generation of stereo models from all pairs of images, including Pancam, Navcam and Hazcams. These models are typically very high quality and are usually produced on demand because existing models do not suffice.
- Generation of stereo models even when there is motion between pairs of images.
- Generation of stereo models combining uncalibrated orbital imagery and descent cameras. The IRG and USGS were requested to perform this service.
- Register left and right Pancam models to produce single images with left and right filters, merged, with the images registered, in conjunction with Pancam team. Scientists use this product to study the combined spectra from a single viewpoint, which otherwise hard because the left and right filters are different on the rovers.

Visualization of data products in the context of rover motion

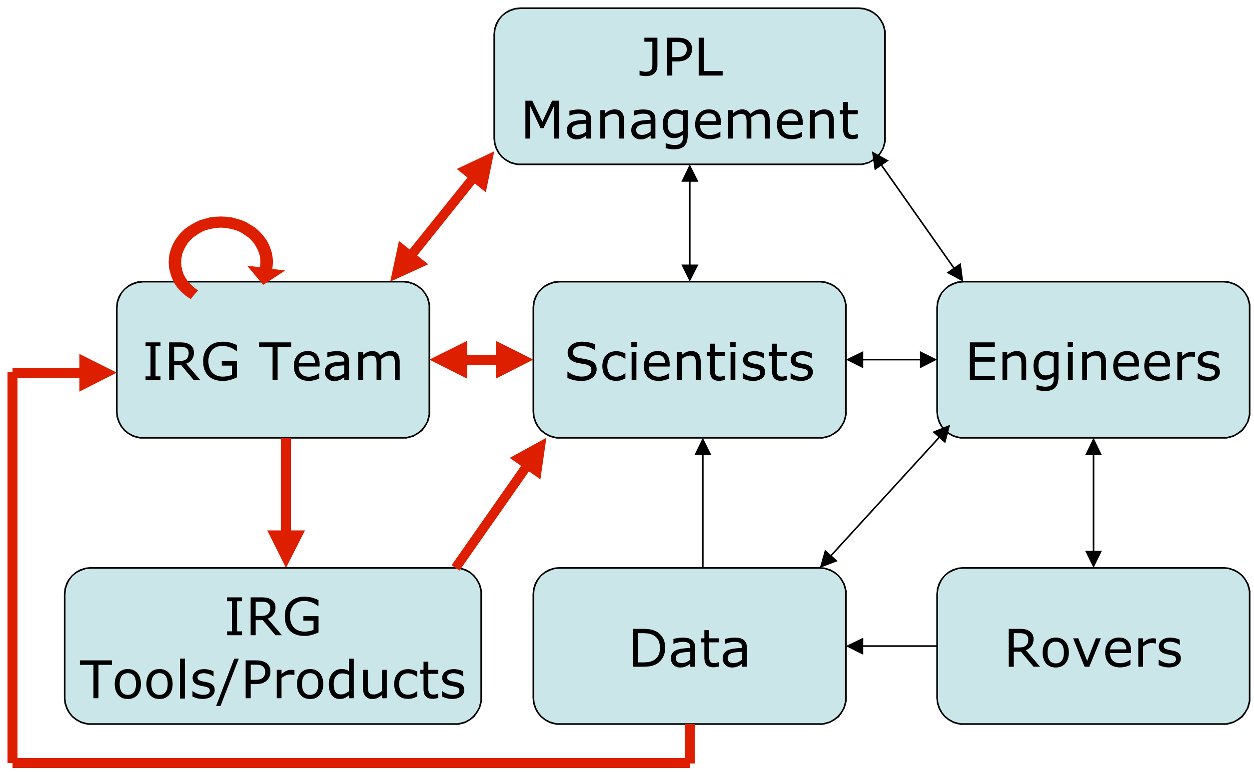
- Rapid MI mosaic generation to ascertain coverage of the science target. This provides fused data to the scientists within *seconds* of the images being sent back to earth.

Data fusion

- Co-register MI and Pancam 3D models, providing context to scientists.
- Overlay 2D MI images on Pancam models, potentially enabling colorization of the models.

In order to provide scientists with these data products efficiently, the IRG team needed to adapt their current stereo pipeline tools as well as generate new tools and scripts to automate the product generation process. Most of the team's time was spent servicing scientists' requests for custom data products and building the tools needed to do so as they went.

It is important to consider that all of the team's activities took place within the context of the larger MER mission. The diagram below is a simplified view of the relationships between various entities involved in the MER mission:



At JPL, the JPL mission managers supervised the mission scientists, rover engineers, and the IRG team. On Mars, the rovers Spirit and Opportunity were sending data back to Earth as the rover engineers at JPL directed them to. This data was used by scientists, and the IRG team used it to generate custom data products. Scientists then used these custom data products; this relationship was made possible by the contact that the IRG team had with the scientists.

The relationships shown in bold in the diagram had the most significant impact on the team and their work. These crucial relationships were:

- The relationship between the IRG team and JPL mission management
- The relationship between IRG team members
- The relationship between the IRG team and the data they needed
- The relationship between the IRG team and their tools and data products
- The relationship between mission scientists and the IRG team's tools and data products
- The relationship between the IRG team and mission scientists

Examining each of these relationships in detail reveals a number of surprising observations about the nature of the MER mission and suggests possible directions for the future work of the IRG.

The IRG Team and JPL Mission Management

From the perspective of IRG team members, the relationship between the IRG team and the JPL mission management was a very difficult one. The IRG team was "low priority" as far as the management was concerned, at least in part due to the official status of Viz. Viz was officially a non-mission-critical, "Class B" software tool. Class B tools can be differentiated from Class A tools in the sense that if a Class B tool fails, the rovers themselves would not be affected; Class A tools were generally those whose failure could result in mission failure. As a Class B tool and a science tool, Viz was not a high priority of the JPL mission managers.

In addition, the JPL mission management tended to remain inflexible in the face of the changing needs of the mission scientists. The IRG team did not originally plan on providing custom data products to scientists, but after arriving at JPL they found that by doing so, they would best be able to help meet scientists' needs. Unfortunately, the JPL management did not seem to acknowledge this contribution; they saw the only function of the IRG team as running Viz for scientists, holding the mouse and clicking buttons.

The JPL management might have preferred the Ames team to work remotely, but this was not possible for a variety of reasons. The MIPL tools the team needed only ran on the MER flight ops machines, and it was not possible to run the exact same version at Ames. The data from the rover was stored in a file system known as the OSS tree, but this too was only available from JPL behind the firewall. The OSS was mirrored by a system called FEI, but FEI mirrors were not organized the same as the OSS tree and stored file version information differently, so it would have been impossible for a team at Ames to develop tools that would work at JPL.

The relatively poor relationship between the IRG team and the JPL management resulted in a wide array of problems that the team had to try and work around. When the team arrived at JPL, members had no official computers of their own and were forced to keep hunting for unused computers with access to the OSS tree to use. Even if a team member could get to the data in the OSS tree and build data products, there was no space allocated in the OSS tree for the team to publish their products so that scientists could use them. The team was able to work around this thanks to the Pancam team, who allowed the IRG team to store products under one of the Pancam directories in the tree.

The problem of getting badges was another significant challenge for the IRG team. Most of the time, most team members had only visitors' badges and were required to be escorted at all times. This meant that those team members were unable to open many of the doors at JPL, which limited their access to the scientists that they were trying to assist. IRG team members were essentially "tied" to their escorts, requiring that everyone have roughly the same sleep and work schedule. Some team members were forced to work only after-hours in order to stay out of sight of the JPL management. Overall, the lack of support from JPL mission management demoralized and frustrated the IRG team members, who were working long hours for the sake of the mission's science goals.

IRG team members suggested a number of reasons why the JPL mission management may have reacted the way that they did. Management at Ames and management at JPL seem to have different attitudes regarding the relationship of software creators to users. Ames management sees the ideal process as one in which researchers produce software and hand it off to its intended audience, at which point the relationship basically ends. JPL management favors a model that includes ongoing product support after delivery, which makes them reluctant to utilize Ames products because they do not expect that they will receive this support. This would suggest that the IRG team should have been received more favorably by JPL because they were providing more services to scientists than simply helping them use Viz. However, Viz's official status brought along with it the "worst of both worlds": Viz was officially part of the mission, which meant that the team was faced with bureaucratic challenges, but it was not a mission-critical application, which meant that it was a low priority of mission management. In addition, one IRG team member observed that there was little motivation for the JPL managers to help the Ames-based team. To JPL management, the fact that the IRG team was addressing unanticipated needs suggested failures in planning on the part of the JPL management; helping out the IRG team would have made this more obvious. Convincing JPL management that helping the IRG team was in their best interests was a difficult diplomatic task. Jim Murphy, a talented Ames manager who had been able to do this, retired roughly halfway through the mission, leaving the IRG team without a liaison to JPL who the JPL managers knew and trusted. This further strained relations between the IRG and the JPL management. In order to work around this problem, at times the IRG team was able to talk directly with JPL technicians, who could in turn make suggestions to their supervisors. This allowed the IRG team to make changes in cooperation with individuals who were well known to JPL managers.

Not only would helping the IRG team potentially damage the reputation of the JPL management, but it also may have been to their benefit to keep the team working on the mission unofficially. If problems persisted despite of or as a result of this work, JPL management would be able to blame the team because they technically should not have been working on those problems in the first place. Thus, unofficial laborers could become scapegoats in the event of a serious problem.

The team also lacked strong support from Ames management because the IRG's work on the MER mission was not something that Ames had planned for. In addition, the fact that Viz was "just" a science tool was problematic because Ames was not receiving funding for science operations. This lack of support from Ames meant that the team could not stay at JPL for as long as they would have liked and that it was difficult for IRG team members to persuade Ames managers to talk to their counterparts at JPL regarding the problems that the IRG team was having.

Recommendations

These observations suggest that for future missions, it would be helpful to begin building strong, positive relationships with individuals and teams at JPL as soon as possible. In addition, interacting with JPL management requires both patience and persistence. Some team members found that after having a request initially rejected by a JPL manager, revisiting the issue at a later time sometimes resulted in a different answer. This may prove to be a useful strategy for future missions as well.

The IRG Team Members

As a result of badging issues and the team's heavy workload, communication within the IRG team proved to be somewhat challenging. Team members reported that they used a variety of means to communicate, including email, cell phones, face-to-face contact, and America On-Line Instant Messenger (IM). While some argued that face-to-face contact was the most effective, it was not always common for team members to be working in the same room at the same time.

The team was frequently separated due to the need to hunt for available computers and the immobility of some team members due to their badging situation. Because of the poor cell phone coverage that most team members experienced, cell phones turned out to be less useful than team members had expected. Eventually the team established an IM chat room which all team members, both at JPL and at Ames, could remain logged into; this provided a means for members to see who was available at any given time. This was valuable information given the difficulty of predicting team members' sleep schedules while working on the mission. While most likely less efficient than face-to-face meetings, the chat room was able to help distant team members work together.

In terms of the team's work habits and schedule, the fact that often escorts were required was a significant challenge. Team members had to try and adapt their work habits to those of their escorts, which could be problematic if an escort needed to work at a time when others were ready to sleep. At other times, team members would be forced to wait until their escort had woken up before being able to accomplish any work. While all of the IRG team members interviewed reported that working with their teammates at JPL was a positive experience, it required them to be very flexible in terms of their own schedules.

The most difficult problem for the team's work schedule as a whole was the problem of prioritizing scientists' requests. There was no formal system for receiving or handling requests; team members would find out about them either by talking to scientists themselves or from other team members who had talked to the scientists. Determining which requests should have the highest priority was difficult, especially for team members who had limited access to the scientists. Without interacting with the scientists who were making requests, it was difficult to tell "who was screaming the loudest" and so whose request to address first. Almost all of the requests that the IRG team handled were time-sensitive because scientists needed to make quick decisions about what the rover should do next based on the data available. Once the rover had moved on, scientists were generally no longer interested in those data products because they had to focus on new data and new rover activities. In order for the team to provide relevant products to scientists, they needed to be able to effectively prioritize the requests they were receiving.

Recommendations

Having more experienced team members share information with team members who are about to join a mission for the first time was very helpful during this mission, and this practice should be continued and encouraged. At the same time, once a person has started working on a mission, becoming acculturated to the mission environment requires time and effort that should be accounted for. The culture of a mission is significantly different from the IRG team's normal working environment at Ames, and so debriefing team members and making sure they have time to adjust may be a good strategy to ensure that team members are not too surprised or overwhelmed when they make the transition to working on a mission.

Another activity that might benefit the next mission is for IRG team members to consider exactly what information is needed when a scientist makes a request for a data product. While it might not be possible to automate the request generation process, having a documented set of required information should make handling in-person requests more efficient and make those requests easier to prioritize.

The IRG Team and the Rover Data

The data that the IRG team used to generate their data products was stored in the OSS tree, a file system that was "not necessarily well-organized, but strictly organized." Files in the OSS tree tended to be organized by the post-processing that had been done to them, which meant that it was very unintuitive; several team members commented that it was virtually impossible to simply browse around the tree until you found what you were looking for. This meant that the team spent a significant amount of time developing automated tools both for making sense of the cryptic filenames used in the tree and also for searching the tree to determine the most likely place where a specific piece of data would be located. These metadata tools proved to be critical for automating the product generation process.

Accessing the data in the OSS tree was also problematic because the OSS tree itself was only available to people who were physically sitting at a flight ops machine. Because of security restrictions, it was also difficult to copy data out of the OSS tree. For example, the team was not able to accommodate scientists who wanted to work with data products on their own laptops.

The other major challenge in working with the OSS tree involved the fact that incomplete data would often be added to the tree and updated at some later time. The team could not afford to wait for the complete data due to the time-sensitive nature of scientists' requests, and so the team had to build tools that were able to handle incomplete data. At the same time, team members wanted to be able to find out when updated data was available so that models could be regenerated if need be. Unfortunately, the only reliable methods to see if new data was available were either to look at the file system manually or to have a script access the file system to check if a file had been updated. The latter approach was to be avoided, however, because the file system was not able to handle large numbers of frequent requests. IRG team members were concerned that their activities might place undue strain on the systems they were using and had to work in such a way as to minimize any negative consequences of their use of these systems.

Recommendations

Because of the large effort required to build effective tools for interfacing with the OSS tree, it would be best to obtain documentation on future mission file systems and access to them well in advance. This will allow the team to develop the basic tools necessary to automate the rest of the data generation process. It would also be helpful to plan in advance how the team will handle incomplete data as well as when and how models will be updated.

The IRG Team and Their Tools

IRG team members generally expressed satisfaction regarding the process by which they developed the tools they needed to generate custom data products. This process was generally ad hoc, with tools being built as they were needed. When the team did not have outstanding requests to fulfill, they tried to invest time in creating tools to further automate the building of data products. These tools generally took the form of Perl scripts, which team members created by working individually. Unfortunately, due to the fact that the team was often dispersed, if one member built a new tool or found a more efficient way of doing something, this knowledge did not always spread quickly to the entire group.

Despite the fact that most tools were built by one person working individually to meet some immediate need, the IRG team took care to ensure that their tools would be reusable between data products. As the mission progressed, the group's collection of tools increased, and the degree to which requests could be automated also increased.

The process of building data products began with the group's deciding what to build. This was mainly accomplished by taking requests from scientists. When no requests were forthcoming, the group actively solicited scientists for requests. The team also monitored the latest data from the rovers and would build models of data that looked sufficiently "interesting" that scientists might find it useful. The actual generation of these models was only partially automated. The team used scripts to help locate the data that the scientists wanted and were able to do some processing using other tools, but the process never became fully automated. Generally, at some point during the process, it was necessary to manually tweak parameters until the model looked its best. Team members felt that this "human-in-the-loop" approach, while potentially time-consuming, resulted in a higher quality of model than the official JPL models, which were the result of an entirely automated process.

The other major tool that the group worked with was Viz, a 3D visualization tool that was used to display their data products. None of the IRG team members had any significant problems with Viz, but they were frustrated by their inability to make some changes that would have been helpful. Because Viz was part of the official mission software, it was "frozen" well before the rovers landed on Mars. This meant that making any changes to Viz required team members to go through an extensive bureaucratic process to ask for permission to make changes to the software. Team members found that the extra time and energy required to go through this process would not be worth it, especially given the high probability that their request would be denied. IRG team members said they would have liked to fix the problem that Viz could not display the official JPL 3D models because the file format changed after Viz was frozen. A couple of people were also frustrated by the fact that they could not fix other bugs in the software, nor could they update it to add capabilities as scientists' needs changed. To work around this, team members had to fix local copies of Viz and use those rather than the officially provided release.

Recommendations

For future missions, team members emphasized the importance of further automating the product generation process. As one team member explained, automation makes it "easier to generate results for ninety percent of requests, so that you can spend the time you need to to do the other ten percent." Increased automation will allow team members to spend less time on more ordinary requests, allowing them to focus their efforts on how to generate the more novel data products that scientists need.

Team members also suggested a number of possible improvements to Viz, including:

- The ability to view more than one model at a time
- Increased speed in loading models, as large models only worked on two machines at MER
- The ability to select points in Viz at small scales, as currently selecting points draws a fixed-size cube which is far too large for a 1.5cm by 1.5cm model
- Consolidating all controls to a single window
- The ability to remove the limits on model rotation so that it is possible to view the back of a model if need be
- Adding a threading fix so that Viz will work with replay tools
- The ability to capture animations and output them to a format like QuickTime
- The ability to interpolate a model to smooth out holes
- The ability to do some automated data analysis, such as counting particles of certain sizes or shapes

The IRG Team and Scientists

Working with mission scientists at JPL was a new experience for most of the IRG team members. They found that the scientists had basically cut themselves off from the outside world and were relatively isolated. In addition, scientists were overwhelmed with the amount of information coming back from the rovers, and they were extremely focused on data analysis and planning rover science activities. Many scientists also tended to distrust 3D models because they were afraid of drawing incorrect conclusions from artifacts in the models. Even though they may have been studying something best visualized in 3D, scientists would often return to original, 2D images after examining a 3D model. In general, the mission scientists were somewhat technophobic, experts in their own scientific discipline but not having much interest in learning new computer technology. They preferred to use familiar tools when possible; three of the most popular software applications IRG team members observed scientists using were Microsoft Word, Microsoft PowerPoint, and Adobe Photoshop. While the scientists preferred to use familiar tools, they were more than willing to work with other tools if those tools did something that the scientists needed; it did not matter to scientists where a tool had come from as long as it was helpful.

Given that the mission scientists were so focused on their tasks and so overwhelmed with data, communicating with them could be difficult. One IRG team member observed that email was “surprisingly ineffective” as scientists essentially never responded to email. The team found that essentially the only way to communicate with scientists was face-to-face. At the same time, it was important to “learn the flow of the science team” to know when it was acceptable to interrupt them. If interrupted at the right time, scientists were generally friendly and willing to look at data products or make requests.

The fact that scientists were overwhelmed and only accessible via face-to-face communication had a number of significant impacts on the data product generation process. Scientists did not always know what to ask for or have the time to ask for it. “Honestly, I think a lot of them were so busy that they didn’t have time to think of what we could do to help them,” explained one IRG team member. The team tried to help by building some models of interesting-looking data and projecting them on screens in the science assessment rooms at the beginning of the day. The scientists were often interested and would walk over to get a closer look at the model. This type of demonstration helped to give scientists a better idea of what the team could do and resulted in more product requests.

Despite the team's efforts to formalize the request process, the vast majority of requests were made in person. If a scientist happened to see an IRG team member in the hall, he or she might stop and make a request; at other times, scientists actively sought out team members to make requests. The IRG team posted their email addresses and cell phone numbers on the Viz website and started mailing lists and IM chatrooms in an attempt to make sending requests easier for scientists, but team members reported that none of these methods were successful. In addition, once a data product was completed, team members had to physically find scientists and tell them to run the script that would bring up Viz website that the team was using to keep track of completed data products. Team members publicized the existence of the website through announcements at science meetings and by taping pieces of paper to computer monitors, but scientists did not generally develop a habit of checking the website and had to be alerted in person when their data products were completed.

Recommendations

According to IRG team members, one of the major reasons why they were so successful at the mission was that they were a "service provider," willing to work with scientists to help them with their data analysis. Given that future mission scientists are likely to be overwhelmed with data and having neither the time nor the energy to use new software tools, the IRG can continue to have the greatest impact on a mission by focusing on providing custom data products and help viewing them, rather than by simply handing scientists software. In addition, establishing solid relationships with future science teams as early as possible will help the IRG to better understand scientists' needs and be in a better position to help with their data analysis.

Scientists and the IRG Team's Tools

The IRG team's MI tools, data products, and Viz were each utilized slightly differently by mission scientists. At the beginning of the mission, the IRG team discovered that the MI team was not using its MI tools at all. The team had expected that after data was downloaded from the rover, an MI team member would run the IRG team's tools on the data. However, because the data received from the rover was rarely complete by the time the MI team member's shift was over, the tools were never used and no data products were generated. It was only after an IRG team member arrived and automated the MI product generation process that the MI team started using the data products created by the IRG tools.

The custom data products that IRG team members created were used by a variety of scientists. Frequently, scientists used these data products as part of their analysis of the field, to better understand what Mars is like, and to plan for future science activities. As an example, most IRG team members mentioned John Grotzinger's use of their models to study crossbedding at the MER-B (Opportunity) site. Team members also took requests from Steve Squyres, the Athena Science Payload Principal Investigator, geologists such as Mike Malin, and soil specialists.

Scientists used products made by the IRG team to help plan where to drive the rover, to calculate where shadows would fall, and to do viewpoint planning.

Several instrument teams also made requests for custom products. Members of the Rock Abrasion Tool (RAT) team used the IRG team's models to determine possible placements for the RAT. The Pancam team used custom data products to study material composition as well as to showcase their own work. The IRG team also generated products for use in press releases.

Scientists viewed these custom products using Viz, with the help of IRG team members. Most scientists preferred for IRG team members to "drive" and navigate through models for them. A few scientists were more interested in Viz and used Viz on their own, most notably the RAT team. On the whole, however, scientists preferred for IRG team members to use Viz for them; they then wanted to export pictures or animations for their own use in more familiar applications such as PowerPoint.

Recommendations

The major lesson to be learned from scientists' relationship with the IRG team's tools and data products is simply that scientists will probably not use IRG tools without the physical presence of IRG team members. It is clear that scientists had need for the tools and data products that the IRG team could provide, but that only when IRG team members were available to provide these as part of a service could scientists' needs fully be met.

Thematic Analysis

Several recurring themes appeared across the thirteen interviews that were conducted as a part of this study.

Importance of face-to-face communication

The importance of face-to-face communication arose in eleven of the thirteen interviews. Not only was face-to-face communication the only way IRG team members could interact with scientists, but it was also the preferred means of communication among team members. One IRG team member also observed that most of the decisions about day-to-day rover science operations were made by scientists talking in small groups rather than at the large group science meetings. A surprising amount of work was accomplished through individuals bumping into each other in hallways. In order to be able to provide scientists with the data products that they needed, it was crucial for IRG team members to be around for scientists to bump into, to be able to go find scientists when needed, and to have scientists be able to find them. By being physically present and providing a service, rather than just a product, the IRG team was able to have a strong positive impact on the MER mission.

IRG team as pocketknife

The fact that the IRG team was as successful as it was seems to be due in a large part to the team's willingness to do whatever was necessary to fulfill scientists' requests. The IRG team was able to adapt existing stereo pipeline tools, to create new tools as needed, and to use their own expertise in order to build high-quality data products. In eight out of the thirteen interviews, IRG team members mentioned the importance of this flexibility. The IRG team was able to become the scientists' pocketknife, providing services to help meet a wide variety of the scientists' needs. For future missions, it will be important for the IRG to have at its disposal a variety of general-purpose tools as well as to be able to use those tools to handle unexpected data and novel scientist requests.

The perils of "second-class citizenship"

In eleven of the thirteen interviews, IRG team members described the numerous problems they encountered as a result of the lack of support they received from JPL management. Obvious challenges such as being unable to get through doors and not having computers to use resulted in a number of other more complex problems, such as the team's being unavailable for face-to-face communication with scientists and being forced to work in physically disparate locations. This also meant that only a few team members might be at JPL at any one time. Overwork was a common problem because only a few IRG team members were trying to service the needs of two rover science teams at the same time. Team members coped as best they could but were frustrated that they were forced to "scurry around in the shadows" and break rules in order to be able to meet scientists' needs.

Scientists and the path of least resistance

One of the most important lessons learned from the IRG team's experience with the MER mission is that scientists tend to take the path of least resistance. Because they are so overloaded, mission scientists will always prefer to do whatever is the most expedient for them. They do not have the time or the energy to learn new software tools unless it is critical that they do so. Instead, they prefer to work with their own familiar tools, such as Word and Photoshop, as much as possible. This conclusion is supported by the fact that so many scientists preferred for IRG team members to use Viz for them. The mission-provided software tool that scientists used the most was SAP, which follows from the fact that using SAP was the only way for scientists to specify science targets. One IRG team member pointed out that one reason why Viz use was not more widespread was that there was no easy way to transfer a target specified in Viz to SAP. IRG team members also had a difficult time getting scientists to check the Viz browser page for updates. The team's experiences suggest that it is virtually impossible to change scientists' habits during the course of a mission and that it is also unlikely that they will readily adopt unfamiliar software. As the team prepares for future missions, team members must be wary of relying on mission scientists to use their tools independently because most likely the scientists will be too overwhelmed to acquire new habits or to learn new technology.

Final Recommendations

This analysis of the team's experiences with the MER mission suggests a number of recommendations for future missions:

- The IRG team should focus on remaining a service provider to the science team. This will allow IRG to contribute to data analysis without placing a burden on scientists.
- The IRG team will need to prepare to be flexible. Several team members have suggested that the team develop a general-purpose toolbox for the generation of 3D models. This will increase the likelihood that the IRG team will be able to respond efficiently to scientists' changing needs over the course of a mission.
- The IRG team should try to establish relationships with the mission science team and understand the science goals of the mission as soon as possible. This will help the team decide what tools may be the most useful to scientists and hopefully reduce the number of requests for types of data products that the team has never built before.
- The IRG team will need official recognition and/or support in order to best meet scientists' needs.
- IRG team members should be physically present with mission scientists.
- The IRG team should conduct rover field tests as a way to understand the types of data products that scientists will need and how best to build them.

By applying the knowledge gained from their experiences with the MER mission, the IRG team will be well prepared to contribute to the success of future Mars rover missions.

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