Multiagent Modeling and Simulation in Human-Robot Mission Operations Work System Design

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Abstract

This paper describes a collaborative multiagent modeling and simulation approach for designing work systems. The Brahms environment is used to model mission operations for a semi-autonomous robot mission to the Moon at the work practice level. It shows the impact of human-decision making on the activities and energy consumption of a robot.

A collaborative work systems design methodology is described that allows informal models, created with users and stakeholders, to be used as input to the development of formal computational models.

1. Introduction

Work systems involve people, machines, tools, documents, and facilities interacting in activities over time. These activities produce goods, services or—as is the case in the work system described in this paper—scientific data. Many work systems we encounter everyday have existed over a long period of time. Improvement of such work systems is often done through business process analysis and reengineering [1]. But managers must also design work systems de novo.

One of the challenges of work system design is that work systems are often large and complex and persist over a long period of time. This makes the design process complex and non-deterministic. In this paper we describe Brahms, a multiagent modeling and simulation (M&S) environment for designing complex interactions in human-machine systems.

In Brahms, we model work processes at the work practice level. We describe a case study in which we used Brahms to design mission operations for a proposed discovery mission to the Moon—the Victoria Mission. We begin by describing our view of work practice and how it is modeled in Brahms. We then describe Victoria, the model, and simulation results.

2. Work Practice

The concept of work practice originates in the research disciplines of socio-technical systems, business anthropology, and management science. Work systems design, as presented here, has its roots in the design of socio-technical systems. This method was developed in the 1950s by Eric Trist and Fred Emery [2], to understand and leverage the advantages of the social and technical aspects of work. Work systems design extends this tradition by focusing on both the informal and formal features of work by applying ethnographic participant observation [3].

A work practice is defined as the collective activities of a group of people who collaborate and communicate, while performing these activities synchronously or asynchronously. In contrast, a Tayloristic view of work abstracts circumstances, tools, and behaviors into an idealized transformation of work products by job functions.

To describe how work actually gets done, we need to include those aspects of the situation that influence individual activity (not only the procedures and problem-solving behavior), such as collaboration, conversations, "off-task" activities, multi-tasking, interruption and resumption of work (and how this is managed), informal interaction such as assistance outside of job function, use of tools, and facilities [4].

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Brahms is a M&S environment for representing work practice using a multiagent rule-based activity language, that can be simulated using the Brahms simulation engine [5].

This paper discusses how we have used Brahms to design the work system for the proposed Victoria mission. The attentive reader might question how we can *design* a work practice? Indeed, a work practice is not designed, but emerges over time. However, our interest is to determine whether a model at the work practice level can be used in the design of a mission. We believe that a work practice model is useful, because it provides a more detailed and holistic representation of work [6] [7].

3. Components of a Brahms Simulation

Brahms has a multiagent language for describing agent and object activities. For a more detailed description of the language see [8] [4]. A Brahms simulation of work practice has seven integrated components:

Agent Model: The group-agent membership hierarchy of the people in the work system. Groups may be formal roles and functions or based on location, interpersonal relations, interests, etc.

Object Model: The class-hierarchy of all the domain objects and artifacts, e.g., tools, desks, documents, vehicles.

Geography Model: The geographical areas in which agents and objects are located, consisting of area-definitions (user-defined types of areas, such as buildings, rooms, and habitats) and areas (instances of area-definitions).

Activity Model: The behavior of agents and objects in terms of the activities they perform over time [9]. Agent or object activities are mostly represented at the group-level or class-level respectively, but are also often specific to agents and objects. Activities are inherited and blended through a priority scheme.

Timing Model: Constraints on when the activities in the activity model can be performed, represented as preconditions of situation-action rules (called *workframes*). Activities take time, as determined by the predefined duration of primitive actions. Workframes can be interrupted and resumed, making the actual length of an activity situation dependent.

Knowledge Model: An agent's reasoning, represented as forward-chaining production rules (called *thoughtframes*). Thoughtframes can be represented at group/class levels and inherited. Thoughtframes take no time. Inquiry is modeled as a combination of activities (e.g., detecting information, communicating, and reading/writing documents) and thoughtframes. Perception is modeled as conditions attached to

workframes (called *detectables*); thus observation is dependent on what the agent is doing.

Communication Model: Actions by which agents and objects exchange beliefs, including telling someone something or asking a question. A conversation is modeled as an activity with communication actions, either face-to-face or through some device, such as a telephone or email. The choice of device and how it is used are part of the work practice.

Typically a Brahms model is sketched by specifying the geography and groups first. The grain size of the simulation clock (time per tick) may vary from 5 seconds or less to 5 minutes or more, depending on the information available and modeling purposes. A model might represent a group of people as a single agent, a useful heuristic in redesigning a work system. Common objects and activities such as telephones and "phone conversation" may be easily reused and adapted from other Brahms models. In general, Brahms models represent work with much more detail than business process models, but somewhat less detail (and far more broadly) than cognitive models (Figure 1).
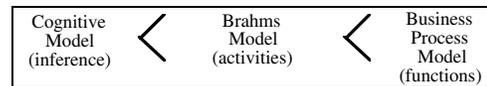

Figure 1. Relation of Brahms models to other models

Considerable effort is devoted to modeling objects (e.g., fax machines) and computer systems, with which people interact to accomplish their work.

4. The Victoria Lunar Mission

Victoria is the name of a proposed long-term semi-autonomous robotic mission to the South Pole region of the Moon. The primary mission objective of Victoria is to verify the presence of water ice and other volatiles within permanently shadowed regions on the Moon. This will be accomplished by gathering the necessary lunar data for analyzing the history of water and other volatiles on the Moon, and by implication in the inner solar system. The Victoria team has decided to use a high-speed semi-autonomous rover.

One of the biggest constraints in any robotic mission is power consumption of the robot. In every activity the rover uses energy, therefore the sequence of activities for the rover is constrained by the amount of power available to complete the sequence. When the robot's batteries are low, it needs to return to a sun-exposed spot to recharge its batteries. During the Victoria mission the rover will traverse into permanently dark regions on the Moon. During these traverses the rover will use its neutron detector instrument to detect hydrogen and the Sample Acquisition and Transfer Mechanism (SATM)

used in   informal static models   used in

Human Activity System   **M1**   Soft Systems Modelers   **M4**   **Work Practice Simulation**

observing work practice   observing simulated work practice

yields   yields

M2 formal modeling of the WP   **M3** simulation

yields   used in   yields

formal static models   used in
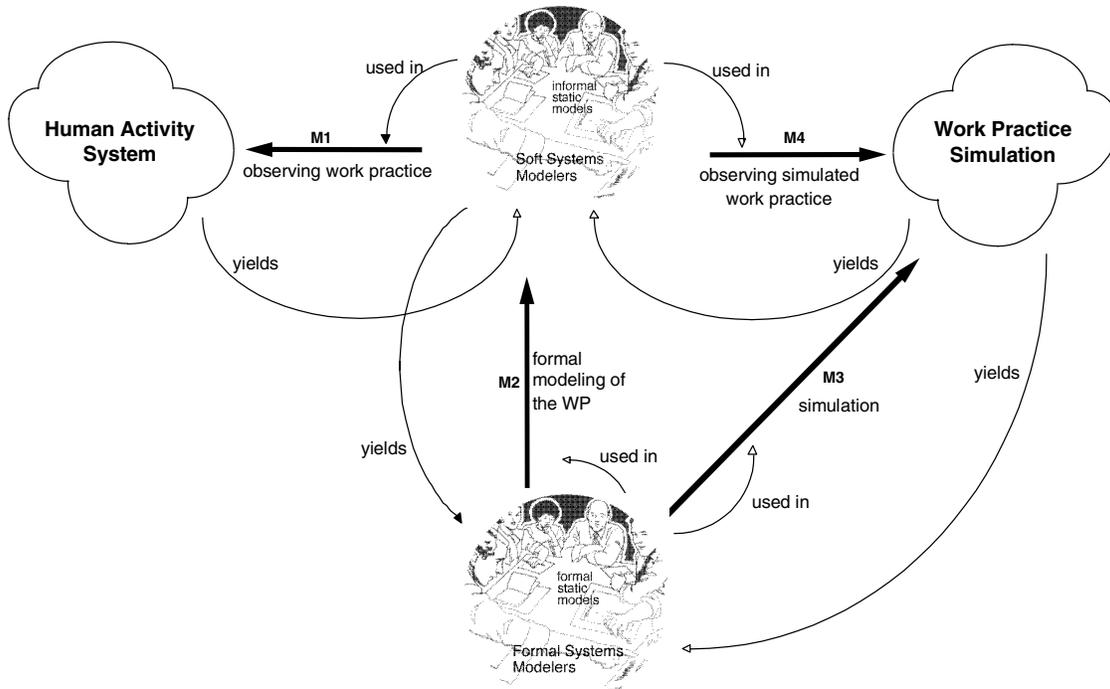
Formal Systems Modelers

Figure 2. Collaborative Modeling Process

to drill into the lunar surface and take surface samples to be investigated using an array of science instruments.

The work system design problem is to configure the mission operations so the robot's activities inside the permanent dark region are most efficient (i.e. consume the least amount of energy).

5. Collaborative Modeling

To develop a simulation of the Victoria work system, we used a collaborative modeling approach with the Victoria mission designers. First, we created *informal static* models of the activities of the people, robot, and artifacts, the communication and geography, in informal design meetings and modeling sessions. Next, we translated these descriptions into formal Brahms models, producing simulation results (including energy measurements described below). The Brahms modeler went back to the mission design team and presented the result of the simulation. Together they discussed and represented more details of the work practice. The Brahms modeler implemented the new details into the simulation. This Brahms modeling-debug-simulate cycle continued until a sufficiently robust and interesting design resulted.

Figure 2 describes our collaborative methodology for developing first an informal model and then a formal simulation model of the Victoria work practice.

Method M1 – analyzing work practice: The purpose of method M1 is to create an informal static description (i.e. a conceptual model) of the work practice of a human activity system. For M1 we use the Compendium modeling method [10].

Method M2 – formal model of the work practice: The purpose of method M2 is to translate the conceptual models from M1 into a Brahms model. The Brahms modelers and the conceptual modelers do not necessarily have to be the same, and in fact, the skill sets for these two types of modelers are very different.

Method M3 – simulation: Using method M3 a Brahms simulation of the formal model is developed, by running the simulator with the formal model as input. M3 is the Brahms compile-simulate-debug method.

Method M4 – observing the simulation: The purpose of method M4 is to observe and investigate the work practice simulation output, and compare it with the actual human activity system. During this cycle the actual objective of the work practice simulation project is accomplished. Frequently, one modifies the model or factual scenarios (e.g., for Victoria, the location of ice in the modeled geography) to perform a what-if analysis.

Thus, there is a modeling and simulation cycle between M1, M2, M3 and M4. The methods have to be closely integrated for the cycle to be efficient. For example, to a certain extent we can automatically produce Brahms model components (M2) from informal Compendium descriptions (M1).
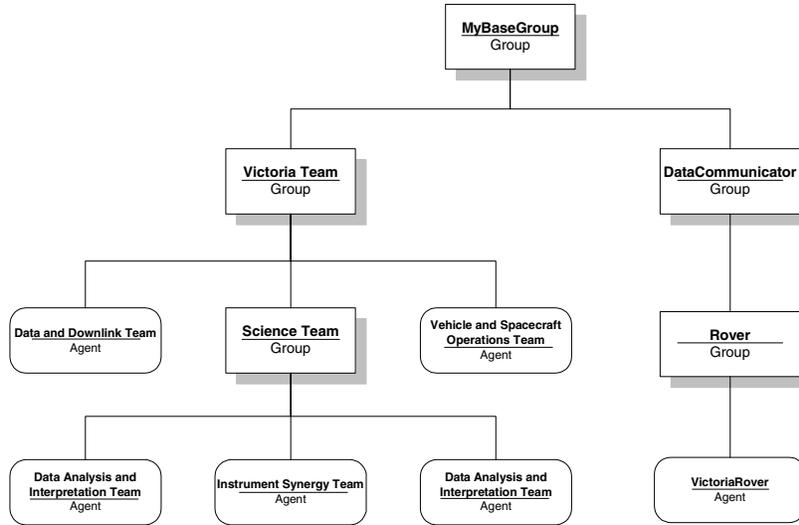
Figure 3. Victoria work system

6. Mission Operations System Design

The work during in the Victoria mission will be distributed over a number of human teams and the Victoria rover. By virtue of being people's arms and eyes on the Moon, the teleoperated rover is more of an *assistant* than a simple tool.

Figure 3 represents the work system elements and their relative location during the Victoria mission. The Science Team consists of co-located sub-teams: the Science Operations Team (SOT), the Instrument Synergy Team (IST), and the Data Analysis and Interpretation Team (DAIT). There are two other supporting teams: The Data and Downlink Team (DDT) and the Vehicle and Spacecraft Operations Team (VSOT). The teams communicate with the Victoria rover on the lunar surface using the Universal Space Network (USN), directly and via a lunar orbiter. The flow of data from the rover will be dominated by contextual data and science data. This data will come to NASA/Ames via the Universal Space Network (USN) data connection and will be automatically converted in near real-time to accessible data formats that can be made available to the teams via data access and visualization applications.

Based on previous experience, the mission designers hypothesized that many issues will affect the decision cycle of the science team, one of which is data overload

[11]. They therefore specifically addressed the following questions in the work system design for Victoria:
1. How will science data be gathered collaboratively with the Earth-based science team, rover teleoperator, and the rover on the lunar surface?
2. How will science data be made available to the science team?
3. What is the affect of a particular work system design on the power consumption of the rover during a science traverse into a permanent dark crater?

To answer these questions we developed a model of the activities of the teams, based on the description of a planned mission traverse. In the next sections we describe the design of this work system through the design of the agent model, the object model, their activity models, and the geographical model.

6.1. Agent Model Design

Figure 4 shows the group membership hierarchy on which the design of the work system is based. The agents in the model are the Earth-based human teams and the Victoria rover, as shown in Figure 3. The teams are represented as single agents, because at this moment it is not possible to prescribe the composition and practices of each team in more detail. For example, the "plan a command sequence" activity of the SOT represents the work of the whole team, while the

Figure 4. Victoria Agent Model

Table 1. Functional activity distribution over Victoria teams

	Science Operations Team	Instrument Synergy Team	Data Analysis and Interpretation Team	Data and Downlink Team	Vehicle and Spacecraft Operations Team	Rover
Uplink process	1. Maneuver commands 2. Command sequences for experiment operation	1. Commands for engineering operation of robot/spacecraft 2. Emergency or anomaly resolution commands	1. Long-term planning for science opportunities	1. Tele-communications commands	1. Maneuver commands 2. Command sequences for experiment operation	1. Command execution
Downlink process		1. Monitoring of health and status telemetry from robot subsystems	1. Data quality assessment 2. Experiment data collection	1. Experiment data collection 2. Data processing and enhancement		1. Experiment data collection

individual activities of each team member remain unspecified. The Victoria rover is modeled as an agent because it has activities, including primitive actions that change the world, movements, and communications.

Table 1 shows a possible distribution of the functions over the Victoria teams [12]. Details of how different teams collaborate to perform these functions constitute the work practice, as specified in the situation-action rules (Brahms *workframes*) of the different agents.

An example workframe for the SOT team for creating a command sequence for finding water ice is (paraphrased): *When I believe that there is a possibility we can find water ice at the current location of the rover, then start the activity of finding water ice.* Generically, a workframe is of the form: When (I believe {X}*) Do {activity A, conclude a new belief and/or fact}*

6.2. Object Model Design

The object model consists of the classes and instances of physical artifacts, as well the statically and dynamically created data objects during the simulation. The Victoria object model (Figure 5) includes classes for the science instruments on the rover and other objects contained in the rover, such as the carousel and the battery. Furthermore, the model includes the data communicator class, which includes the objects for S-band and UHF communication. The model also includes the software systems that receive and convert the mission data. A Brahms object represents the data visualization systems that present data to the Victoria team. The Data and CoreSample classes allow dynamically creating objects representing specific data and lunar core samples during the simulation.

6.3. Geography Model Design

The geography model represents locations on Earth and the Moon (Figure 6). The areas of interest on Earth are Building244, where the Victoria teams and systems are located, and UsnSatelliteLocation, where the
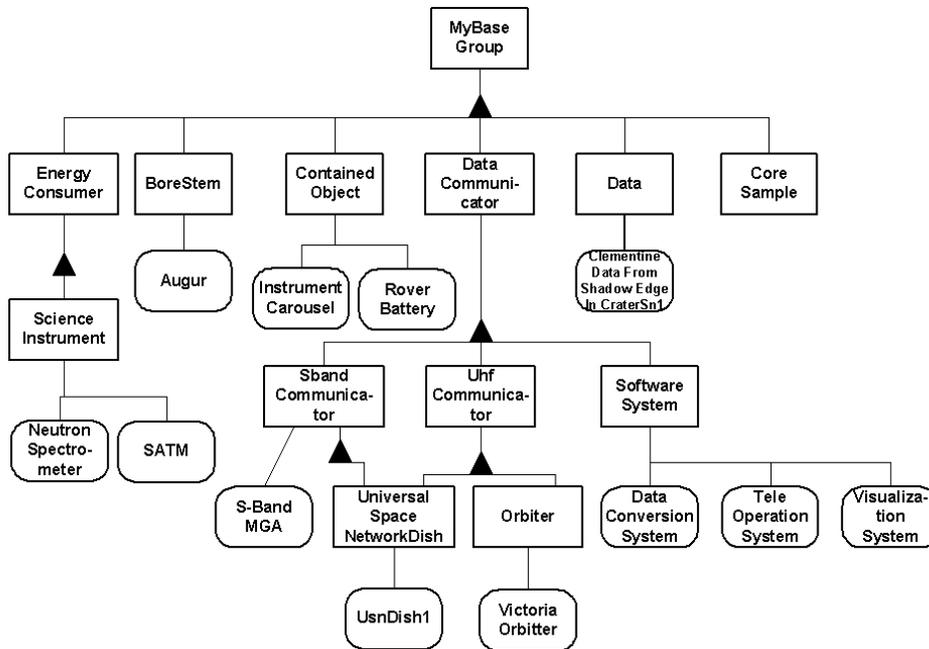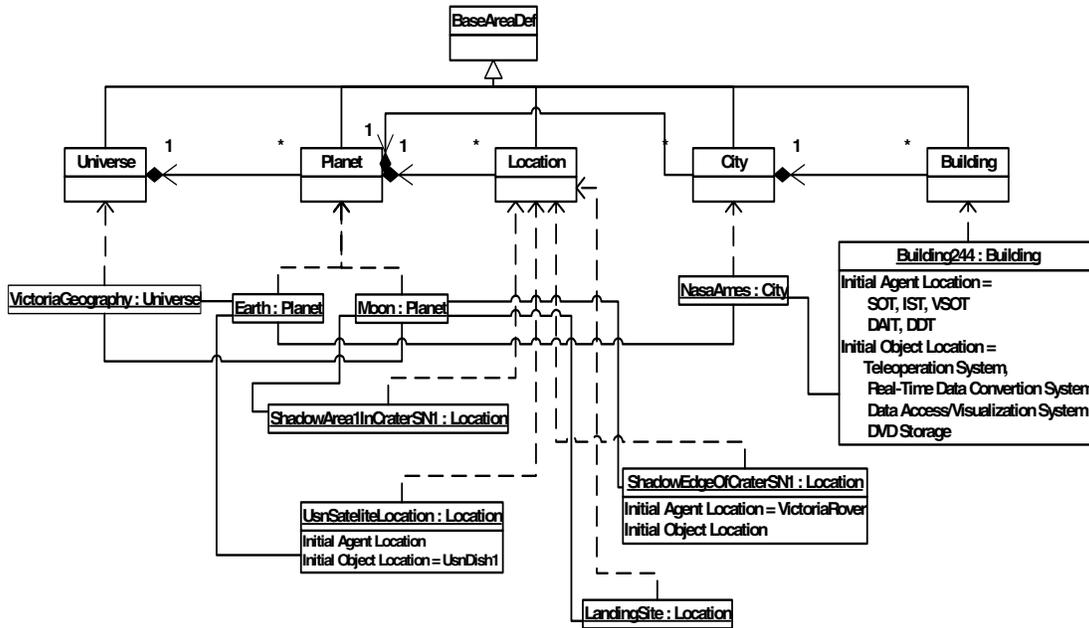
Figure 5. Victoria Object Model

Figure 6. Victoria Geography Model

UsnDish1 satellite dish is located. Locations for the simulated scenario are represented on the Moon

ShadowEdgeOfCraterSN1 represents the location the rover at the start of the simulation (the shadow edge in crater SN1). ShadowArea1InCraterSN1 represents the area in the permanent shadowed SN1 crater where the rover will perform a drilling activity. The LandingSite area is represented only for completeness.

7. Victoria Simulation Scenario

The case study selects one of the key surface activities, searching for water in permanently shadowed craters:

The rover has arrived at the shadow edge of crater site number 1. The battery has been fully charged. Based on the data analysis by the Earth-based teams, of

Figure 7. Victoria Rover scenario activities

the Clementine data available for the shadow edge area of crater site number 1, the science team now decides where to go into this crater and search for water ice. While the rover is traversing into the crater, it is taking hydrogen measurements with the Neutron Spectrometer. When the rover arrives at the assigned location within this crater and it finds hydrogen there, the science team decides it should start drilling 10cm into the surface using the SATM, and collect a 1.0cc lunar sample. When the rover receives this command, it starts the drilling activity and finally deposits the sample into the instrument carousel.

The rover uses two instruments in this scenario: the Neutron Spectrometer (to detect hydrogen—most likely caused by water ice—within the first half meter of the lunar surface below the rover) and the lunar surface drill (Sample Acquisition and Transfer Mechanism — SATM).

The backbone of the simulation model consists of three primary activities: Data uplink, Rover operations, and Uplink. These are described in the next section.

8. Simulation Results

The simulation provides visibility into the behavior of the work system over time, that is, activities, communication, and movement of each agent and object. After the model is developed and compiled, the Brahms simulation engine executes the model. A relational database is created, including every simulation event. An end-user display tool called the *AgentViewer* uses this database to display all groups, classes, agents, objects, and areas in a selectable tree view. The end-user can select the agents and objects he/she wants to investigate. The AgentViewer displays an activity time line of the agents and objects selected, optionally showing agent and object communications. Using this view the end-user can investigate what happened during the simulation. In the next three sections we explain the key behaviors during the simulation.

8.1. Data Uplink Activities

The scenario starts with the Data Analysis and Interpretation Team (DAIT) retrieving the Clementine data image of the shadow edge area, where the rover is located at the start of the scenario. They review this image using their visualization system, represented in the Brahms model as a VisualizationSystem object. According to the work practice, they do this without anyone requesting that they look at the data.
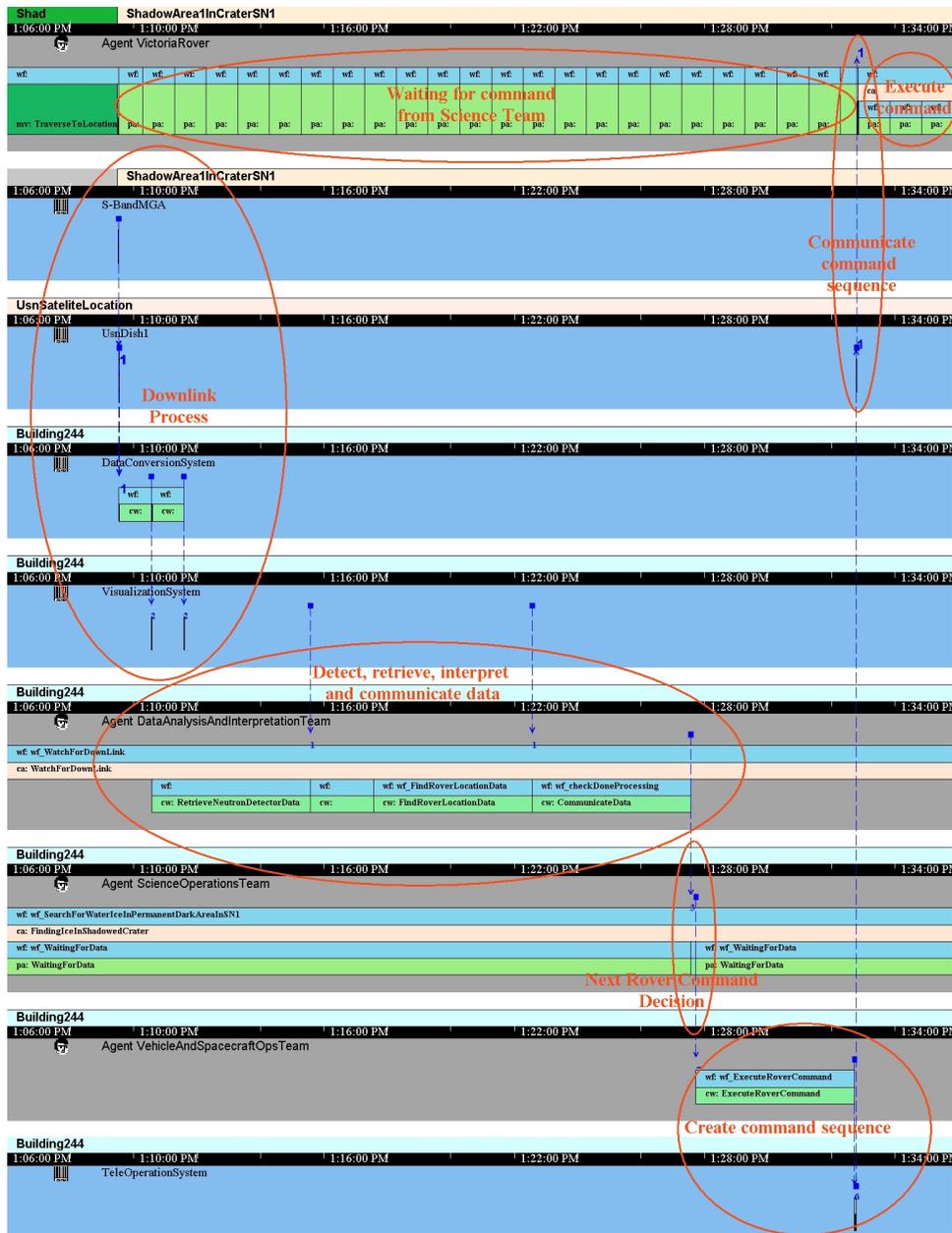
Figure 8. Simulation of downlink and second
uplink command activities

This means that the DAIT needs to be know: 1) the location and situation of the rover at all times, 2) whether data is available and needs to be retrieved, and 3) where and how they can retrieve data.

Once the DAIT has retrieved the images, it communicates this to the Science Operations Team (SOT), and they collaboratively analyze these images (the AnalyzeRoverImages activity). When done, the SOT plans the first rover command sequence. According to the scenario being simulated, the SOT decides that the rover needs to drive for a specified amount of time (15 min) into the crater to a specific location (ShadowArea1InCraterSN1), and while driving it should be using its neutron detector instrument to detect hydrogen in the lunar surface. This decision is communicated to the Vehicle and Spacecraft Operations Team (VSOT), as well as to the DAIT. After this communication, the SOT waits for the rover's downlink data.

8.2. Rover Activity

The Victoria rover is modeled as an agent, whereas

the neutron spectrometer and SATM instruments are modeled as separate science instrument objects contained in the rover agent. In the scenario model, the Neutron Spectrometer object is active and creates a HydrogenData_1 object containing the hydrogen data that is sent to Earth while the VictoriaRover is traversing to a permanently shadowed area within the crater SN1. The rover then waits for the next command sequence from Earth. During this time the teams on Earth are analyzing the hydrogen data and deciding what to do next. In the Uplink activity, the rover is given the command to search for water ice in the permanent dark area. This triggers a traverse, during which the SATM instrument will start the drilling activity.

To collect a sample the SATM has to 1) lower its augur to the surface, 2) drill to the depth given as part of the command by the SOT (in this scenario the command says to take a 1.0cc sample at 10cm depth), 3) open the sample cavity door, 4) continue to drill to collect the sample, 5) close the sample door when done, 6) retract the drill from the surface, and 7) deposit the collected sample on the instrument carousel. (see "Drill 10cm into surface and take 1cc sample" in Figure 7).

In the Brahms model, the Augur object creates the LunarSample_1 object as part of its activity to capture the lunar sample, after opening the sample door and continuing the drilling to collect the 1.0cc sample. The activity times for drilling into the surface are dynamically derived during the simulation.

8.3. Downlink Activity

When the rover detects hydrogen in ShadowArea1InCraterSN1 the downlink process starts (represented by the Brahms AgentViewer in Figure 8). The VictoriaRover agent contains the S-BandMGA object, which represents the S-Band transmitter on the rover. The VictoriaRover creates a data object with a) the current rover location information and b) the hydrogen data. This data object is then communicated to Earth, via the UsnDish1 object. The UsnDish1 object communicates this data to the DataConversionSystem, located at NASA Ames.

As can be seen in Figure 8 (see "Downlink process"), the DataConversionSystem performs two conversion activities, one for the hydrogen data and one for the location data from the rover. The work system design requires that the data conversion system interact with the visualization system without human intervention.

When the VisualizationSystem receives the newly converted data, the system alerts the DAIT. A member of the DAIT monitors the VisualizationSystem while in the activity WatchForDownlink (see "Detect, retrieve, interpret and communicate data" in Figure 8). When the DAIT agent detects that there is newly available neutron

detector and location data, it retrieves the data from the VisualizationSystem object (the activities RetrieveNeutronData, InterpretNeutronData, and FindRoverLocationData).

Next, the DAIT communicates their findings to the SOT. In the example scenario, the data suggest that the rover has found hydrogen in ShadowArea1InCraterSn1. Given this finding, the SOT quickly determines the next command sequence for the rover and communicates this decision to the VSOT (see "Next Rover Command Decision" in Figure 8).

The communication informs the VSOT to transmit the command sequence to the VictoriaRover (see "Create command sequence" in Figure 8). The command sequence tells the VictoriaRover to start the SearchForWaterIceInPermanentDarkArea activity. It also tells the VictoriaRover that its sub-activity is to perform the DrillingActivity. Parameters indicate how deep to drill and how big a sample to collect at that depth. Figure 8 shows part of this second uplink process.

The duration of the downlink and second uplink processes determine the duration of the second DoNothing activity of the VictoriaRover, simulating the time the rover is waiting for the Victoria science team to decide the next command sequence (see "Waiting for Command from Science Team" in Figure 8).

8.4. Modeling Energy Consumption of Rover

To calculate the total energy used by the rover, we need to represent in the model the energy needed for each subsystem during a rover activity (see equation (1)). The total power consumption of the rover during the scenario can then be calculated (equation (2)).

$$\text{Total Power Consumption} = \sum_{i=0}^{n} E_{act_i} \quad \textbf{(1)}$$

$$E_{act_i} = \int_{\text{start of } act_i}^{\text{end of } act_i} \text{Prover}(t)\, dt \quad \textbf{(2)}$$

The energy consumption for every rover activity during the simulation of the scenario is shown in Figure 9. In particular, the energy the rover uses during the *Waiting* activity (see "waiting for command from science team" in Figure 8) is defined by the energy needed for *Thermal Protection during driving + Command and Data Handling during driving*. While the rover is standing still and "doing nothing," it consumes power for its thermal protection and its commanding and data handling for its subsystems, such as its processor board.

Besides the power left to use after the scenario, another interesting variable is the energy usage rate by the rover (equation (3)).

$$\boxed{EnergyRate = Total\ Power\ /\ Pbattery(start\ of\ traverse)}\quad \textbf{(3)}$$

This equation shows that given the energy used in the scenario—drive 900m into the crater, and take one 1.0cc sample at 10cm depth—with the current work system design, the robot has used almost a third of its power:
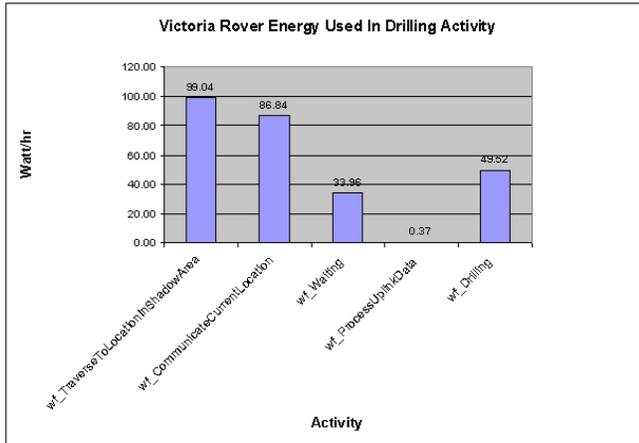
EnergyRate(drilling in permanent dark crater) ≈ 0.30

Figure 9. Rover energy used in high-level activities from simulation history database

This variable represents the rover power consumption, a measure of the effectiveness of the work system design, which can be used to compare different work configurations for the modeled scenario.

9. Conclusions

In this paper we described how Brahms was used to design the mission operations work system for the Victoria mission.

The Brahms simulation showed the impact of the work practice of Earth-based teams on activities and energy consumption of the rover. The simulation allows mission designers to compare different work system designs before critical mission decisions have been implemented.

We have shown an instance of a collaborative work system design methodology incorporating simulation. The Brahms simulation framework provided guidance to mission and robot designers, replacing a spreadsheet approach by a more transparent and flexible multiagent representation.

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