Agent Based Modeling of Collaboration and Work Practices Onboard the International Space Station

Alessandro Acquisti
School of Information Management and Systems, UC Berkeley
102 South Hall, Berkeley, CA 94720
510-823-5008
aacquisti@mail.arc.nasa.gov

Maarten Sierhuis
RIACS, NASA Ames Research Center
MS T35B-1, Moffett Field, CA 94035
650-604-4917
msierhuis@mail.arc.nasa.gov

William J. Clancey
NASA Ames Research Center & Institute for Human and Machine Cognition, University of West Florida
MS 269-3, Moffett Field, CA 94035
650-604-2526
bclancey@mail.arc.nasa.gov

Jeffrey M. Bradshaw
Institute for Human and Machine Cognition, University of West Florida
40 S. Alcaniz, Pensacola, FL 32501
850-232-4345
jbradshaw@ai.uwf.edu

Keywords:
Agent-Based Social Simulations, International Space Station, Human-Computer Interaction, Agent Teamwork.

ABSTRACT: *The International Space Station is one the most complex projects ever, with numerous interdependent constraints affecting productivity and crew safety. This requires planning years before crew expeditions, and the use of sophisticated scheduling tools. Human work practices, however, are difficult to study and represent within traditional planning tools. We present an agent-based model and simulation of the activities and work practices of astronauts onboard the ISS. The model represents "a day in the life" of the ISS crew and is developed in Brahms—an agent-oriented, activity-based language used to model knowledge in situated action and learning in human activities.*

1. Introduction

The International Space Station (ISS) is one the most complex projects ever. Numerous interdependent constraints must be met in order to ensure productivity and crew safety. This requires planning efforts starting years before crew expeditions, and the use of sophisticated planning and scheduling tools.

Human work practice onboard the ISS, however, is not easily represented within traditional tools. Expedition ship logs highlight recurring discrepancies between planned crew activities and the reality of onboard life. In addition, scheduling constraints make it hard to replan onboard activities. The need emerges for tools able to model the work activities of astronauts onboard the ISS and their interactions with other people and systems onboard and on earth.

In this paper we present our ongoing modeling of the work practice of the ISS crew using Brahms. Brahms is an agent-oriented, activity-based language developed to model people's situated action, communication, and collaboration, as they interact with systems. Brahms links knowledge-based models of activities with discrete-event simulation and an activity subsumption architecture (see [1], [2]). In Brahms, agents' behaviors are organized into activities, inherited from groups and located in time and space. Hence, in our modeling of the ISS work environment we are able to consider resource availability, human/machine interaction, scheduled and unscheduled activities, and the emergence of work practice onboard the station out of procedures developed by engineers and mission controllers.

Our research has two functions. One function is to provide an *artifact* (i.e. a simulation model) that can help us study and understand the way work is done onboard the ISS. As such, our Brahms model might be of help in creating new procedures for the ISS crew (e.g., by predicting the time needed to implement activities never executed before), in assisting daily planning, in predicting behavior in emergencies, in future orientation and training of ISS crews, and in developing human-centered robotic systems for the ISS (such as the Personal Satellite Assistant—see [3, 14]—and the Robonaut—see [4]) that need to be aware of the activities and practices of the crew. A second and more abstract function of the model is to explore the use of Brahms in representing manned space missions. In this regard Brahms can be considered an "agent-based social simulation" tool (see [5]), and this model (and future Brahms models) could prove useful for internal NASA coordination of research and engineering.

The rest of this paper is structured in the following way. Section 2 discusses the ISS, its goals, the activities of its crew and the planning procedures adopted on ground by Mission Control and onboard by the crew. Section 3 introduces the Brahms programming language. Section 4 presents our approach to the Brahms model of the ISS and our simulation results. Section 5 discusses future directions and uses of our research. Section 6 concludes the paper.

2. The International Space Station

The ISS Alpha opened for business on November 2nd, 2000, when Expedition Commander Bill Shepherd, Soyuz Commander Yuri Gidzenko, and Flight Engineer Sergey Krikalev opened the hatch between the Soyuz vehicle that had brought them in orbit and the Russian Service Module (one of the earliest components in the assembly of the ISS). That day represented the climax of years of preparation and planning during which the ISS objectives and procedures were defined. In this section we discuss the ISS goals, the activities of its crew, and their planning procedures.

The ISS was designed to provide an "Earth orbiting facility that houses experiment payloads, distributes resource utilities, and supports permanent human habitation for conducting research and science experiments in a microgravity environment." ([6], p. 1-1). To achieve this goal, several assembly flights of Shuttle, Soyuz, and Progress vehicles have been operated and several crew "expeditions" have been onboard.

While crews from initial expeditions spent most of their time in assembly and maintenance activities, more recent expeditions had more time to accomplish some of the research for which the ISS was created: experiments in areas such as life sciences, microgravity, and space sciences, as well as commercial product development and engineering technology. However, because of several constraints (described below), a crew of three spends most of its time maintaining the station rather than focusing on the research experiments that were originally planned. This creates a strain on the NASA ISS program, and has caused scrutiny of its actual benefits, and consequently its funding.

In a typical day, each ISS crewmember divides his or her time between physical exercise, maintenance, experiments, communication with ground personnel, personal time, and bio-needs activities (e.g., rest, eating). These activities are critical for the well-being of the crew. Hence, the planned maintenance and research activities must be scheduled around them. At the same time, several interdependent structural constraints ensure crew safety and productivity: thermal control, power management, communication bandwidth management, and regulation of other systems. These form a network of components that must be accurately timed and orchestrated around crew activities and needs.

For these reasons and many others, coordinating human and technical constraints onboard the ISS is an extremely challenging task. Unlike other space missions, the ISS operates on "a continuous basis, with execution planning, logistics planning, and on-orbit operations occurring simultaneously for long periods of time" ([7], p. 1.1-1). Preparations for crew expeditions start months or years ahead with the strategic planning phase. This phase poses the basis for ground rules and constraints that are used in later phases of the planning process. Tactical planning, which starts about 30 months before an expedition, defines the resources, priorities and objectives of an expedition. Pre-increment planning, starting 18 months before an expedition, defines the high level activities of an expedition and produces the reference material and the procedures (Operations Data Files and Systems Operations Data Files) necessary to implement the strategic plan. Finally, as the expedition begins, new just-in-time artifacts are prepared (such as the Onboard Short Term Plan, or OSTP), to be executed on the ISS.

This elaborate planning process is necessary to meet the human and system constraints discussed above. The planning complexity is such that the major planning rule for the ISS is actually: “Thou shalt not replan” (see [7], p. 2.1-21). This means that—with the exception of “unacceptable failures” and “job jar” items left to the self-organization of the crew—any activity that can not be performed at its allotted time will *not* be replanned in real-time. It will simply not be performed, “with the expectation that [it] will be rescheduled into the operational flow at some later date” ([7], p. 2.1-21).

Considering this, it is apparent that any unexpected event or discrepancy between the time allocated for a planned activity and the actual time required in the face of the realities of onboard life will have far-reaching impacts on the completion and timeliness of crew activities, and therefore will drastically reduce efficiency and productivity onboard. Such discrepancies are actually frequent, as the comparison between daily plans and actual ship logs shows. Thus, in order to develop tools to improve planning and efficiency, it becomes important to study how crew work practices emerge from planned activities and written procedures. Two objectives of our research are to understand how well the planned ISS activities and their written procedures fit the reality of onboard life, and, more specifically, to determine the work practices that have evolved on the ISS since Expedition 1. To address these questions we use a multi-agent modeling and simulation language called Brahms.

3. The Brahms Language

Brahms is an Agent-Oriented Language (AOL) with a well-defined syntax and semantics. A Brahms model can be used to simulate human-machine systems, for what-if experiments, for training, “user models,” or driving intelligent assistants and robots (see [1], [2]). The run-time component—the Brahms virtual machine—can execute a Brahms model, also referred to as a simulation run.

The Brahms architecture is organized around the following representational constructs:

Groups of groups containing
    Agents who are located and have
        Beliefs that lead them to engage in
            Activities specified by
                Workframes
Workframes consist of
    Preconditions of beliefs that lead to
        Actions, consisting of
            Communication Actions
            Movement actions
            Primitive Actions
            Other composite activities
        Consequences of new beliefs and facts
Thoughtframes that consist of
    Preconditions and
    Consequences

Physical objects are represented as entities whose states change within factframes, while conceptual objects are conceptualizations made by people, but have no physical embodiment.

Brahms is based on the idea of “situated action” (see [8], [9]) and offers to the researcher a tool to represent and study the richness of activity theory and “work practice” (see [10], [1]). A traditional task or functional analysis of work leaves out informal logistics, especially how environmental conditions come to be detected and how problems are resolved. Without consideration of these factors, analysts cannot accurately model how work and information actually flow, nor can they properly design software agents that help automate human tasks or interact with people as their collaborators. For these goals, what is needed is a model that includes aspects of reasoning found in an information-processing model, plus aspects of geography, agent movement, and physical changes to the environment found in a multi-agent simulation – such as interruptions, coordination, impasses, and so on. A model of work practice (see [11]) focuses on informal, circumstantial, and located behaviors by which synchronization occurs (such that the task contributions of humans and machines flow together to accomplish goals) and allows the researcher to capture (at least part of) the richness of activity theory (see [10]).

Brahms relates knowledge-based models of cognition (e.g., task models) with discrete simulation and the behavior-based subsumption architecture. In Brahms, agents' behaviors are organized into activities, inherited from groups to which agents belong. Most importantly, activities locate behaviors of people and their tools in time and space, such that resource availability and informal human participation can be taken into account. A model of activities doesn't necessarily describe the intricate details of reasoning or calculation, but instead captures aspects of the social-physical context in which reasoning occurs. Thus Brahms differs from other simulation systems by incorporating the following:

- Activities of multiple agents located in time and space;
- Conversations;
- Descriptions of how information is represented, transformed, reinterpreted in various physical modalities.

4. The Brahms Modeling of the International Space Station

The ongoing effort to model the collaboration and work practice onboard the ISS developed through three phases—1) data gathering; 2) conceptual modeling; and 3) Brahms modeling—that we discuss in the next subsections.

4.1 The Data

We sought data that could lead us to understand and represent a generic “day in the life” of the ISS crew. However, we also dedicated more attention to specific activities and scenarios (such as emergency scenarios) that appeared of great relevance to our research objectives. We consulted ISS documentation and manuals, onboard procedures and flight rules, crew daily plans and ship logs, crew de-briefings, and, particularly, ISS crew videos. This information was interpreted, analyzed, and validated through interviews with astronauts, astronaut trainers, and flight controllers at Mission Control. While the day chosen for modeling was May 7th, 2001[1] (when Expedition 2 was onboard; see Table 4.1), we generalized the model so that we could later simulate any typical day.

On a typical day (that does not involve EVAs) an ISS Crew member wakes up at 6.00 GMT and (after or before activities such as personal hygiene and breakfast) he or she reviews on a laptop computer the plan of the day. The scheduled activities include several sessions of physical exercises, communications with grounds, experiments and maintenance tasks. The crew executes these tasks by performing individual and collaborative activities, sometimes altering the order proposed by the mission planners, sometimes removing or inserting activities into the daily plan with or without previous coordination with Mission Control. At the end of their day, the astronauts tend to eat dinner together and then participate in some post-dinner activities such as watching a movie, reading a book, or writing personal email.

Figure 4.1 - Onboard the ISS (Commander Yuri Usachev, Expedition 2)

4.2 The Conceptual Model

In our analysis of the data gathered during the first phase of our research we looked for patterns in the crew activities and the emergence of work practices that are specific to onboard life. We generalized and represented the individual astronaut’s daily behavioral patterns as learned and shared activities at the (conceptual) group level. For example, the activity of eating breakfast onboard the ISS is represented at the ISS Crew group-level. This way, all agents that are a member of the ISS Crew “know” how to perform this activity. The group structure also allows us to represent differences between social, cultural and other type of communities (for example, the behavioral differences between American and Russian crewmembers, and between male and female crewmembers; see 4.3).

Table 4.1 - A Day in the Life of the ISS Crew (Derived from the onboard plan for May 7th, 2001 uploaded to the ISS)

06:00 - 06:10 ISS morning inspection
06:10 - 06:40 Post Sleep
06:40 - 07:30 Breakfast
07:30 - 08:00 Prep for work
08:02 - 08:17 DPC via S-Band
08:30 - 09:15 (FE-1) TVIS Video Survey
08:15 - 08:30 (FE –2) SSC Daily Maintenance
08:35 - 08:50 (FE –2) MEC card swap
09:00 - 10:00 (FE –2) Physical Exercise, Active Rest
09:15 - 10:45 (FE –1) Physical Exercise, Active Rest
09:00 - 09:15 (CDR) URAGAN, visual observations
09:50 - 10:20 (CDR) Replacement of urine-receptacle in Toilet
10:00 - 10:30 (FE –2) MEC Exercise Data Downlink
10:20 - 11:00 (CDR) ECLSS maintenance by MCC GO
10:55 - 11:20 (FE –1) LAB PL Status/Monitor
11:00 - 11:30 (CDR) SOYUZ Window Inspection
11:30 - 11:50 7A TAGUP via S-Band
12:00 - 13:00 LUNCH
13:05 - 13:25 WPC via S-Band
13:30 - 15:30 (CDR) Wet Cleaning/ ODF Medical Support
13:30 -16:30 (FE -1, FE –2) Back Up MDM S/U
16:15 - 17:15 (CDR) Physical Exercises, VELO-1
16:55 -17:15 (FE –1) Prep of Delta File (IMS)
16:45 - 18:15 (FE –2) Physical Exercise, Active Rest
17:15 - 18:15 (FE –1) Physical Exercise, Active Rest
17:15 - 18:15 (CDR) Physical Exercise. RED-1
18:15 - 18:45 Fam with next day's plan
18:45 - 19:30 Prep of Report
19:05 - 19:20 DPC via S-Band
19:30 - 19:55 Dinner

In order to make our model reusable and applicable to any typical day and scenario on the ISS, we represented procedures, daily plans, and flight rules as objects and conceptual objects in the model, that agents can access, have beliefs about, manipulate, and act upon. We categorized activities according to a 2 by 2

[1] An important factor in the choice of the day was the amount of available data relevant to that particular day.

matrix, with the degree in which the activity was scheduled (scheduled vs. unscheduled activities) represented on one axis, and the uniqueness or repeatability (day-specific vs. recurrent activities) of the activity represented on the other axis (see Table 4.2). This allowed us to model elements of the crew's situated action (see [8]) by letting the crew agents perform a *just-in-time replanning activity*[2] through which they change their mental plan—that was first constrained by the OSTP and coordinated with Mission Control—during the day, based on the situational context of the day's activities.

Table 4.2 - A 2 by 2 matrix of sample ISS activities

	Scheduled activity	*Unscheduled activity*
Day-specific activity	Maintenance activities (e.g., Replacement of urine-receptacle in Toilet). Experiments (e.g., LAB PL Status/Monitor). …	Emergencies. Job-Jar activities Unexpected maintenance or repair activities. …
Recurrent activity	Physical exercise. Daily Planning Conference. Eating (lunch, dinner, breakfast) …	Going to the toilet. Sending personal email. …

4.3 The Brahms Model

In this section we discuss the current features of our model and we analyze the resulting simulation, of which Figure 2 offers a graphical output. We use as guidelines some of the *sub-models* that define a Brahms simulation: the agent-, geography-, activity-, and knowledge models.

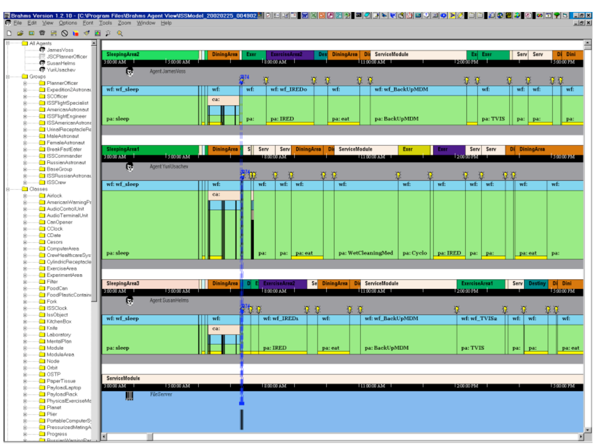

Figure 4.2 - A Day in the Life: 2D output of a Brahms simulation

[2] We do not suggest that astronauts perform this activity by executing a computational algorithm similar to artificial intelligence planning systems. We rather represent the astronaut's ability to change the order they decide to perform their activities, based on situational awareness and context.

Agent Model: The Brahms Agent Model of the ISS includes both the crew and ground controllers (Houston, Moscow, and Payload operations). Hierarchies and organizational structures are explicitly modeled; for example, different planning officers and flight controllers are modeled, each with their activities and responsibilities. The representation of group membership for the ISS crew agents reflects the different roles of the agents (e.g. ISS Commander; Flight Specialist; Soyuz Commander), their nationalities (Russian or American), their sex (male or female), as well as a grouping by type of activities they can perform (e.g. "BreakfastEaters"). By putting activities in groups we can abstract the representation of activities when they can be generalized for a group of agents that can perform them, and we can instantiate them more specifically for lower-level groups or individual agents as these impact the agent's situated activity behavior.

Activity Model: The Brahms Activity Model of the ISS represents a day in the life of the ISS crew. Recurring activities (such as breakfast, lunch, physical exercise, and ground communication) are modeled as well as activities that are unique and only performed on a particular day (such as a specific experiment or a specific maintenance task, see Table 4.2). The model represents the onboard life as a combination of activities scheduled by mission control, unscheduled activities left to the discretion of the crew, and emerging work practices. Discrepancies between plan and reality come out of the simulation of the model, as they do during the actual day of the astronauts. While procedures and scheduled activities suggest a certain idealized scenario, several issues can emerge (see also [12]: "the highly motivated crew members sacrifice personal time to 'get the job done'"): procedures might not be clear, American and Russian versions of the same document might slightly differ thereby generating confusion, the time needed to complete an activity might be longer than expected, tools might get lost, and, more importantly, new work practices might emerge (see Table 4.3).

The discrepancies we refer to are not only those caused by imprecise timing of new activities, or triggered by unforeseeable error and mismatches with systems or procedures.[3] As Table 4.3 shows, we also focus on more substantial discrepancies that involve a deliberate (though possibly not planned-in-advance) behavior of the crew. A traditional planning approach typically does not take into consideration some of the items highlighted in Table 4.3. More importantly, they rarely

[3] In this regard, Expedition 2 reported a substantial improvement with respect to Expedition 1 in the accuracy of the predicted duration of scheduled activities and in the feasibility of the planned daily workload.

deal with the concatenated effects caused by the highlighted discrepancies (e.g., the activity of printing out a procedure rather then reading it on a laptop implies that the astronauts must move to the printer location; it also implies that paper must be available, otherwise new paper must be fed into the printer). In contrast to typical planning approaches, the Brahms simulation is capable of showing how the practice of onboard activities often diverges, both in timing and execution, from the originally scheduled activities and procedures. Distances and movements, noises, tools location, work practice, and so forth are considered. Hence, delays caused by crew movement constraints, the search for tools and other items, and the inability to share resources or access to electronic procedures can come out from the simulation. For example, we model the fact that the work practice of the astronauts is to move from one module to the other to communicate face-to-face, rather than using the internal audio system.

Table 4.3 - Discrepancies between plan and practice[4]

Cause of Discrepancy	*Example*	
	Plan	*Practice*
Procedures not easily accessible or not clear	During emergency, refer to procedure	During emergency, rely on training and memory
Noise level on internal audio system	Use internal audio system to communicate between modules	Move from module to module to communicate with crew members
Personal preferences	Do medical tests as scheduled	Do medical test in the morning
Shared resources not always available	Upload on laptop computer medical/physical data after experiment/exercise	Upload data rarely
Personal habits	Read procedure	Read electronic procedure (from laptop), or read printed procedure
Inventory system not always reliable	Use tools indicated in procedure	Tools must be found and time can be lost in this operation
Inventory system not always reliable	Use bar-code reader for inventory	Rarely use bar-code reader

[4] Sources: ISS Ship logs; Expedition 2 debriefs; interviews with ISS training specialists.

Geography Model: The Brahms Geography Model represents the physical spaces within the modules of the ISS where the crew lives and works, with particular attention and detail for those locations where the astronauts spend most of their time (lab, crew quarters, etc.). This means that some modules are represented with a higher degree of fidelity than others. For example, the American Destiny module (which is used as the ISS laboratory) is modeled with internal locations for experiments (e.g., the Human Research Facility), controls for the robotic arms, and physical exercise machines. Some of these locations, in turn, are decomposed into sub-areas—this allows modeling the locations of objects and other places within a particular area. For example, pliers and can-openers can be located inside boxes behind panels of a module, or attached to hangers on the walls. This model of the ISS geography is a prerequisite to the Brahms representation of the astronauts' situated activities. For example, the model represents how the relative locations of the astronauts inside a module or the noise level in the background affect interaction and coordination.

Knowledge Model: The knowledge model represents what the agents can know about (i.e., have beliefs about) as well as their reasoning and problem-solving behavior—inference rules—that can be used to create new beliefs. We thus distinguish the agent's knowledge of how to perform activities and when (i.e., situation-action rules), from the definition of an agent's possible beliefs and inference rules to create new beliefs or change old beliefs. For example, the simulated astronauts learn the daily activities from the OSTP they read in the morning and access or refer to online procedure whenever they do not already know how to execute a particular activity. By reading the procedures (i.e., an activity) they will acquire beliefs about how to perform the OSTP activities. This makes the Brahms model highly reusable, because by changing the daily plan provided as an initial condition of the model, and by adding new procedures taken from the real counterpart in the procedure documentation, the simulation can take completely different paths.

The Brahms model of a day in the life of the ISS crew is not hard-coded, in the sense that the model does not represent a single specific day. Instead, we can simulate any typical day by feeding a different daily plan as input into the model. The simulated agents (i.e., the Brahms agents that model the ISS crew) organize their day in a similar way to how the crew organizes its daily life in practice. The agents can react in (simulated) real time to the events of the day, deciding whether there is a need to consult with Mission Control about a procedure or whether they can abandon the written procedure whenever there is a certain work around. For this reason, our ongoing efforts to model emergency scenarios might be of use to predict outcomes of such eventualities under different scenarios. Given this, we believe that the simulation of a work practice model can help the mission planners in creating short-term schedules.

On the other side, the boundaries of our analysis are determined (as for any other agent-based social simulation) by the availability of data and by the degree in which human behavior can be captured in a model. Regarding the data, since we are unable to conduct an ethnographic study onboard *the ISS, we must rely on secondary sources such as videos, reports, and transcripts, and on the validation of our interpretation of these sources through interviews with astronauts, mission controllers, and so forth. The model describes behaviors that are more or less situated (through situated-action rules), but cannot replicate the flexibility of human behavior in all its complexity, which involves breaking patterns, and especially establishing new practices. In addition, since Brahms is not used to model human* cognition*, our model depends on initial conditions such as the knowledge given to the agents about procedures and—what we have observed to be—their work practice. Thus, the model cannot exhibit the full variety and creativity of human improvisation and interpretation: in absence of ground intervention, the simulated agents would not be able to find new solutions to unexpected problems.*

5. Uses and Future Directions

The work practice analysis of the ISS data and the comparison between planned activities and daily logs highlight frequent discrepancies between the plan and the practice (cf. Table 4.3). Moreover, they also suggest opportunities for improvement of certain procedures through the use of robotic assistants.

Therefore, while one of the uses of the Brahms model of the ISS is to support planning and training, the ultimate goal of this analysis will be realized as its focus changes from that of a model of a simulated environment to a real-time capability that can operate in conjunction with KAoS policies and agent services (see [13, 15]). This combined system could contribute to the design and implementation of robots such as the PSA ([3, 14]) and the Robonaut ([4]), that will work closely in teamwork fashion with humans. Such robots, and the software agents that implement their behavior, need to be aware of the detailed social and environmental context in which they are operating and of the shared goals and intentions of the astronauts they are assisting. For more information on the use of Brahms and KAoS to support human-centered design and operation of the PSA see [3].

6. Conclusions

We are developing an agent-based model of the work practices of the ISS crew. We use Brahms—an agent-oriented, activity-based language—to model the ISS crew's situated action, communication, and collaboration during the course of their daily activities. In our modeling of the day in the life onboard the ISS we include resource availability, both scheduled and unscheduled activities, and the emergence of work practices. In addition, we model human/machine interaction (such as the collaboration between the Crew and robotic systems such as the PSA and the Robonaut). In our continued research we are exploring the use of the ISS model as part of an environment for teamwork between ISS crews and onboard collaborative software- and robotic agents, and as a short term planning and scheduling tool for mission planners. Over the long term, we hope our work will benefit those who plan and participate in ISS work activities, as well as those who are interested in design and execution tools for teams of robots that can function as effective assistants to humans.

7. References

[1] M. Sierhuis: "Modeling and Simulating Work Practice; Brahms: A multi-agent modeling and simulation language for work system analysis and design" Ph.D. thesis, Social Science and Informatics, University of Amsterdam, Amsterdam, The Netherlands, 2001.

[2] W. J. Clancey, P. Sachs, M. Sierhuis, R. and van Hoof: "Brahms: Simulating practice for work systems design" International Journal on Human-Computer Studies, Vol. 49, pp. 831-865, 1998.

[3] J. M. Bradshaw, M. Sierhuis, A. Acquisti, Y. Gawdiak, R. Jeffers, N. Suri, M. Greaves: "Adjustable Autonomy and Teamwork for the Personal Satellite Assistant" In Agent Autonomy, H. Hexmoor and R. Falcone (eds), Kluwer, in press.

[4] R. Ambrose, C. Culbert, F. Rehnmark: "An Experimental Investigation of Dexterous Robots Using Eva Tools and Interfaces" AIAA, 4593, 2001.

[5] P. Davidsson: "Agent Based Social Simulation: A Computer Science View" Journal of Artificial Societies and Social Simulation, Vol. 5(1), 2002.

[6] National Aeronautics and Space Administration: "International Space Station Familiarization" ISS FAM C 21109, TD9702, Rev. B, Johnson Space Center, Houston, TX 2001.

[7] National Aeronautics and Space Administration: "International Space Station – Operations and Planning Training Manual" ISS OPS & PL TM

21109, TD 9711, Rev. A, Johnson Space Center, Houston, TX 1999.
[8] L. A. Suchman: Plans and Situated Action: The Problem of Human Machine Communication, Cambridge University Press, Cambridge, MA 1987.
[9] W. J. Clancey: Situated Cognition: On Human Knowledge and Computer Representations, Cambridge University Press, Cambridge 1997.
[10] W. J. Clancey: "Simulating Activities: Relating Motives, Deliberation, and Attentive Coordination" Cognitive Systems Review, special issue on "Situated and Embodied Cognition", in press.
[11] J. Greenbaum, M. Kyng (eds): *Design at work: Cooperative design of computer systems*, Lawrence Erlbaum Associates, Hillsdale, NJ 1991.
[12] B. Peacock, S. Rajulu, J. Novak: "Human Factors and the International Space Station" Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting, 2001.
[13] J. M. Bradshaw, M. Greaves, H. Holmback, W. Jansen, T. Karygiannis, B. Silverman, N. Suri, A. Wong: "Agents for the masses: Is it possible to make development of sophisticated agents simple enough to be practical?" IEEE Intelligent Systems, Vol. 53-63, March-April 1999.
[14] Y. Gawdiak, J. M. Bradshaw, B. Williams, H. Thomas: "R2D2 in a softball: The Personal Satellite Assistant" Proceedings of the ACM Conference on Intelligent User Interfaces, pp. 125-128, ACM Press, New York 2000.
[15] J. M. Bradshaw, N. Suri, A. Cañas, R. Davis, K. Ford, R. Hoffman, R. Jeffers, T. Reichherzer: "Terraforming Cyberspace." pp. 48-56, IEEE Computer, July 2001.

Authors Biographies

ALESSANDRO ACQUISTI (MLitt, MSc, MIMS) is a Doctoral candidate at the School of Information Management and Systems, UC Berkeley, and a visiting researcher with RIACS at the NASA Ames Research Center. His research interests include agent-based simulations of social and economic systems. Web site: http://www.sims.berkeley.edu/~acquisti.

MAARTEN SIERHUIS is a Senior Research Scientist at RIACS, an institute of the Universities Space Research Association. He leads the Brahms Project at NASA Ames Research Center, Computational Sciences Division, since 1998. He holds a Ph.D. in Social Science and Informatics from the University of Amsterdam in and an Engineering degree in Informatics from the Polytechnic University of The Hague, The Netherlands. His current research interest is in modeling and simulating work practices in human organizations, and multiagent systems, as it relates to the development of human-centered systems.

WILLIAM J. CLANCEY is a Senior Research Scientist in the Institute for Human and Machine Cognition at the University of West Florida, Pensacola. Since February 1, 1997, Dr. Clancey has held a joint position at the NASA/Ames Research Center, Computational Sciences Division, where he is Chief Scientist for Human-Centered Computing. His current research relates symbolic cognitive models to activity theory and neuroscience. Web site: http://WJClancey.home.att.net.

JEFFREY M. BRADSHAW has led research teams at The Boeing Company, EURISCO, and most recently at the Institute of Human and Machine Cognition. His work on KAoS policy-based agent domain services is currently sponsored by the DARPA CoABS, Augmented Cognition, and Ultra*Log Programs, as well as the NASA Intelligent Systems and Cross-Enterprise Technology Programs. A Fulbright Senior Scholar, he is former chair of ACM SIGART, a member of the NASA Ames RIACS Science Council, and of the Autonomous Agents Steering Committee. He received a PhD in Cognitive Science from the University of Washington.

Acknowledgements. This work is being funded by the NASA Intelligent Systems Program in the area of Human-Centered Computing. We acknowledge the many contributions of other members of related projects: M. Breedy, J. Brodsky, D. Clancy, T. Cowin, G. Dorais, K. Ford, Y. Gawdiak, M. Greaves, V. Gupta, P. Hayes, B. Hockey, R. Hoffman, F. James, R. Jeffers, S. Kulkarni, J. Loch, J. Lott, D. Prescott, M. Shafto, M. Sibenac, N. Suri, A. Underbrink, A. Uszok, R. van Hoof, and B. Williams.