Multi-agent Modeling and Simulation Approach for Design and Analysis of MER Mission Operations

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Abstract

A space mission operations system is a complex network of human organizations, information systems, deep-space communication systems and spacecraft hardware. As in other organizations, one of the problems in mission operations is managing the relationship of the mission information systems to how people actually work (practices). Brahms, a multi-agent modeling and simulation tool, was used to model and simulate NASA's Mars Exploration Rover (MER) mission operations work practice. The objective was to investigate the value of work practice modeling for mission operations design.

From spring 2002 until winter 2003, the first author participated in mission operations design sessions and observed operations field tests for the MER mission held at Jet Propulsion Laboratory (JPL). We discuss mission operations designers' interaction with the Brahms tools, their reactions to the simulation output during model validation and our work on modeling computer systems and people's interaction with systems. This project spurred JPL's interest in the Brahms model, but it was never included as part of the formal mission operations design process. We discuss why this occurred. We also suggest how Brahms might have been used differently to reveal human-computer interaction problems with operations software, which emerged in training exercises and during the mission.

1. BRAHMS

Brahms was conceived as a business process modeling and simulation tool that incorporates the social systems of work, thus illuminating how formal process flow descriptions relate to people's actual located activities in the work place [1-2].

Brahms consists of an agent-based modeling language and simulation environment called the Brahms Integrated Development Environment (IDE) [3]. The

Brahms Composer (Figure 1), part of the IDE, offers various connected design views that are based on the World Modeling Framework [4], including: organization/people, artifact/system, data/information, geography/location, communications, activity/task and timing/flow. These design views hierarchically present concepts such as agent groups, objects and geography, etc. for convenient access.

The Composer's multiple views also allow a modeler to graphically create and edit concepts; these are automatically converted into the Brahms modeling language for simulation.
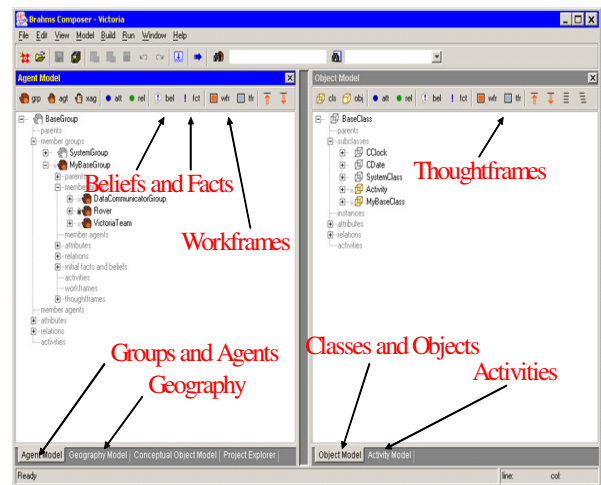

Figure 1. Brahms Composer

The Brahms Agent Viewer (Figure 2), another part of the IDE, provides the simulation visualization. The visualization shows a chronological history of what activities are performed by people or robots, usage of tools and systems and communication between people, robots and systems.
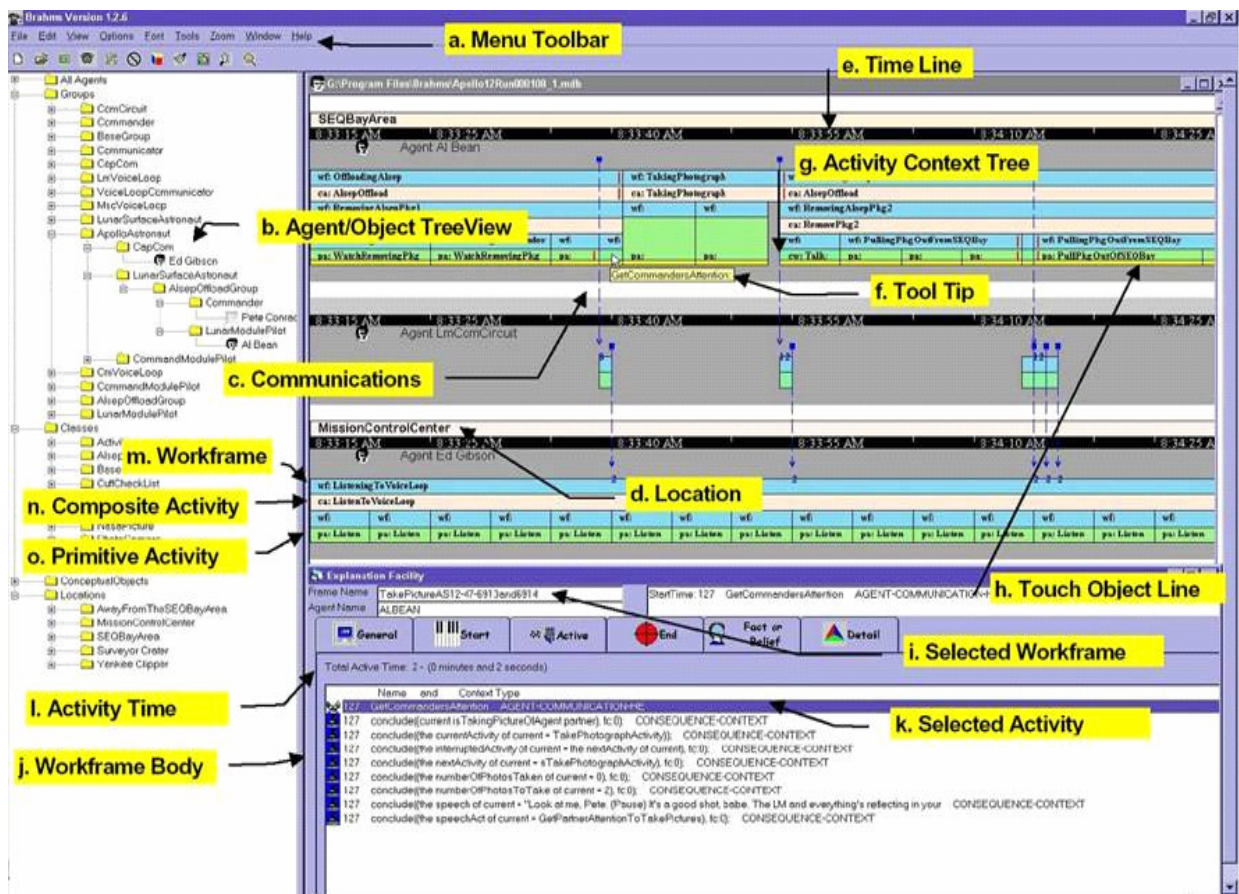
Figure 2. Brahms Agent Viewer:
Behaviors are modeled as conditional actions (Workframes) organized hierarchically into Activities. Locations, Communications, actions (Primitive Activities), and Objects touched by Agents are represented on a timeline.

2. MARS EXPLORATION ROVER (MER) MISSION

MER is a dual-robot, Mars surface mission. With a complement of remote sensing and in-situ science instruments, scientists seek to determine the history of climate and water at a site on Mars where conditions may once have been favorable to life.

Both rovers, Spirit and Opportunity, landed safely in the early part of 2004. The Jet Propulsion Laboratory (JPL) in Pasadena, CA, started twenty-four hour, round-the-clock mission operations; after the first three months, JPL scaled back operations to a roughly eight hours a day schedule.

3. BRAHMS MODEL OF MER

The task of the MER mission operations designers was to integrate legacy systems with newly developed systems plus set up work processes for scientists and engineers in three shifts during a twenty-four hour period.

In late 2002, the first author participated in JPL's mission operations design meetings and researched the mission operations design documentation. He interviewed key MER team members, asking them to describe their future MER mission operations job activities, information needs, interfaces and tools. From this data and a model previously created for a lunar mission (Victoria), we created an initial MER mission operations model and simulation in Brahms [5].

3.1 Contents of Model

We chose a scenario that covered a complete sol (Martian day) of mission operations, including activities to receive data from the rover, convert data for analysis, discussions and archival, make decisions on what the rover should do next, and then send command data to the rover. Scientists and engineers work together to create Rover Activity Plans, which contain activities the rover will perform and are the focus of their discussions everyday.

To expand our initial model beyond a bird's eye view of the mission operations work system, we chose to focus on the workflow for processing the Rover Activity plan in each sol, called the Uplink Process. Similar to order processing, the Rover Activity plan is developed by several people using several software applications (Figure 3).

First, scientists using the Science Activity Planner (SAP) [6] create separate plans after they have evaluated the scientific data returned by the rover. The Science Operations Working Group (SOWG) Chair provides guidance when scientists negotiate among themselves and ensures they produce one consolidated plan.
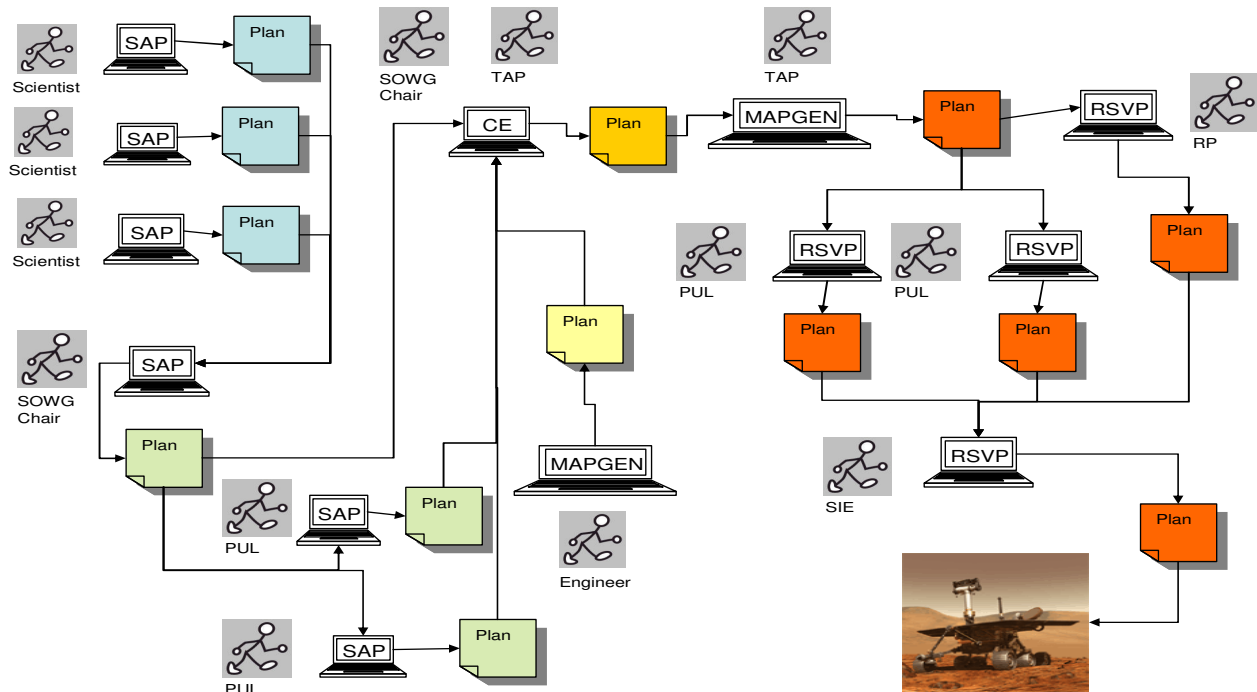
Figure 3. Uplink Tools Process Flow

Next, the Tactical Activity Planner (TAP) adds temporal constraints to each activity within the plan using the Constraint Editor (CE) [6]. The TAP also adds activities to the plan that the engineers have deemed necessary to maintaining the rover's safety.

The TAP loads the plan into the Mixed-Initiative Activity Plan Generator (MAPGEN) [7] to verify and adjust the plan so that it does not violate mission and flight rules. For example, MAPGEN makes sure that the plan stays within safe boundaries for resources like battery power.

At the same time, the Payload Uplink Leads (PUL) are inspecting the plan to ensure that proper parameter values are set for each instrument on the rover. Also, the Rover Planner (RP) uses the kinematics simulation capabilities in the Rover Sequence and Visualization Program (RSVP) to expand rover movement activities.

Finally, the Sequence Integration Engineer (SIE) translates the activities on the plan into commands that the rover understands using RSVP and these commands are sent to the rover in a process called "uplinking".

In early field tests, JPL broke up the process and exercised only one piece of software per test. Without access to software specifications, the first author observed the field tests to gain an understanding of the activities people performed in the process and functionality of the software. After each field test, more details of the user interactions and software features were modeled. Table 1 provides a measure of the complexity of modeling the functionality of each software application in Brahms.

Table 1. Brahms Model Metrics for MER Mission Software

Software Module	Number of Workframes	Number of Activities
SAP	73	88
CE	29	51
MAPGEN	62	76
RSVP	28	64

4. USER VALIDATION OF MER MODEL

We approached the mission operations designers for validation and verification of the Brahms Uplink model.

4.1 Validation Using Brahms Composer

At the time, the Brahms Composer was still being developed so we did not have design views to present the model to the designers. To show the designers what was contained in the model, we used simple class-object diagrams (Figure 4).

4.2 Validation Using Brahms Agent Viewer

We could not install the Brahms Agent Viewer on JPL's predominantly Apple computers because of operating system incompatibility. However, we collaborated with another group developing a large computer-based white board, called the MERBoard (Figure 5) [8], for the MER mission, and we were able to display the model's simulation visualization on it.
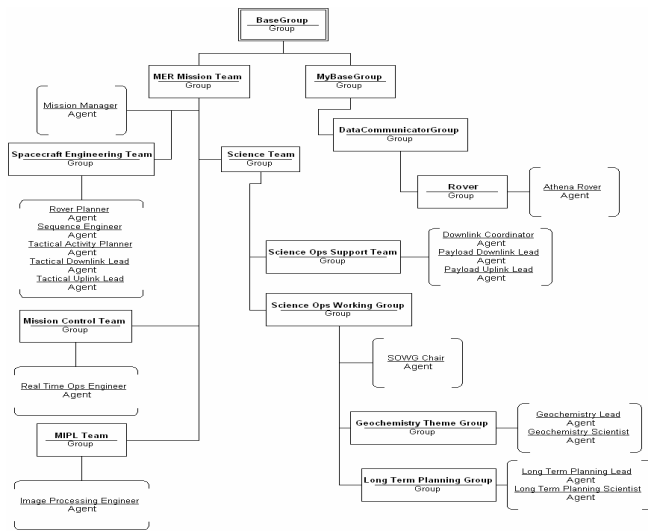
Figure 4. MER Mission Operations Agent Group Hierarchy

4.2.1 Observation of Brahms Agent Viewer Usage

Using the MERBoard as a platform, we could get the designers to interact with the model. We trained them on how to use the Brahms Agent Viewer and discovered that they had very little trouble navigating the simulation visualization. We believe that because the designer's mental model [9] of the MER mission operations timeline (Figure 6) was very close to Brahms Agent Viewer's presentation of the simulation (Figure 2). The designers were able to quickly analyze the simulation output.

We presented to the designers a problematic exchange of information between agents on the MER mission operations timeline that we had discovered in the simulation output. We listened to the designers' discussions about this issue and observed how they interacted with the Brahms Agent Viewer.

From their discussions, we understood that the designers were looking in the work system design for someone who would be available to receive the information during the problematic period on the timeline. This person would need to pass the information along at a later time to someone else who required the information but was unavailable during the earlier time period.

We observed the designers looking at multiple agents' activities on the timeline displayed by the Brahms Agent Viewer. The designers were constantly scrolling up and down within the Brahms Agent Viewer because it could only display three agents or objects on the screen (Figure 2). For the same reason, we noticed the designers were closing and opening different agent timelines for display.
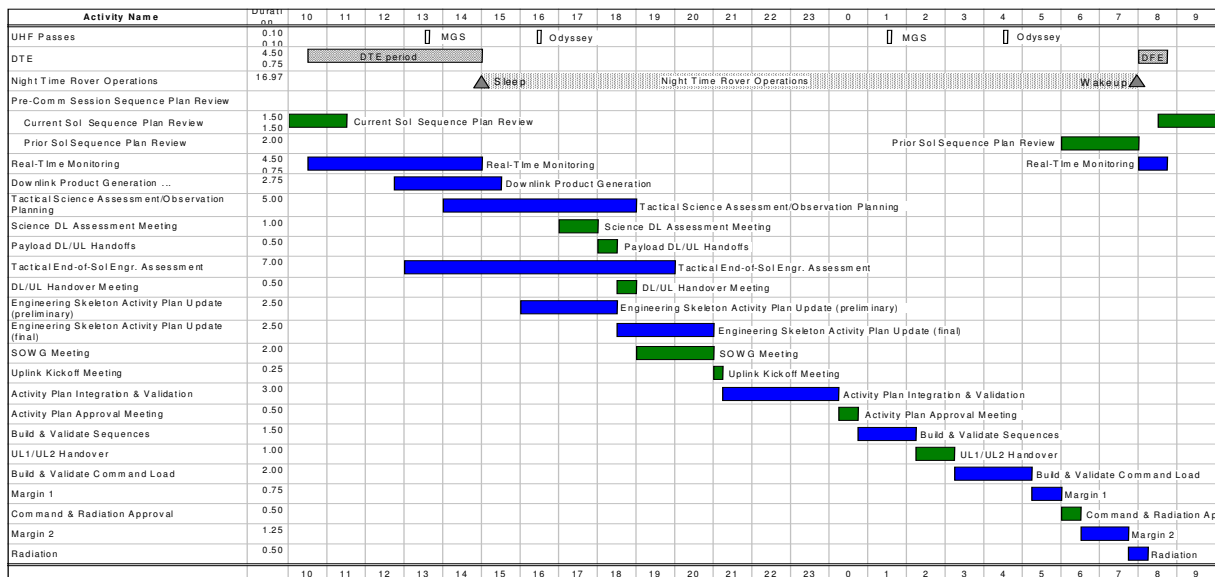

Figure 5. Brahms Agent Viewer on MERBoard

Figure 6. MER Mission Operations Timeline

4.3 Validation of Uplink Tool Process Flow Model

As mentioned, we never had access to software specifications and could not get designers or software developers to validate this process model. To validate the model, the first author conducted ethnographic observations during field tests of the work practice and compared these observations to the model and process diagrams.

Later field tests tested the entire process flow and integration of software. An integration issue between SAP and MAPGEN arose that led to the creation of CE. The issue was that SAP did not communicate temporal constraints to MAPGEN.

We examined our model to question why we did not predict this gap. We found that the model made an erroneous assumption based on how we interpreted the SAP user interface. SAP has a spreadsheet-like interface for users to input scientific observations (broad ways of using the rover) and rover activities (specific settings) within each observation (Table 2). Ordering of observations appears to be top to bottom. SAP also has a "Details" screen for each observation that allows users to input start times and end times. Based on this design, we modeled in Brahms that SAP saves temporal information about the plan when the user hits the "Save" button and this information is loaded into MAPGEN when the user "Opens" the plan. The model reflects user actions and what is on the SAP screen, but not what the SAP software actually outputs.

Table 2. Example of SAP interface

Observation 1	
	Activity 1
	Activity 2
Observation 2	
	Activity 3

5. USE OF MER MODEL FOR MISSION

We gained valuable experience by participating in a mission operations design process and understanding what designers need. However, we could not provide timely modifications and sufficient insights from the model so Brahms was never included as part of JPL's formal design tool for the MER mission.

5.1 Request for Procedures for Mission Operations Training

The designers requested that we generate a listing of the activities each agent performs within a timeline period. They wanted to use the listings to develop operational procedures for mission operations personnel. We exported this data from the simulation into a spreadsheet.

5.2 Request for Posters for Mission Operations Planning

The designers also could not install the Brahms Agent Viewer because Brahms, at the time, did not run on their Apple computers. So they asked for personal paper copies of the output and mentioned that they would annotate on paper and provide us with feedback. Instead we generated a very large paper poster by capturing screen-shots of the Brahms Agent Viewer which we posted on a large wall in their office area. We saw no annotations on the poster when we returned to inspect it when the mission started.

5.3 Request for Simulation Visualizations

The designers also wanted to be able to easily see where people were located at different times, especially during meetings.

Also, the designers asked if the simulation could provide a view of what information is put on a rover activity plan as the plan gets progressively modified during daily operations. This view would help them to analyze, design and validate the Uplink Process.

In addition, they suggested it would be helpful to show communication networks that get created and grow as information gets communicated between agents as the day progresses.

Within the time and resources available, we could not provide these simulation visualizations.

5.4 Request for Further Analysis

From the initial simulation, we gave designers insights into the work system's communication activities, handover activities and movement activities [5].

By the second month of the mission, the designers began to design an approximately eight earth-based hour mission operations timeline converted from the Mars day (sol) timeline. We were approached to model this new timeline and provide feedback within a week. However, agent and object behaviors in the original model were linked to a Mars clock, not earth hours.

In addition, the designers needed to consider how satellite communications schedules, which change daily, would affect the time available between analyzing data returned from the rover and creating new activities for the rover to execute. We had a simple model of satellite communications, which did not include a varying schedule for space communications. Again, with resources available, we were unable to revise the model to provide feedback to the designers within one week.

6. NEW USE OF MER MODEL

In summer 2004, a group at NASA Ames Research Center was formed to collaborate with JPL to research and develop new architectures and technologies for operating future autonomous robots on planetary missions. Most of the people in the group had been involved with the MER mission as developers of applications used by the mission operations team. We were asked to participate in the group to share the broader workflow and mission operations knowledge we had gained from the MER mission.

6.1 MER Model in UML

We were told by the group that they preferred to use a modeling technique with which they were all familiar, the Unified Modeling Language (UML) [10]. They wanted a

modeling tool that used UML, could produce printouts and be exportable into other graphical modeling or ontology tools.

We learned about a standard, called XML Metadata Interface (XMI) [11], currently being used by several UML tool vendors for importing and exporting models created by UML tools or non-UML tools. We were able to export the model to XMI format and then import into a UML tool. As a benefit of importing to a UML tool, we could now print out our models instead of manually drawing diagrams or capturing screen-shots.

Currently, the group is extracting information from the UML models that we generated from the MER model to prepare for a pilot demonstration of their technology architecture at the end of 2005.

7. CONCLUSION

With the original goal of investigating the value of work practice modeling for mission operations design, we gained valuable experience by observing and participating in the MER mission. We had an initial broad model without much detail so we chose to focus on modeling the Uplink Process. But the appearance of the SAP software interface led to erroneous model assumptions, and hence we did not uncover integration issues prior to mission tests.

To detect integration issues, we would have had to focus the model even more. MAPGEN was in fact a likely choice because it was developed by our Ames colleagues. Thus, we might have pursued more details and validated the model of software I/O more rigorously. On the other hand, in focusing on the Uplink Process, we turned away from a holistic simulation of human and rover operations. Here we missed the chance to include in the simulation space communication schedules and their relationship to operations turnaround time.

In this effort, we have learned ways to make the Brahms tool more useful during mission operations design. For example, having experienced difficulty with not being able to get users to interact with and validate the model because of operating systems incompatibility, we have now ported the Brahms environment to different operating systems. We also continue to make our Brahms environment compatible with other existing modeling tools so that users will have access to the models we create. Lastly, we continue to conduct research on visualizations necessary for people to understand information within the model and simulation.

But user-friendliness and accessibility are not important if the simulation doesn't produce insights worth knowing. Now that we know more about the kinds of breakdowns that can occur in mission operations, we may be better able to scope our efforts in future Brahms simulations of human-computer interaction.

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