Mobile Agents: A Ubiquitous Multi-Agent System for Human-Robotic Planetary Exploration

Integration of Systems and Human Sciences

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Abstract

Future human planetary exploration creates challenges both for technology and mission management. Ubiquitous computing principles and applied artificial intelligence are promising approaches in making planetary surface missions safer and more effective. Architectures which integrate both approaches and facilitate the interaction and collaboration between astronauts, robots, systems, and remote science teams are necessary to achieve these goals. The Mobile Agents project uses a real-time distributed multi-agent architecture and system to provide model-based real-time distributed support for human-robotic collaboration, science data collection, mission-plan tracking, and health monitoring. The Brahms agent-oriented modeling environment provides a layer of abstraction for enabling a diversity of software, hardware, and humans to be integrated into data management and workflow. Brahms agents facilitate the communication between different mission participants and interact through voice interfaces with astronauts, remote science teams, and mission control. This paper presents the astronaut-robotic planetary exploration environment as an example of ubiquitous computing. It also discusses an area largely unexplored in the ubiquitous/pervasive literature, namely human-robotic interaction through a localized or tele-operated ubiquitous computing system. The Mobile Agents Architecture is presented and the agent-layer aspects which related to human-robotic pervasive systems are further discussed. We conclude with remarks about evaluation of the architecture through field testing.

1. Introduction

Future human planetary exploration provides increased challenges for both technology and human mission management. These challenges necessitate closer collaboration between humans, robots, and systems to achieve the science objectives of these missions. Planetary exploration, and in particular Mars, poses additional requirements for mission execution and coordination. The inter-planetary time-delay makes real-time mission management from Earth infeasible. This necessitates localized mission control of extra-vehicular activities (EVA). Access to the planet's surface is also limited by crew size and the allowable numbers of EVA in which each can participate. Expertise on exploration activities might not be on site but rather remotely located in a Mars-based habitat or Earth. At the same time, remote science teams (RST) need to be able to actively participate with the exploration astronauts to maximize scientific work. Finally, EVA astronauts' cognitive focus should be spent on scientific data collection, rather than on mundane support functions. Hazardous exploration missions further necessitate mobility of systems which provide localization and contextual-awareness which can be assisted by remote tele-operation and collaboration.

Advances in mobile devices, protocols, sensors, and systems have enabled the advancement of architectures which can support pervasive[1] computational applications envisioned by Weiser [23] His notion of disappearing technology which becomes part of the fabric of work practice could prove critical in answering the challenges of planetary exploration. Such systems require new paradigms of interaction and control. Artificial intelligence has been successfully used to deal with smart interfaces, location and situation awareness, and resource control [16]. At the same time, ubiquitous computing has produced an array of technologies, algorithms, and devices to deal with location-awareness [19][2] and context-awareness [18][14]. Wearable computing applications [21] further explored mobile computing capabilities. Agent architectures have also been used to provide contextual awareness with localization services [11].

Agent architectures may further provide the interfaces between disparate components and participants with such missions, linking devices, sensors, and humans with each other. The agent layer of the Mobile Agents Architecture (MAA) provides such integration capabilities to a mobile computing ubiquity system. The Mobile Agents project’s main objective has been to develop a model-based, distributed agent architecture which integrates diverse components in a system designed for lunar and planetary surface operations [6, 7, 8, 9]. The agent architecture provides interfaces between humans, robots, systems, sensors; provides relational storage of science data; and provides intelligent assistance to the mission's local and remote participants.

In the next section we discuss how the MAA integrates many different aspects of ubiquitous computing in an integrated way different from other systems. We further discuss assumptions used in the model and how they relate to existing ubiquitous systems. The integration of these different research approaches allows Mobile Agents to investigate their interaction. We then present the agent layer of the MAA, and discuss the three main tasks that the agents perform: (a) plan management, (b) science data management, and (c) mission data management. Each task's agent responsibility is further discussed in the context of mission objectives and constraints. We then conclude.

2. Mobile Agents as a Multi-Agent Ubiquitous Computing Environment

Different ubiquitous computing environments and systems[3] have been implemented, each of which deals with a particular aspect of ubiquitous computing research, namely, location-awareness, context-awareness, security, privacy, interfaces, ambient displays, smart objects, collaboration and information sharing. Most projects deal directly with a problem of limited scope and few provide general solutions to more complex problems. The complexity of planetary exploration missions, however, requires that the MAA takes into consideration a diverse set of research questions and provide holistic solutions.

Given the diversity of data sources and components to be integrated, the agent-oriented language Brahms [5][20] has been used as a common communication and computation layer in integrating these diverse systems. It serves as a common programming layer to control devices and to integrate and manipulate captured information.

The Mobile Agents project is one of the few projects that draw on diverse ubiquitous computing and distributed artificial intelligence ideas and approaches into an integrated system for planetary surface exploration. Previous work in the context of campus-based systems for localization and services [11][17] have taken similar but less general models. The ubiquitous computing characteristics implemented in Mobile Agents are described below:

- **Context-Awareness**: The distributed agents have knowledge of other agents in the system and their work practice expectations for performing mission operations and monitoring. Mission plan

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[1] Ubiquitous computing and Pervasive computing have been used in the literature interchangeably for extensions of computation beyond the computer. We will use the terms interchangeably.

[2] See references in related work in [12].

[3] An extensive list of projects was started by McCarthy, Jenkins, and Hendry [17] http://www.ucrp.org/

knowledge allows the agents to provide assistance in monitoring mission status.

- **Location-Awareness**: The MAA uses GPS tracking devices[4] on all-terrain vehicles (ATV), astronaut suits and the EVA robotic assistant (ERA) to keep track of GPS coordinates of astronauts, created locations, science data collected, robots. The agents have situational knowledge in reference to static locations. Localization knowledge is further exploited by monitoring agents to provide guidance to humans and robots with regards to deviations from mission transversal paths and time-to-completion.
- **Remote Interaction**: The habitat communicator (HabCom) can monitor, communicate, and command EVA components remotely, given the ability to have situational awareness of the mission through the agent architecture. Remote Science Teams are also able to model the scientific data collection process through data communicated from the field by the agents.
- **Data Storage**: Agent belief-states serve as data storage for all mission-related data. This approach has been previously used, utilizing agents as data storage devices [22].
- **Mobility**: Mobile ubiquitous systems can be thought of as static monitoring environments with sensors, or mobile environments integrated to the clothing of a human (wearable computing applications [21]). The astronauts have integrated computing systems in their suits with connections to health-monitoring sensors. Wireless connectivity enables teams of astronauts to perform similar activities in different locations.
- **Multi-modal Interfaces**: Astronauts can communicate with the agent system through the use of naturalistic speech recognition - a list of commands and responses is listed in [7, 8]. The speech interface is also used for creation of science data (i.e. voice notes) as well as for mission management (i.e. request current location) and for commanding other components (i.e. robot take a picture of me). The HabCom monitors agent interactions through a variety GUI monitoring interfaces and may also perform tasks using the human speech-computer interface.

The MAA consists of layers of functionality which enable agents to collect information from local and remote components and devices. Agents reside with particular systems and devices which are part of astronaut space-suits, all-terrain vehicle computers, robotic assistants, biomedical monitors, and mission control operations. Some of these components have fixed geographic locations, i.e. the habitat mission control commander, and others are inherently mobile, i.e. the astronauts performing the planetary transversal. The agent layer provides a common language and decision management for coordinating disparate devices, humans, and robots.

Given the scope of its problem domain, the MAA had further requirements and features which are not commonly addressed in ubiquitous computing projects. These assumptions are further challenged and investigated with each natural experiment during field tests [7, 8] and new considerations and problems which arise provide future research endeavors. These qualitative differences and assumptions are listed below:

- **Hybrid Ubiquity**: The MAA system is a combination of static and mobile components. This allows the propagation of a persistent computational environment which moves with the components which need it the most, e.g. astronauts. At the same time, stationary remote science teams and mission control participate through science data exchange, EVA plan development and execution monitoring. This necessitates the ability of the system to have situational knowledge of static and dynamic components. Furthermore, the expectation is that the EVA teams will operate in environments where there is minimal outside infrastructure to support operations. The only assumption is of a habitat in a fixed location and a localization system (at this point an Earth-based GPS system). Wireless network connectivity is provided from the habitat through the use of repeaters with satellite connection to the internet to communicate with earth-based remote science teams.
- **Heterogeneity of Components**: The MAA system provides a common interface and language for robots, astronauts, remote scientists, HabCom, sensors, and systems to collaborate in the context of their shared work practice information.
- **Persistent Monitoring**: The MAA system provides persistent monitoring of mission progress, astronaut and system health, and provides alerting for potentially dangerous situations. Unlike ubiquitous systems that have strong privacy concerns [15] monitoring is at the heart of the MAA, as the movement, health, and activity of astronauts is persistently tracked. This is necessitated by the context of operating in hazardous environments. Similar monitoring has

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[4] We assumed the existence of a localization service. This is an active area of research outside the scope of this project, for example [13].

been applied to ubiquitous multi-agent location-specific contexts [2].

- **Integrated Data Collection**: The MAA system integrates data from different input devices and pushes them to remote science collectors, enabling the collaboration between local and remote human teams. The systems described in [17] usually deal with a restricted set of data or have multiple collection points which do not integrate the information collected. One of MAA's advantages is to enable the local and remote integration and correlation of mission data from disparate sources. Furthermore, new types of devices can be easily integrated into the system through the use of the Brahms Java Application Programming Interface (JAPI).
- **Expansion through Agent Models**: Additional astronauts and robots can be added to the system with minimal integration work, by replicating the agent models. Unlike traditional multi-agent environments which integrate atomic agents, the MAA integrates agent models, which consist of many agents.
- **Resource Management**: Currently the MAA provides basic monitoring of battery power-levels, health-data, and plan workflow data, which can be used in resource management. At this stage, the assumption is that the EVA mission is performed within the energy constraints of the devices utilized. This assumption, however, is qualitatively different than issues explored in the literature with regards to sensors [4]. The role of agents in resource management has been previously investigated through economic mechanisms [10]. Applying resource allocation mechanisms into is a topic of future research for the MAA.

The ability to collect and integrate information from multiple audiovisual input sources is facilitated through the use of the distributed agent environment which takes advantage of the KaOS architecture [1]. The advantage of using a common language to integrate data and functionality is in allowing the use of basic modeling ideas to deal with semantically dissimilar data. Designing an agent to command the robot is semantically equivalent to designing an agent to create a voice annotation from the speech of an astronaut. It also allows the use of common abstractions for performing particular tasks (i.e. Speech Act Theory for communication using FIPA-compliant protocols). In the next section we describe the components of the agent layer in the MAA focusing on the aspects which are directly handled by the community of agents.

3. The Agent Layer in the MAA

The distributed agent community in the MAA is separated into independent Brahms models running on networked computing devices. Figure 1 shows a schematic of the MAA. Each Brahms model consists of a group of agents in each of the work practice components, i.e. astronaut models, robot models, HabCom models. Each human is supported by its own personal agent in each model. Personal agents perform tasks on behalf of the human or device they represent. Their primary function is to translate commands and responses from the astronauts to the MAA. Human input is facilitated through dialog agents, which translate human speech to Brahms beliefs and vice a versa. Brahms inter-agent communication is facilitated through FIPA-compliant communicative SpeechAct definitions. Brahms agents further interact with software logic on other systems and robots through java-based communication agents. All data recorded during the science mission is kept in belief sets of agents. Data may include biomedical information from the biovest sensors, images from digital cameras, voice notes from the speech system, GPS location from the MEX system, and plan tracking information. The belief information is in effect metadata of actual data and/or images further propagated to applications which handle science data.

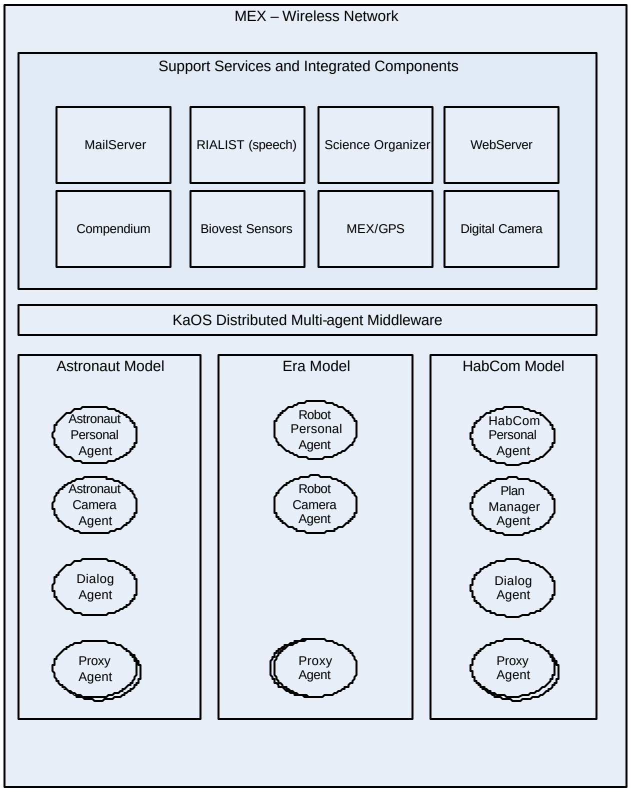

Figure 1: Mobile Agents Architecture

Figure 1 shows a schematic of the mobile agents architecture. There are three types Brahms models, each one running on its own Brahms virtual machine. One model supporting each astronaut exploring, one controlling the EVA Robotic Assistant, and finally a model supporting HabCom and providing mission monitoring, system monitoring, and data management

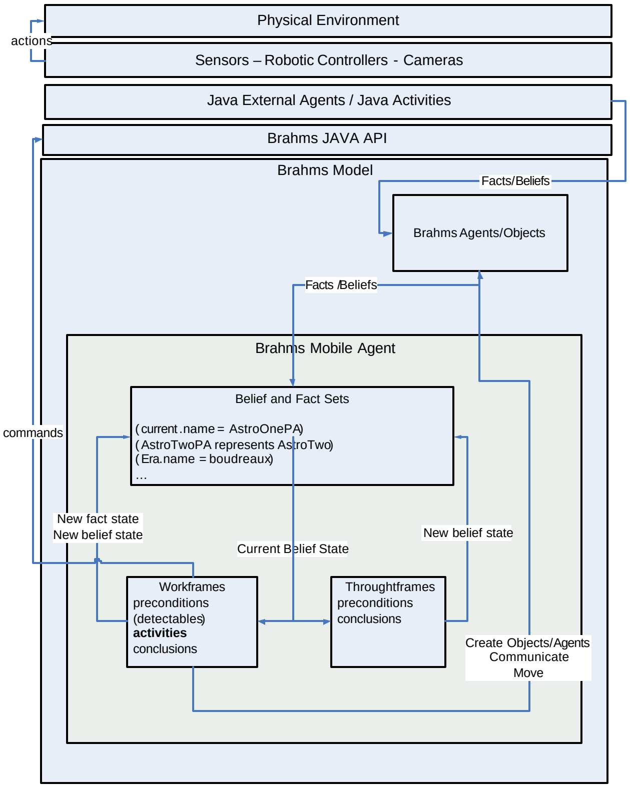

Figure 2: Anatomy of a Brahms Mobile Agent

Brahms agents maintain knowledge of their current state of the world through beliefs and facts[5] Beliefs represent the information that an agent has about its own state, the state of other agents, and the state of the physical environment as perceived through sensors. An agent may receive beliefs from another agent, from sensors, or from making conclusions based on its own beliefs and results of its own actions. The activities that agents are predominately involved in are communication activities. Their purpose is to update other systems, humans, and robots about their own state of the world. They are also used for commanding and subsequent responses. They also create conceptual objects to represent scientific data collected and generate associations between different sources of data and context based on the agent's beliefs. Figure 2 shows the anatomy of a Brahms mobile agent. The agent receives beliefs about the physical environment from sensors which in turn use the Brahms JAPI to insert beliefs into the agent's belief set. The new beliefs maybe preconditions for *workframes* or *throughframes* (production rules) which in turn trigger conclusions about new beliefs and/or trigger activities. In some cases *workframes* are triggered by *detactables* which are activated when a particular fact is inserted into a Brahms model. An agent's activities may generate interaction with other agents and objects within the Brahms model or across models utilizing the KaOS infrastructure. The infrastructure allows for locating and communicating with other agents on separate Brahms virtual machines across a TCP/IP network.

They may also generate a command to sensors, systems, or robots for commanding or retrieving information through Java activities or through a Java Agent who is integrated with such a system.

We further elaborate on the role of agent models in three functional areas of interest: human-robotic collaboration, plan management, science data management.

3.1 Plan Management

Plan and activities are represented graphically using Compendium[6].The mission plan delineates which activities will be performed by whom, their duration, location, and thresholds for deviations from standard operating conditions. The plan is uploaded by plan-monitoring agents, who reside within the astronaut personal agents in their respective models. As such, the personal agents provide monitoring capabilities of the state of the mission and provide appropriate alerts to the local and remote mission participants. The alerts are generated when astronauts fail to progress to activities assigned in the plan.

The agent system keeps track of mission data and reacts to the actual mission progress with respect to plan duration and localization constraints. Hence, personal agents keep track of current mission status. Each activity has attributes which denote the limits of the activity instantiation: time limits and location limits. The personal agents provide alerting services when these limits are exceeded. For example, if the astronaut deviates by more than 10 meters from the direction of transversal, a voice warning will be generated by the personal agent tracking location data.

Personal agents can also modify the starting location and/or duration of an activity as per astronaut command. At the same time they keep track of the new plan activities and provide alerts for deviations. The dynamic configuration of plans is facilitated through local agent commands and remote communications with the HabCom who oversees the mission. Currently, during a mission, all astronauts are involved in the same activity. In future scenarios, we will investigate coordination amongst

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[5] In this exposition we use facts and beliefs interchangeably. See discussion in (Clancey, Sachs, Sierhuis & van Hoof, 1998) for explanation of modeling differences.

[6] For a detailed description of the software and methodology behind compendium visit: http://www.compendiuminstitute.org/.

astronauts who are performing overlapping yet separate activities and how their personal agents can assist such coordination.

Keeping track of mission scientific tasks, health status, and localization is a rather formidable set of activities for astronauts. Alerting astronauts of deviations is monitored by agents who can more easily track GPS data and compute when a deviation has happened. Astronauts are informed about the plan and what activity they should be participating in. They are also informed about the expected duration of each activity and get warnings when an activity's projected duration is over. Monitoring the plan is critical given the limited life-support and energy resources available and radiation exposure limits. Plan parameters, such as activity location and duration, can be changed dynamically through the agent layer therefore allowing for the distribution of new plans.

3.2 Science Data Management

The primary objective of all planetary exploration missions is the collection of scientific data. Given the high levels of radiation exposure, astronauts need to be rotated for EVA missions. This necessitates maximizing the scientific data collection during EVAs. The agent system performs science data management including tracking separate sources of information and data files as well as generating associations between them. These data is communicated to the science organizer and remote science teams enabling them to evaluate the science data collected as the EVA is being performed. The data collection and handling is completely transparent to the astronaut performing the EVA. The science data collection requirements include the capture of images of geologically important locations and artifacts, voice-annotations, localization of activities and science data collection, and sample-bag creation and tracking.

The personal agents communicate with remote science team agents whose purpose is to populate a science database shared with the Remote Science Team. The Remote Science Team is comprised of scientists who analyze the results of the EVA. The information is stored in the science organizer, a knowledge management database system for scientific data management. The purpose of having the agents deal with the repeated task for generating, keeping track, and associating science data, has to do with the principle of maximizing astronaut science activity time. Had the astronaut have to do all the aforementioned tasks for every science observation, then the length and mass of data collected would be less. At the same time, the agents provide the necessary communication with the RST, who may also make requests with regards to the science data collection. In that instance, the astronauts may serve as an extension of the RST on to exploration site. This is facilitated through the agent layer which permits remote interaction.

3.3 Mission Data Management

There are different levels of mission data that are kept track of using the multi-agent environment. At each location that an astronaut is, she can give a voice command to its own personal agent who in turn creates objects in the multi-agent system and populate the object with the object's meta data.

Agents monitor the state of the wireless network, the GPS tracking status, the battery levels and issue alerts when needed. These are monitored by the personal agents of the astronauts who are responsible for keeping track of vital systems for the astronaut they represent. Thresholds for maximum and minimum readings are integrated into the logic of the agents, who in turn generate alerts when the GPS tracking goes down, when a command has not been responded for a long time, when the heart-rate or respiration rate of the astronaut is too high, or when batteries are critical. These warnings are critical both for safety and for re-planning given changing environmental and system conditions.

The purpose of pushing mission data management tasks to agents stems from the complexity of tasks that astronauts on EVA are entailed in. It would be cognitively taxing for an astronaut to monitor her health status, battery levels of her computers and perform all mission related work. Since safety is the primary concern with missions, having the agents provide remote information to the mission control at the habitat, further allows remote and local monitoring for critical information. Off-loading these tasks to automated agents brings issues of when and how to provide information regarding health and system status. We expect future field tests to provide us answers to these questions.

4. Conclusions

We have presented the mobile agents architecture as one which integrates many ubiquitous computing and multi-agent approaches into a system which deals with the challenges of planetary exploration. The agent layer of the MAA provides a way for integrating human activity and monitoring devices with data and workflow management systems in an effort to off-loading tasks from human participants. Agents collect, associate, and distribute mission and science data, and manage the mission plan. In order to achieve this, the MAA makes use of different ubiquitous computing technologies and ideas, which are integrated together. The integration of these different research approaches allows Mobile Agents to investigate their interaction through an iterative work-practice analysis approach, with field tests being an integral part of it. This approach resonates with ideas voiced in the ubiquitous computing literature [14] of naturalistic experiments. Requirements collected during the last

MDRS field test (April 2004) are forming the basis for the improvement of the current MAA. Extensions, including autonomous robotic collaboration and human-robotic teamwork models are integrated into the new architecture to be field tested in April 2005.

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