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Collaborative Systems for NASA Science, Engineering, and Mission Operations

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ABSTRACT

We describe a set of ten collaborative systems projects developed at NASA Ames Research Center over the past ten years. Our goal is to design new information technologies and collaboration tools that facilitate the process by which NASA engineers, scientists, and mission personnel collaborate in their unique work settings. We employ information management, artificial intelligence, and participatory design practices to build systems that are highly usable, augment human cognition, and support distributed NASA teams. NASA settings and applications serve as valuable testbeds for studying collaboration and developing new collaborative technologies.

KEYWORDS: collaborative systems, space mission operations support, intelligent agents, human-robot collaboration, scientific discourse, virtual teams

1. INTRODUCTION

This brief overview summarizes a set of ten collaborative systems projects developed at NASA Ames Research Center over the past ten years[1]. As NASA missions become longer and more scientifically complex, support for cooperation among geographically distributed, collaborating teams – on and off earth – will become ever more crucial. With increasing deployment of intelligent software and hardware, we must address the challenge of mediating collaboration between human teams and a wide array of automated systems. Our goal is to design new information technologies and collaboration tools that facilitate the process by which NASA engineers, scientists, and mission personnel collaborate in their unique work settings. We employ information management, artificial intelligence, and participatory design practices to build systems that are highly usable, augment human cognition, and support distributed NASA teams.

The thumbnail system sketches described in the following sections span collaboration across a wide range of NASA science, engineering, and operations teams. Science teams direct scientific research and analyze data generated from a variety of sources: from earth-based field work and exploration field tests; from earth-observing satellites; from experiments on the International Space Station; and from planetary spacecraft instruments. Mission operations teams launch, monitor, and control these space systems, and engineering teams design, diagnose, and maintain them. Understanding the collaboration needs of these teams, and building real-world mission-critical systems to support them is challenging but rewarding work. NASA settings serve as valuable testbeds for studying collaboration and developing new collaborative technologies for the future.

2. SEMANTIC ORGANIZER

Point of Contact: Richard M. Keller
References: [1-4]
Web: http://sciencedesk.arc.nasa.gov/

SemanticOrganizer [1] is a collaborative knowledge management system designed to support the information-sharing needs of distributed NASA project teams, including multidisciplinary teams of scientists, engineers, and mission operations personnel. At its core, SemanticOrganizer consists of a customizable,

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[1] While this set of collaborative systems projects is by no means exhaustive, it is a reasonable sampling of work being performed at NASA R&D facilities.

semantically-structured information repository that stores, integrates, and interrelates heterogeneous information products generated by collaborating teams during their normal work processes. The repository also serves as a collection point for information generated by hardware or software systems used by team members in performing their work. Sample work products include engineering design diagrams, electron microscope images, software requirements, sensor data, research papers, audio notes, and many other products. Users access the repository via a standard web browser. In contrast with traditional hierarchically-structured repositories, SemanticOrganizer utilizes an intuitive knowledge network structure that captures relationships among stored information products. This structure facilitates rapid retrieval of information using familiar work concepts and a custom-designed vocabulary that is designed for the collaborating team.

SemanticOrganizer has been applied in two primary domains. ScienceOrganizer [1, 2, 4] is a science-themed application of SemanticOrganizer that was developed in collaboration with distributed science teams in the NASA Astrobiology Institute. These teams needed to organize and maintain a large body of data accumulated during their fieldwork and subsequent laboratory experimentation. ScienceOragnizer was also applied to support the Mobile Agents field science operations team (see Section 4), where it served as the science data repository for information relayed from astronaut-explorers and intelligent agents in the field [4]. InvestigationOrganizer [1, 3] is an engineering-themed application of SemanticOrganizer and was developed in partnership with NASA engineers and mission assurance personnel to support the work of distributed NASA mishap investigation teams, most notably the Shuttle Columbia and CONTOUR accident investigations.

3. HYPOTHESIS BROWSER

Point of Contact: Richard M. Keller
References: [5]
Web: http://mason.arc.nasa.gov/hypothesis-browser/

The Hypothesis Browser [5] is a novel internet resource being developed to promote dissemination of scientific information, facilitate scientific discourse, and encourage interdisciplinary collaboration. Scientists use a structured, wiki-like community forum to discuss, debate, and examine the current scientific concerns in a given area. Scientists contribute research questions and hypotheses, along with supporting and refuting evidence and documentary citations from the literature; scientists and the public can search and browse the information. The intent is to create a vibrant community where scientists and advanced students dialog about the key questions in their field.

Aside from functioning as a scientific community “watering hole,” Hypothesis Browser serves as a repository of scientific literature citations. But instead of being conventionally organized by keyword or subject, research papers citations are organized based on the hypotheses that they support or contradict. Users can view full citations to papers, export citations to their databases, and explore evidence and hypotheses relevant to papers.

The initial version of Hypothesis Browser is being tested in the field of astrobiology. This discipline is well suited for this purpose, as it is inherently interdisciplinary and strongly driven by hypotheses that are often the subject of intense scientific debate. The browser can be readily extended to other scientific disciplines and has potential to become a valuable educational resource that encourages students to think critically and learn to formulate and test hypotheses rather than accumulate isolated facts.

4. MOBILE AGENTS

Point of Contact: William J. Clancey
References: [6-9]
Web: http://ti.arc.nasa.gov/tech/cas/work-systems-design-evaluation/mobile-agents/

The time-delay of communications with Mars explorers will preclude having the relatively immediate, direct collaboration support that was provided by the CapCom communications officer during the Apollo missions. The CapCon served as the intermediary through which all voice communication was transmitted between the space-based crew and the ground-based mission control personnel. In the Mobile Agents project, we sought to automate the routine information communication functions of CapCom using intelligent agents, while supporting enhanced situation awareness for support personnel on Earth and collaboration with “backroom” scientists. To pursue this approach, various Mars and Moon "analog" sites on Earth have been the location of simulated planetary exploration activities conducted by the Mobile Agents project. These sites include the Mars Desert Research Station near Hanksville, UT; the Kilauea, HI volcanic shield; and Devon Island in the Canadian arctic. At these analog sites, simulated off-Earth EVAs (Extra-Vehicular Activities) are performed involving humans playing the role of astronaut-explorers who are doing actual field science, assisted by robots and software agents [7]. Research activities conducted during these simulations includes studies of the process of scientific collaboration, activity planning, sharing and review of collected scientific data, and the design and development of computer-based tools to support these processes [9].

The Mobile Agents system is a key component of this research on the nature of scientific exploration. Mobile Agents is a distributed, multiple-agent system in which the agents are software programs written in the Brahms activity-based language [6]. The agents contain and are linked by models that make "intelligent" operation possible. The agents are "mobile" because they are on movable platforms (spacesuit backpacks, all-terrain vehicles, robots). They enable workflow automation and interoperability of arbitrary hardware and software systems used during EVAs [8]. The agents facilitate collaboration among the humans, hardware, and software systems. (Also see related work described in Sections 2 and 6.)

5. THE OCA MANAGEMENT SYSTEM (OCAMS)

Point of Contact: William J. Clancey
References: [10, 11]
Web: http://ti.arc.nasa.gov/tech/cas/work-systems-design-evaluation/ocams/

Operations onboard the International Space Station (ISS) are supported by dozens of specialists on Earth who continuously update astronaut work plans and provide technical instructions or specifications for operating equipment and running a wide variety of experiments. Ground support personnel also forward the crew’s email, news, and entertainment media. The ISS crew transmits data from experiments, including many photographs, medical data such as exercise performance, email, etc. This data is all exchanged as computer files, which have until recently been transmitted manually by a “switchboard” operator in Mission Control at NASA Johnson Space Center (JSC) in Houston, TX. The Orbital Communications Adapter Management System (OCAMS) has been developed to automate all of the routine work previously performed by this 24/7 position [10, 11], thereby facilitating effective collaboration between the ISS crew and operations staff on Earth.

OCAMS is the first application of multi-agent systems integration technology in NASA’s mission operations. It automates and coordinates workflow by applying a library of file operation procedures, which are either scheduled or requested on demand by support specialists via a flight note system. OCAMS thus acts to coordinate all file exchanges between the ISS crew/computers and ground support. It reads and validates flight note requests and awaits approval from the Flight Director for protected operations. OCAMS then interacts with a special FTP program for uplinking, downlinking, deleting, moving, copying, and renaming files, as well as running script files onboard ISS computers. OCAMS delivers files to ground personnel and notifies them via email and/or flight note about the status of completed operations. OCAMS automatically logs all operations in the format conventionally used by ground personnel.

One of the collaboration challenges addressed by OCAMS is the scheduling and prioritization of information flow between the ground and ISS. Windows of communication with ISS are limited due to the inability of ground-based tracking relay stations to receive signals at various points in the ISS orbit. OCAMS sequences information flow within these windows based on time deadlines and priorities established by requestors of the information transfer.

Incremental versions of OCAMS have been deployed and used since July 2008, with completion in spring 2011. The team of researchers and software engineers from NASA Ames Research Center and flight controllers from NASA Johnson Space Center received JSC’s Exceptional Software Award in June 2010.

6. EXPLORATION GROUND DATA SYSTEM (XGDS)

Point of Contact: Matthew C. Deans
References: [12]
Web: http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/

The Exploration Ground Data System (xGDS) [12] is a flexible and agile platform for ground data systems to enable lightweight and cost effective support for analog missions, as well as a research testbed for ground data systems prototype tools and concepts. The Intelligent Robotics Group at NASA Ames Research Center conducts robotic field tests each year in planetary analog sites on earth – frequently in extreme environments, including the Canadian Arctic and the Arizona dessert. During these field tests, robotic software and hardware conduct operations to simulate exploration on remote planets. The tests are run as simulated missions, with collaborating teams of mission operations and science personnel performing ground control functions. (Also see related work in Section 4.)

Simulated lunar or cis-lunar missions operate on much faster time scales than the Mars Exploration Rover mission or other deep space missions. Operators and scientists are required to maintain real time situational awareness, quickly assimilate information from the spacecraft or crew, and plan or replan activities on the fly. xGDS enables scientists and operators to work together to create and modify plans dynamically based on up-to-the-moment information, to track location, status, and progress of robots and crews against plans, and to visualize new data products as soon as they are captured, thereby maximizing efficiency in the field test.

xGDS provides software for interacting with mission data during robotic field tests, and includes tools that enable scientists to work together effectively, create robot or crew vehicle plans, visualize the operating environment and vehicle telemetry, understand what is being accomplished during and after plan execution, and search and explore data. xGDS is built on several open source packages, including the Apache web server, the MySQL database, the Django web framework for Python, and the jQuery JavaScript library.

7. COLLABORATIVE INFORMATION PORTAL (CIP)

Point of Contact: Joan C. Differding
References: [13, 14]

From 2001 to 2003, NASA developed the Collaborative Information Portal (CIP) [13] to address the data access, time management, collaboration, and workflow requirements of the upcoming 2003 Mars Exploration Rover (MER) mission. In mid-2003, the two rovers, Spirit and Opportunity, were launched and subsequently arrived at Mars in January 2004 after their seven–month journey from Earth. NASA scientists designed these twin robotic geologists to search for evidence of liquid water in the past on the Martian surface. In 2011, the MER mission is still ongoing – well beyond its expected 3-month mission timeframe – with one rover still functioning and the other presently silent, in an unknown state of operations. Today, the mission operations team still manages the mission and sends commands to the rovers; the science team analyzes the downloaded data and images.

Starting with the rover landings in 2004, and continuing through mid-2010, mission personnel used the Collaborative Information Portal (CIP) to help them perform their daily tasks – whether they were working inside MER Mission Control, in the science support areas at the Jet Propulsion Laboratory, in their homes, schools, or offices. In particular, CIP enabled the mission operations team to view and manage schedules, download data and image files generated by the rovers, display clocks and timers, and send and receive broadcast messages. These are essential functions required to support mission operations team.

One of the specific collaboration challenges addressed by CIP was the coordination of activities across separate, but collaborating mission operations teams. Each rover was controlled by a separate operations team, but certain personnel were shared across these teams. For mission operations staff, keeping track of activities and responsibilities – both within teams and across teams – was a difficult coordination and collaboration task. To make things even more challenging, in the early days of the mission, most team members worked on Mars time, rather than on Earth time. (A “sol” is a Martian day, which is nearly 40 minutes longer than an Earth day.) On Earth, members of the team were located in different time zones; on Mars, each rover was in its own Martian time zone. Furthermore, each person may have had different operations roles at different times of the day. Keeping mission support personnel on schedule by providing an awareness of time was a key function of CIP. This coordination function was achieved through a combination of tools that displayed staffing and event schedules, provided event countdown clocks, and converted between Mars and Earth time zones. All the tools supported presenting time in user selectable time zones. So for example, a user could show clocks in any Earth or Mars time zone, and the schedule viewer could display any individual time zone or a combination of multiple zones in the schedule depiction.

8. NASA ASTROBIOLOGY INSTITUTE (NAI) / NASA LUNAR SCIENCE INSTITUTE (NLSI)

Point of Contact: Estelle Dodson
References: [15]
Web: http://astrobiology.nasa.gov/nai
http://lunarscience.arc.nasa.gov

The NASA Astrobiology Institute (NAI) and the NASA Lunar Science Institute (NLSI) are two "virtual" institutes managed by NASA Ames Research Center in the Silicon Valley. NAI's charter is to explore the origins and nature of life in the universe including life on Earth; NLSI's goal is to facilitate scientific exploration of the Moon and provide support for the associated research community. These virtual institutes comprise teams distributed across the country that are engaged in coordinated investigations with researchers located at hundreds of universities and organizations. Spanning a period that saw the birth of Web 2.0 and the current explosive growth of social networking tools such as Facebook and Twitter, these two NASA institutes have a broad perspective on building and running collaborative communities.

This poster overviews the collaborative infrastructure of these virtual institutes and shares what has been learned over ten years in building and connecting distributed scientific communities. It is not sufficient to make collaboration technology available to members, successful collaboration requires relationship building, training, continuity, and many other organizational and human factors. To successfully build the community and its supporting technologies, the institutes thoroughly assess user needs and employ this information to evaluate technology choices. Combined with carefully designed implementation planning, our goal is to allow optimal access across organizations and their firewalls. By leveraging training resources, modeling culture change, and facilitating community-wide debugging and tightly coupled feedback loops between users and developers, we are creating simple and reliable collaborative environments.

9. COLLABORATIVE DECISION ENVIRONMENT (CDE)

Point of Contact: Francis Y. Enomoto
References: [16]
Web:
http://ti.arc.nasa.gov/tech/cas/information-sharing-integration/cde/
http://www.nasa.gov/centers/dryden/research/wsfm.html

The Western States Fire Mission (WSFM) is demonstrating improved wildfire imaging and mapping capabilities resulting from the use of sophisticated imaging sensors and real-time data communications equipment developed at NASA Ames Research Center. The Collaborative Decision Environment (CDE) [16] is a collaborative decision support system designed for wildfire disaster managers participating in WSFM. CDE supports distributed wildfire mission planning, situational awareness, and visualization of fire data streamed from an unmanned aircraft surveying an active fire site.

CDE allows integrated, web-enabled data sources and fire-related geospatial information sets to be collaboratively viewed and manipulated. Fire incident command teams are provided access to the CDE data ‘mash-up’ service during wildfire emergencies. A wide variety of information is available through CDE, including real-time weather information (and associated pertinent datasets), satellite-derived fire 'hot-spot' detections, wildfire observational aircraft tracking information, real-time imagery feeds, and information related to FAA airspace. CDE provides the common operating picture in which WSFM and incident command teams collaborate on prioritizing remote sensing requests.

CDE uses the Google Earth geospatial freeware package for visualization of integrated wildfire data, but also includes QuickTime video streaming from the aircraft and Jabber instant messaging for group collaboration. The aircraft imaging sensor is capable of peering through thick smoke and haze to record hot spots and the progression of wildfires over a lengthy period. Data is downlinked in near real-time, overlaid on Google Earth maps, and made available to fire incident commanders to assist them in allocating their firefighting resources.

Some of the early challenges encountered in developing CDE were the lack of network connectivity and limited bandwidth in remote areas where wildfires typically occur. These limitations have lessened in recent years with expanding 3G cellular networks, more regular use of portable satellite communications, and modern bandwidth optimization techniques. Apart from these technical challenges, CDE’s introduction created cultural challenges within the firefighting community. The availability of real-time mission data impacted existing fire incident management processes and precipitated changes in the pace of collaboration within firefighting teams.

Use of CDE to share real-time wildfire data during the widespread California wildfires in 2007 and 2008 was found to improve situational awareness and coordination between state and federal fire incident managers.

10. MERBOARD

Point of Contact: Jay P. Trimble
References: [17]
Web:
http://ti.arc.nasa.gov/tech/cas/user-centered-technologies/

The MERBoard platform [17] was developed specifically to help science and operations teams perform surface operations planning activities during NASA’s Mars Exploration Rover (MER) mission. (See Section 7.) A MERBoard Collaborative Workspace consists of several distributed, large, touch-enabled, plasma display systems loaded with custom MERBoard software. The display panels are networked together to share information among panels and with key MER data servers.

During the mission, MER surface operations planning teams could gather around the board to retrieve, view, share and annotate mission data and rover images. The board provided an immersive work environment while its touchscreen literally put information at the team members' fingertips, enabling a user to drag and drop data to a personal or group icon. Any data on the screen could be captured and annotated on MERBoard's whiteboard, and new content could be created dynamically on the whiteboard. One MERBoard panel could provide a view of what was happening on another, enabling collaboration from one board to another. A personal computer also could be displayed or controlled from a MERBoard at the touch of a button, and data transferred to and from the MERBoard and personal computers.

One of the key requirements motivating the design of MERBoard was the need to display, distribute, and share information generated as a by-product of real time scientific collaborations. To enable shift-handovers for members of the MER science team, this information had to be saved for subsequent recall and redisplay. Ubiquitous, fluid access to information from anywhere in the sprawling physical space occupied by the science team was another driver behind MERBoard's 'view anywhere' functionality.

11. CENTER FOR COLLABORATIVE SCIENCE AND APPLICATIONS (CCSA)

Point of Contact: Michael Sims
Web: http://www.cmu.edu/silicon-valley/ccsa

Humans are only able to build large modern engineering systems, such as radio telescopes and nuclear reactors, by collaborating across space and time. We need the geniuses of Maxwell and Newton and the labor of miners and technicians to accomplish them. But our proposed future human spaceflight endeavors are among the most complex tasks in which humanity has ever engaged. In a broad spectrum of arenas, we need to find better ways to accomplish these complex tasks via collaborative activities. Examples of these collaborative activities include team design of space missions, open sourcing of mission data products, and peer and crowd processing of complex engineering tasks. A significant problem in achieving these activities within a collaborative team is to represent and share extremely complex design and development environments in a way that is comprehensive, robust, easily manageable, and dynamically responsive to the changes in the process.

To address these challenges, the Center for Collaboration Sciences and Applications (CCSA) was formed in 2010 as a partnership between NASA Ames Research Center, Carnegie Mellon University Silicon Valley, and Lockheed Martin to share valuable knowledge and experience about the art and science of collaboration, and to study collaboration from a holistic perspective.

CCSA has established the following goals:

- Serve as a multidisciplinary Center of excellence in pioneering collaboration studies
- Provide state of the art expertise and recommendations to projects, missions and teams doing collaborative work
- Create, evaluate and implement collaborative systems, social protocols, and procedures
- Provide open environments for the investigation and application of collaborative technologies

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