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Agent-based Mission Modeling and Simulation

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Abstract

A simulation environment for agents is presented, enabling agent-based modeling and simulation of people, systems and robots in space exploration missions. The environment allows the analysis and design of mission operation work procedures, communications and interactions between people and systems, co-located or distributed on Earth and in space. The MODAT (Mission Operations Design and Analysis Toolkit) is the integration of NASA Ames' Brahms multiagent modeling and simulation environment, the Mission Simulation Toolkit (MST), a 3-D Visualization and Surface Reconstruction (Viz), plus JPL's Virtual Mission Operations Framework (VMOF) into an agent-based end-to-end mission modeling and simulation environment. This paper describes a work in progress.

Introduction

Simulation-based design tools enabling mission designers to simulate and analyze systems-of-systems impact are critical to the success of Exploration Missions. Innovations affecting human-robot work processes must be evaluated before designs are implemented. In our End-to-end Mission Modeling and Simulation (EMMSE) project, funded by NASA's Exploration Systems Mission Directorate, the objective is to develop an agent-based mixed fidelity end-to-end mission simulation capability to baseline, verify and validate human and robot mission operations. An end-to-end mission modeling and simulation environment provides a holistic approach to mission design and analysis of human-robot teams that was heretofore not possible. Multiple "what if" scenarios can be tested and the impact of ground/crew and human/robot interactions analyzed at a systems level. Mission operations designers can simulate the least costly and most efficient mission operations. In this paper we discuss the integration of NASA Ames' Brahms multiagent M&S environment [Clancey, et al. 1998, Sierhuis 2001], the Mission Simulation Toolkit (MST) [Pisanich, et al. 2004], a 3-D Visualization and Surface Reconstruction (Viz) [Nguyen, et al. 2001], plus JPL's Virtual Mission Operations Framework (VMOF) [Lee & Weidner 2004], into an end-to-end mission modeling and simulation environment called MODAT (Mission Operations Design and Analysis Toolkit).

The Brahms multiagent environment enables modeling of people, systems and robots, work procedures, communications, and interactions with systems in different locations. Subsystems can be simulated in more detail in the other environments: MST simulates vehicle or robot kinematics and dynamics under Brahms' control. Viz enables 3D reconstruction of planetary surface landscapes; the VMOF simulates the spacecraft and telemetry systems, uplink and downlink and command sequences. We will develop an agent for mission planning and scheduling (in the simulation environment) that interfaces with an adaptation of MAPGEN [Ai-Chang, et al. 2004]. This provides mission designers with the ability to simulate mixed-initiative planning operations with humans in the loop. By integrating these simulation environments, behavioral agents and objects will be able to communicate with components in MST, Viz and VMOF, and vice versa, creating a mixed-level end-to-end mission simulation environment.

MODAT has at least four important long-term uses. First, it can be used to design any mission. Second, mission concepts can be modeled at different levels of abstraction, so the models can be used at different design stages. As the actual mission systems are being developed, simulated components can be replaced with actual systems, enabling verification based testing. Third, the agent models can be embedded in actual runtime systems as intelligent workflow agents, enabling a "simulation to implementation" engineering approach. Finally, the system can be used as a training and requirements discovery environment (e.g., like operation readiness tests) prior to completion of all the subsystems.

End-To-End Mission Operation Modeling and Simulation

End-to-end mission operations is: *"The control of one or more information gathering devices on board in space [and of people and vehicles on the surface or in space] and the associated operation of the [vehicle] systems in order to support information gathering [command and control]."*

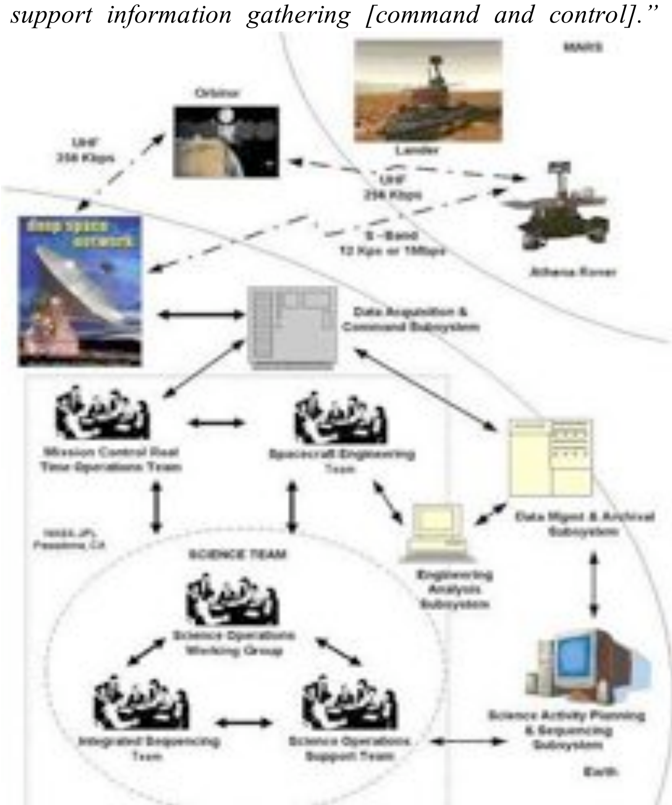


Figure 1. MER End-to-End Mission Operations

[Wall & Ledbetter 1991]

MODAT supports a modeling and simulation approach for the design of an end-to-end mission operations work system process, including the ground engineering operations, uplink, spacecraft command execution, downlink, and mission science planning processes. Figure 1 illustrates essential components of the MER mission operations work system, from the groups and roles of people in the process, to the mission systems, communication infrastructure from Earth to Mars and back and the robots with their science instruments on the surface of Mars. The different components can be simulated at different levels of fidelity in different simulation environments, depending on the objective and need for the simulation. Simulation-based design tools enabling mission designers to simulate and analyze systems-of-systems impact are critical to the success of the exploration mission. However, today's mission operations are designed without the ability to computationally model and simulate the work processes to examine the integration of people, robots, systems and dataflow.

For example, in the design of the recent Mars Exploration Rover (MER) mission operations, the team decided to plan only one Sol—a Mars day—at a time. Consequently, with the focus on a linear single-Sol process—science intent, rover plan, sequence program, uplink, downlink—the feedback cycle, which came to be known as "round-trip data tracking", became an issue during the mission itself. With a simulation model, scientists, engineers and managers could have worked out a variety of planning scenarios, both single and multi-sol, and made choices on a cost benefit basis and then modified tools or processes as appropriate.

MODAT Architecture Development

In this section we describe the MODAT architecture and the components that it is based on. Figure 2 shows that MODAT consists of a number of component simulations and planning environments. These environments are integrated together using the High-Level Architecture (HLA) based MST transport layer shown in Figure 2. Instead of building a big monolithic simulation system from scratch, MST allows us to combine existing simulation systems with new ones.

The central simulation component is a multi-agent model of people, robots, systems and information flow in the Brahms environment (the darker box in Figure 2). Brahms is the system's controller. MODAT will support two modes of operation: *low-fidelity* and *high-fidelity*. In the low-fidelity mode, all components of the system will be emulated as agents within the Brahms multi-agent simulator. In the high-

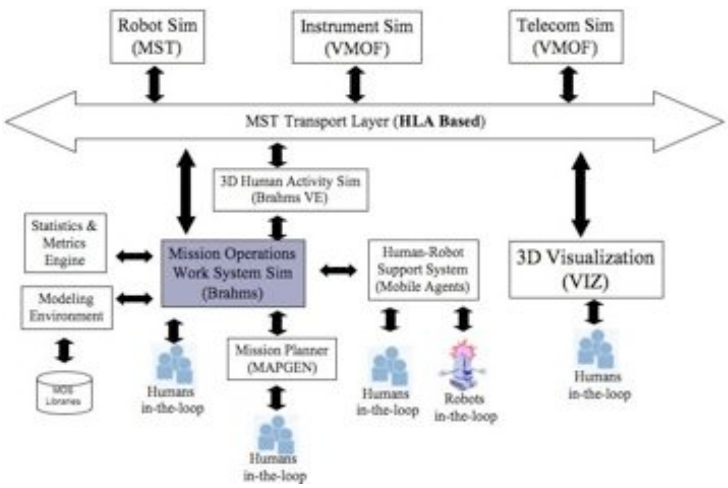


Figure 2. MODAT Architecture

fidelity mode, MODAT is composed of several independent subsystems that provide accurate higher-fidelity simulations of the various system components (see Figures 2 & 3). Brahms simulates ground and surface operations (work processes and procedures). It is also the module that drives the overall simulation. It generates commands for the simulation's robots and sends those commands to the Brahms Telecom module to be forwarded to those robots. The Telecom module simulates the uplink command operations. In low-fidelity mode, the Telecom low-fidelity module simply makes the appropriate updates to the Brahms database (shown in Figure 3). In high-fidelity mode, the module sends the command sequences to the VMOF Telecom high-fidelity module (*uplink*) and updates Brahms with the results returned (*downlink*). The Robot low-fidelity module controls a robot's instruments and either simulates the operation of a robot (in low-fidelity mode) or forwards commands to the MST robot simulators (in high-fidelity mode). The Instruments low-fidelity module simulates the operation of any instruments the robot might have. This system operates under the control of the Robot low-fidelity module that will send it instrument commands. In low-fidelity mode, the Instruments low-fidelity module uses a script to regenerate science data in response to the executive's commands. The science data will be stored in Brahms objects. In high-fidelity mode the Instruments low-fidelity module forwards the commands to the VMOF Instruments high-fidelity module. This will allow a simulation of a complete human-robot mission scenario with integrated mission systems and human-in-the-loop capability.

Table 1. MODAT Component Comparison

Component	Objective	Implementation Tool	Feature	Application
Mission Operations Work System Simulation	Simulate people, mission operation systems, data flow, facilities.	Brahms	Multiagent M&S environment.	Simulation of human behavior for: • MER mission, "Day in the life onboard the ISS", Apollo astronauts. Mobile Agents Architecture: • Work and data management system for exploration.
Robot Simulation	Dynamic simulation of a robot.	Mission Simulation Toolkit (MST)	Vehicle models based on either kinematics or dynamics.	Autonomy research for robotic systems.
Instrument Sim	Virtual instruments that can compute science-data-acquisition-related operations.	VMOF/VIS	Virtual in-situ environment. Instrument-generic measurement simulation.	Microscopic Imager and PanCam simulation.
Telecom/Telemetry Sim	Simulate telemetry uplink and downlink.	VMOF/TTS	Telecom performance	MER communication to/from Earth via the

Component	Objective	Implementation Tool	Feature	Application
			analysis & operation simulation.	Mars Odyssey satellite.
3D Vizualization	Visualize robot operations in a high fidelity virtual 3D World.	Viz	Visualization with photorealistic rendering providing situational awareness.	Virtual Martian environment for MER Mission.
Mission Planner	Science activity planning.	MAPGEN/EUROPA	Constrained-based activity planning.	MER mission rover activity planning system.
Human-Robot Mission Support System (Mobile Agents)	Supporting EVA astros, Hab crew, remote science teams, mission support and robots in teamwork activities.	Brahms	Human-Robot Teamwork, mission monitoring and data capture and distribution.	Human-Robot EVAs.
Human-in-the-loop	Human user input during simulation.	Java	Enable people in the simulation.	Mission training.

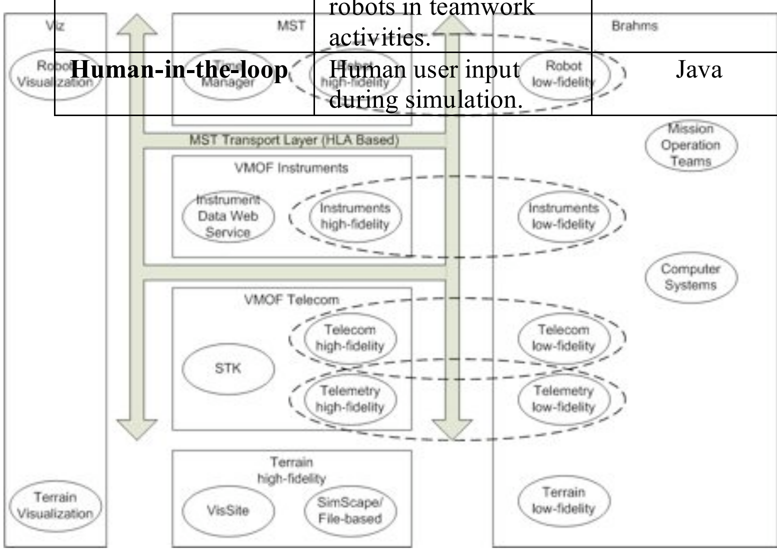


Figure 3. MODAT Software Modules

Table 1 gives a comparison of the component roles, objectives and features in the MODAT architecture. It also lists the implementation modeling and simulation tools we are using for developing these components.

The Mission Operation Work System Simulation, shown in Figure 2 and Figure 3, connects all the simulation models to all the other components. This work process sim in Figure 2 is developed as a multiagent Brahms model where each person and mission system in the work process is simulated as communicating agents. As agents communicate with each other, information and data flowing through the work system is simulated. Robots and instruments are also simulated as agents in Brahms and interact with the external simulation environments through the use of Java-based external ComAgents [Sierhuis, et al. 2005].

<u>MST Transport Layer</u>

MST's HLA implementation and runtime system provides a publish-subscribe scheme with

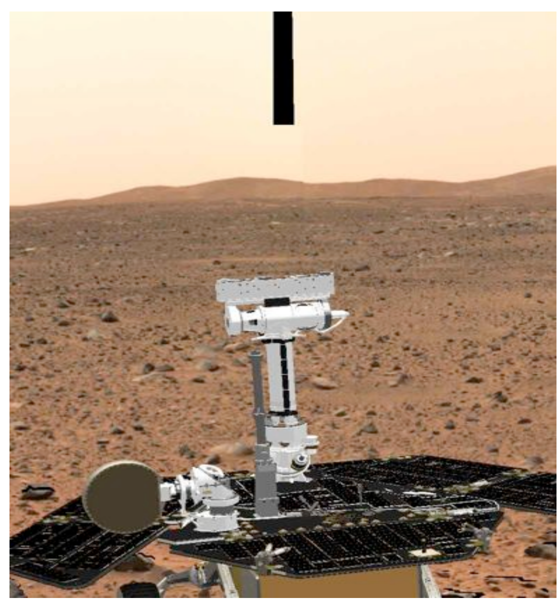


Figure 4. Viz for MER Mission

services to time-synchronize components. The MST transport layer provides a layer on top of HLA, which abstracts several HLA services and automatically ensures the enforcement of HLA rules. This additional layer simplifies the integration of new components into MST simulations, while helping component developers to observe all the HLA conventions without having to master all the HLA complexities. This approach allows new models to be plugged in to replace existing ones with the same services, thus providing significant simulation flexibility, particularly in the mixing and control of fidelity level.

Robot Sim

The MST allows autonomy researchers to simulate robotic systems. The MST provides a software test bed that includes simulated robotic platforms. This simulation capability is applicable to a wide range of robotic applications, ranging from early concept studies through the evaluation of mature autonomy technology. MST simulates robots at a high fidelity, from simulating movement of the robot drive train, to the application of instrument payloads (such as cameras and robotic arm). MST also simulates power consumption.

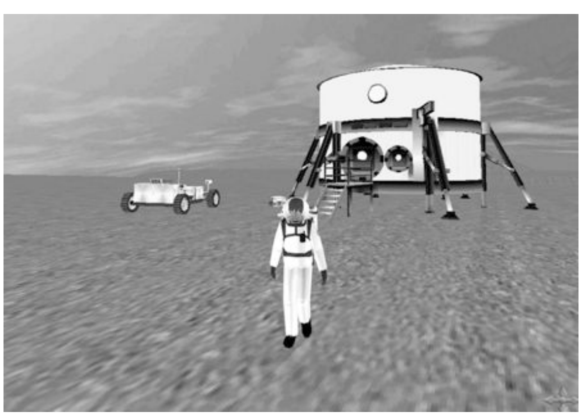
Surface, Robot and People Visualization

The Viz environment provides a 3-D model of the remote environment (e.g. Mars or Moon) and the ability to simulate robot operations in its virtual 3-D world using an accurate kinematics simulator. Viz was used throughout the Mars Exploration Rover (MER) Mission to put teams working at mission control in Pasadena into the virtual Martian environment (see Figure 4). The Viz environment currently does not allow for the visualization of people and surface habitats but this capability is highly desirable if we want to simulate human-robot missions. The BrahmsVE is a virtual environment, developed by DigitalSpace, enabling Brahms simulations to be visualized in a 3D virtual world (see Figure 5). BrahmsVE will be used to visualize Brahms agents, representing people, as virtual characters within the Viz environment [Clancey, et al. 2005].

Telecommunication, Telemetry and Instrument Sim

The JPL VMOF environment enables, among other capabilities, telecom operation, telemetry generation and robot instrument operation modeling and simulation. The telecom operation will address telecom opportunity analysis and the simulation for command uplink and data downlink processes. Telemetry simulation will address the collection and organization telemetry data for downlink usage. The instrument operation simulation will address simulation of a science observation by generating instrument science data and telemetry data. We will develop instrument simulations for the MER rover instruments. The telecom simulator will be responsible for providing telecom operation planning and relating information to the Mission Operations Systems (MOS) agents (see Figure 3). Interaction between the Uplink process simulator and the MOS agent will be performed via HLA. A resource usage analysis module is used so that time-based resource availability can be tracked during uplink operation. A special Brahms Java-agent interface mechanism services the downlink telemetry stream. The telemetry stream is divided into engineering packets for status monitoring and instrument data packets for science information processing.

Simulation Time Management



Modeling of virtual environment for a Mars habitat, rover and astronaut from first BrahmsVE feasibility project.

Planning meeting simulation from 2002 BrahmsVE project to model a day in the life of an analogue Mars habitat.

Figure 5. Visualizing Brahms simulations in BrahmsVE (Graphic courtesy DigitalSpace, Inc.)

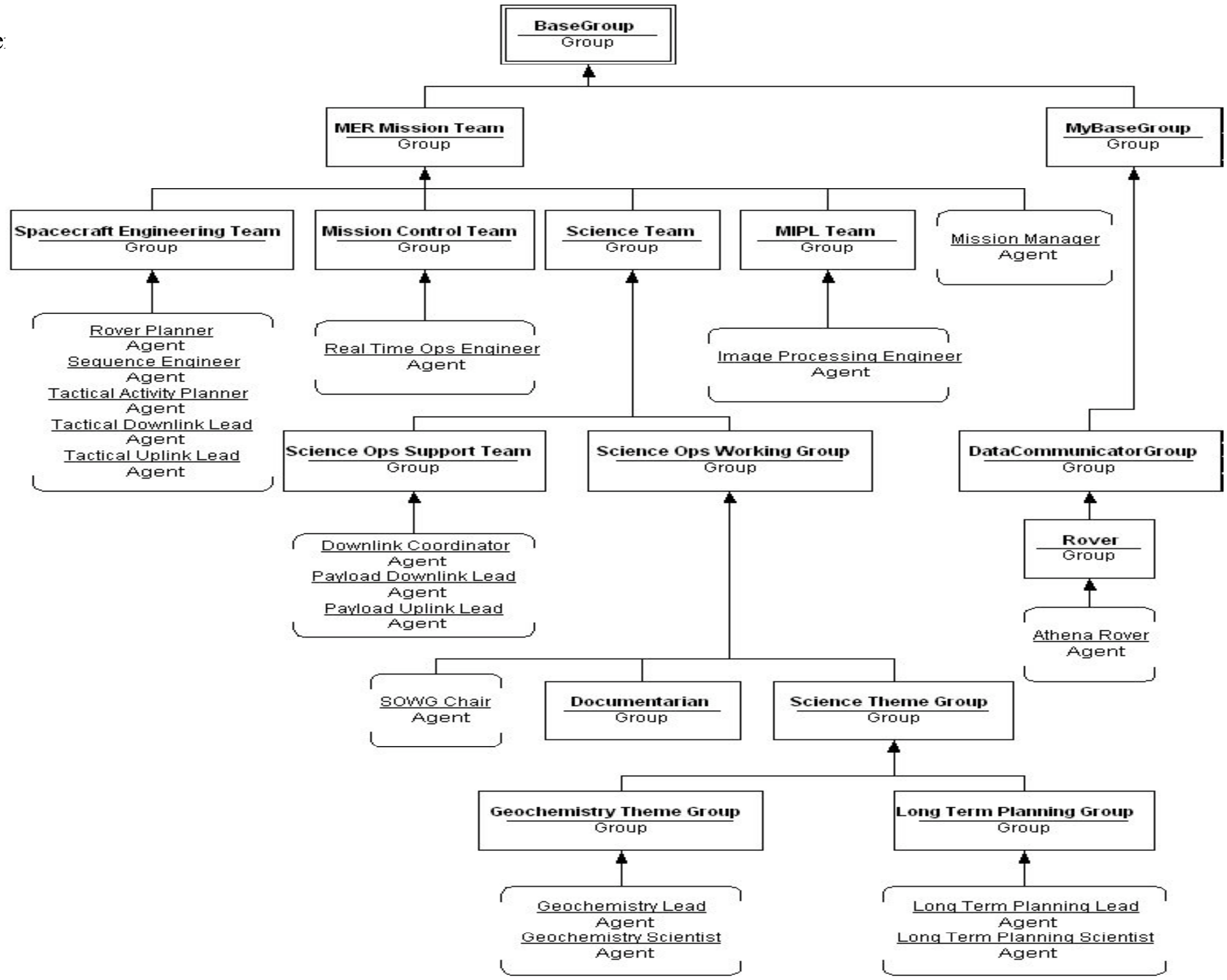


Figure 6. MER Mission Operations Groups and Agents

To simulate all elements together it is extremely important that the simulation time between all of these elements is coordinated to ensure that no simulation subsystem gets ahead or falls behind another simulation subsystem. There are two different time management mechanisms used by the different simulation subsystem, *time-step* and *discrete-event*. The MST uses a time-step time management mechanism. Each MST module processes all of the simulation updates received from the other modules and then computes its new state for the *time t + time-step*. When a module is done with its computation it requests the time manager to advance the time by the specified time-step. When the time manager has received a time advance request from all modules, it advances the simulation time to *t + time-step*. The current time-step used is 100ms of simulated time.

The Brahms and VMOF subsystems use a discrete-event based time management mechanism. Brahms has a scheduler that coordinates time between the various Brahms agents. Each agent performs a unit of work starting at *time t* and ending at *t+x*. The start and end of these units of work are time-stamped events. Before an agent processes an event, it notifies the scheduler that the agent is ready to process event(s) at *time t* and is waiting to get a go-ahead from the scheduler to process the events for that time. For some agents the next event time is at *time t* for others it is *t + y*. If *all* registered agents are waiting for a go-ahead from the scheduler then the scheduler will notify all agents to process their set of events at the next earliest notification *time t*. This discrete event approach allows Brahms agents to jump ahead in time if there is no work to be done.

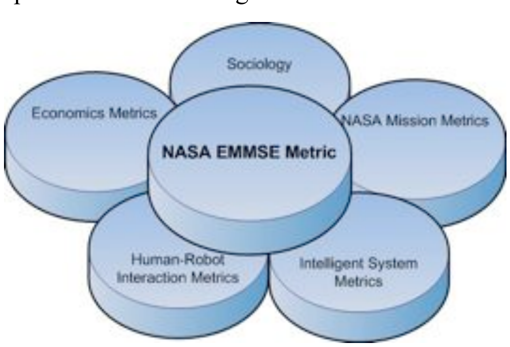
MODAT is a mixed fidelity modeling and simulation environment, meaning that the model designer can decide what parts of a model need to be simulated at a high fidelity with a lot of detail and which parts can be simulated at a medium or low fidelity. The fidelity of the simulation generally determines the grain size of the time step that can be used, and is an indicator of how much time it takes to simulate a model. Our goal is to simulate end-to-end, multi-day missions faster than real time. The idea is to step over chunks of time in those parts of the simulation with low fidelity and to significantly reduce the size of the time steps where the simulation requires a high fidelity. When simulating mission operations at low fidelity the time steps are generally on the order of minutes or more, while the time steps are generally very short, on the order of milliseconds, when simulating rover components at a high fidelity. MST provides the central Time Manager (TM) using HLA's distributed time management capability. Each simulation module reports to the TM the time it is ready to simulate or advance to the next time, and waits until it gets a notification from the TM to go ahead and advance to the next time. The TM will notify all simulation modules of the next earliest time to advance to. This approach implies that all modules will be notified by the time manager at the rate of the module with the smallest simulation time step.

Model Libraries

To increase the ease, timeliness and turn around capabilities of future model development, we are developing a set of re-usable model libraries of behavioral agents for human and robot mission roles in deployment, construction and exploration tasks. In 2002-2003, we used the Brahms environment to assist in the design of mission operations work system for the Mars Exploration Rover (MER) mission [Seah, et al. 2005, Sierhuis & Clancey 2003]. We have abstracted the MER model into a set of agent and object mission libraries. For example, the mission operation roles library will contain hierarchies of mission operation roles (modeled in Brahms groups). This library is developed from the MER mission groups and agents (see Figure 6).

Metrics

We are developing a metrics engine within MODAT. With this engine, mission designers can evaluate different designs. Metrics in mission performance evaluation is based heavily on the foundation of agent-based systems, human-robot interaction, intelligent system performance, and economics. Therefore, it is important to have a thorough understanding of existing metrics in related fields. Several disciplines have embarked on the development of metrics. Figure 7 lists the foundations on which our metrics framework is built. Several methodologies have been proposed in the planning and business literature to measure performance, effectiveness, or cost efficiency of tasks and processes. These methodologies include cost benefit analysis [Dasgupta & Pearce 1972], activity-based costing [Staubus 1971] [Wegen 1996], and economic value added [Stewart 1991]. While successful for market-oriented organizations, these approaches do not fully address the needs of research-oriented organizations like NASA. Detailed metrics evaluating the performance of robotic missions (e.g. the MER mission) have been developed by Weisbin, et al, at Jet Propulsion Laboratory [Weisbin & Rodriguez 1999].



Our goal is to create a new, targeted methodology and metrics to understand, forecast, and measure the economic impact of mission operation work system designs, drawing from and combining: 1) the economic literature on the impact of IT investment and innovation [Acquisti 1998], 2) the growing literature on metrics to evaluate human-robot interactions [Olsen & Goodrich 2003], and 3) the literature on system processes and human factors modeling, as well as the literature on computational organization theory (e.g. [Carley & Prietula 1994]).

We are developing an appropriate methodology for the proposed economic approach, and appropriate metrics based upon it will be generated for specific domains.

Future Flight Central

The demonstration test bed is NASA Ames' Future Flight Central facility (FFC). The facility is a two-story structure that provides a full-scale tower simulation environment for air traffic control research (see Figure 8 for a virtual representation of the second floor of the actual structure). The facility is approximately 24 feet in diameter. The out-the-window scene is accomplished with 12 rear-projected optical screens, each 10 feet x 7.5 feet. The twelve screens are abutted to form a full 360^o by 22.5^o field of view. The facility has been used to display and study panoramic images acquired by the MER 2004 rovers and provides compelling "presence".

As a virtual test bed representing mission operations, the FFC enables the mission designers to study the performance and interactions of simulated mission operations with humans in the loop prior to mission operations readiness tests in the field. The insights and efficiencies gained will streamline the design cycle and produce better mission designs.

Figure 8. FutureFlight Central Facility Displaying Mars Surface Features from the MER Mission.

Conclusions

In this paper we described the concept and architecture of the Mission Operation Design and Analysis Toolkit, for designing and analyzing future mission operations for missions to the Moon and Mars. MODAT is being developed as part of the End-to-end Mission Modeling and Simulation Environment project. EMMSE is a four-year project funded by NASA Exploration Systems Mission Directorate. We are currently within the first year of the project. This paper provides an overview of the intended environment. At this moment we are integrating all the different simulation components within the MST HLA environment, and we are working on a first-year demonstration of the environment using a scenario based on a six sol traverse from the MER mission. In this scenario we will demonstrate the simulation of mission operations at JPL, the command-sequence uplink process, the Spirit rover executing the commands on the surface of Mars, as well as the downlink process.

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