COOPERATING INTELLIGENT SYSTEMS FOR SPACE MISSION SUPPORT

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ABSTRACT

Ford Aerospace Corporation has been investigating the use of intelligent systems for space mission support since the early 1980s. Our research is motivated by the concept of independent, yet cooperating, intelligent systems operating in the survivable mobile ground stations of the future. Each intelligent system (IS) functions independently for localized situations and cooperates with other ISs to address situations of global system influence.

This paper describes our research approach for implementing cooperating intelligent systems in a space systems environment. A satellite power management scenario is used to illustrate the approach.

INTRODUCTION

Various space related research projects have demonstrated feasibility for using machine intelligence to perform selected space operation functions. The resulting capabilities of machine intelligence, however, are currently limited to narrowly focused problem domains with little or no integration of the independent intelligent systems into a cooperating distributed network. There exists a need within NASA and the DoD for integrated intelligent control systems to enhance the effectiveness and responsiveness of future space missions and reduce the cost of operations and maintenance.

Ford Aerospace Corporation has been investigating the use of intelligent systems for space mission support since the early 1980s. One important focus in our research is centered in the field of Distributed Artificial Intelligence (DAI), specifically, cooperating intelligent systems. Our overall objective is to develop and extend software technology so the degree of automated support for space mission operations would allow significantly reduced numbers of people to operate a constellation of satellites. It currently requires, depending upon the constellation size, at least six to as many as fifty people to perform the functions of spacecraft health and status (H&S), ground station H&S, payload(s) data analysis and H&S, constellation control, communication network control and mission planning. Figure 1 displays a possible future space mission configuration where a reduced number of people in a mobile environment must perform the functions currently performed by teams of people.

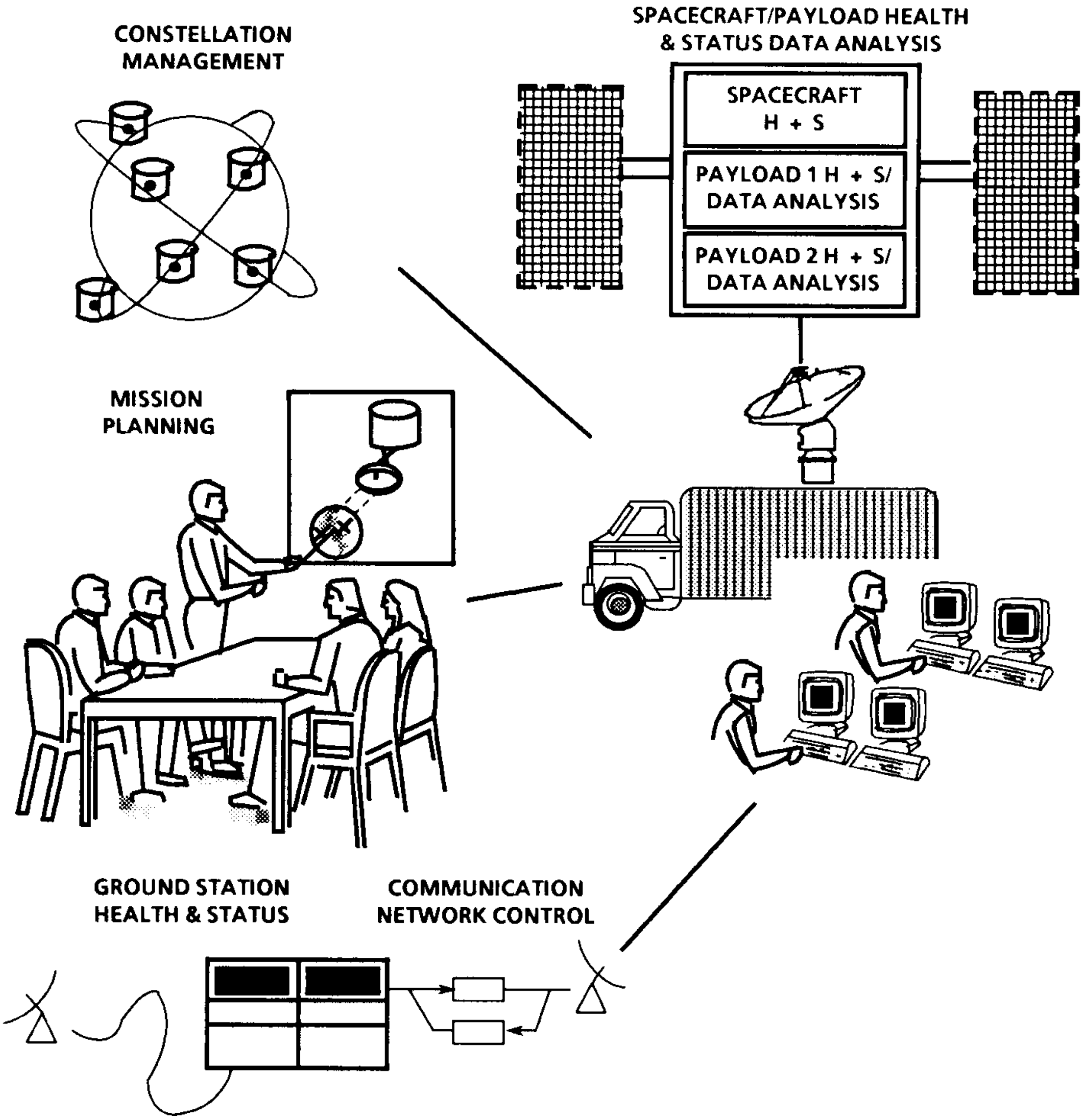

Figure 1. Future space missions will require a reduced number of operators to handle all functions currently performed by teams.

This paper presents our research approach for implementing cooperating intelligent systems in a space systems environment. A satellite power management scenario is used to illustrate the approach. A satellite is considered a spacecraft together with its payload(s). A spacecraft is the bus which supports the payload(s) by supplying power, attitude control, etc. A payload is the system that accomplishes the mission function, such as earth surveillance, weather determination, etc.

DISTRIBUTION IN SPACE MISSION SUPPORT

The satellite operations world consists of a set of loosely-coupled, lateral activities. Expertise and authority is dispersed across many functions with no centralized person or team of people having all knowledge about, or control of, the system. Operations are organized functionally with separate teams of people exercising expertise and authority over designated portions of the domain. Part of each team's responsibility is to cooperate with the other teams to achieve a successful mission. Through cooperation, each team makes decisions and performs actions within its own domain of influence with knowledge about the impacts and benefits to the systems as a whole.

As intelligent systems begin to replace humans in the performance of space mission functions, the need for cooperation does not disappear. The intelligent systems will also need to make decisions and perform actions with knowledge about the impacts and benefits to the other intelligent systems that are elements of a whole.

UNCERTAINTY IN SPACE MISSION SUPPORT

Another important characteristic of the satellite operations world is the presence of uncertainty, uncertainty being defined as the difference between the knowledge available about the state of the world and the knowledge necessary to make a good decision(1). One source of uncertainty is that satellites can be out of contact with ground stations for long periods of time. During these periods, the state of the satellite is unknown. Even when satellites are in view, the information (telemetry) they relay to the ground is incomplete; or, in other words, not all information the analysts on the ground need to know is observable. This is due to the prohibitive cost of telemetry instrumentation. Another source of uncertainty is the behavior of new equipment and sensors in space which, in many cases, is difficult to capture or predict without operations experience. In addition, there is uncertainty associated with the behavior fluctuations of (space-based) equipment over time. Yet another source of uncertainty is the space environment itself. There are phenomena in space that are still unknown and even the known phenomena are not always predictable or controllable, such as solar flares which impact electronic equipment. To summarize, incomplete knowledge about the world is the norm for space mission operations.

DISTRIBUTED ARTIFICIAL INTELLIGENCE CONCERNS

The field of Distributed Artificial Intelligence (DAI) has considerable influence on our development of a system that can address the satellite operations environment. DAI is concerned with the cooperative solution of problems by a decentralized and loosely coupled collection of agents(4). A few of the exemplary systems to date are the Contract Net, Actors and Open Systems, and the Distributed Vehicle Monitoring Testbed (DVMT)(1,4,5).

The Contract Net, by Davis and Smith, is a collection of agents that cooperate through negotiation to perform a given task. The negotiation, governed by a strict protocol, is based on task announcement, bid and contract award to achieve its goals. The Contract Net approach is not appropriate for our application since problems are organized within a strict hierarchical decomposition and novel situations cannot be addressed. Also, there is no provision for global considerations in the resolution of problems, nor a mechanism for the reassignment of tasks in the event of failure.

The Actors and Open Systems approaches can be viewed as a pattern of messages passing among a collection of low-level computational agents. This approach is not applicable since the satellite domain effectively cannot be reduced to a network of fine-grained computational nodes.

The DVMT consists of complex, identically structured problem-solving agents with each agent responsible for a region of the entire domain(6). As part of the DVMT's sophisticated local control capability, each agent obtains a view of the entire system by having a high-level representation of the domain and problem-solving capabilities of the system's agents. This allows each node to understand the context of its responsibilities and roles with respect to the entire system. Also, the DVMT approach inherently allows for the incorporation of emerging technologies.

An important research area to our continued progress is developing an adequate organizational structure. The organizational structure contains the functional IS components, their roles and responsibilities and the resources that are available to each(7).

MODEL-BASED INTELLIGENT SYSTEMS

In our early research (early 1980s), we applied rule-based systems to problems within the space mission support domain. We found that rule-bases were difficult to manage, maintain, verify and validate, and limited the use of generic processing(3). In addition, we found that rule bases were inadequate for novel problem situations. Our research then began the transition from rule-based technology to model-based technology. In the process, we began developing our own model-based environment since we were not satisfied with existing tools. This environment, called Paragon, is developing and evolving today and has become central to our research in intelligent systems for space mission support.

Paragon allows developers to create in-depth models of problem domains and the reasoning processes for reasoning about the models and the associated domain activity. For distributed applications, where systems must cooperate to perform their functions, reasoning processes for cooperation are necessary; and, in addition, knowledge about the roles and responsibilities of each IS in the distributed network is necessary for supporting this cooperation. The reasoning processes include data monitoring, situation assessment, planning, causal reasoning, constraint propagation, dealing with uncertainty, hypothesis generation and more. A complete discussion of the reasoning is beyond the scope of this paper.

PROBLEM SOLVING IN THE SPACE MISSION SUPPORT ENVIRONMENT

For space mission support, we have selected a decentralized approach over centralized decision making. We feel this approach is a natural fit with the domain characteristics. One significant advantage for decentralization is the reduction of the communication and computation bottleneck created by having centralized decision making. Also, decentralization addresses the issue of survivability, allowing the system, as a whole, to experience graceful degradation rather than catastrophic failure when one or more elements fail. Each intelligent system within the larger space mission support system is an independent entity with full capabilities and authority to deal with situations within its own domain of influence.

In addition, the ISs must be able to recognize when situations require joint IS cooperation; where the intelligent systems work together, each performing problem-solving activities within its domain of influence with knowledge about the impacts and benefits it has on other IS domains. Each IS must not take action (or advise a satellite operator to take action) that can cause harm to some other element in the system unless all elements (ISs) determine that the action is necessary from an overall system perspective. Each IS contains knowledge of the domain, the roles, and the responsibilities of the other ISs as parts of a whole system. This allows each IS to determine when sharing information, goals, and plans with other ISs is necessary and desirable.

“Problem solving” within the satellite operations world is a phrase that is too easily associated solely with anomaly resolution. This is actually a narrow view of problem solving. While anomalies (unexpected equipment failures, degradations, behaviors, etc.) can and do occur in both ground-based and space-based equipment, problem solving actually occurs across a larger spectrum of satellite operations. Dealing with normal system maintenance during the course of operations can be problematic and sometimes requires complex planning. Also, planning a test to verify a certain satellite performance capability can be a complex task.

Problem solving during an anomaly is actually problems solving. In particular, it is very rare for only one system problem to result when a satellite component failure occurs. Usually, many system problems result. This is illustrated later in a space mission scenario.

PROBLEM-SOLVING ARCHITECTURE FOR SPACE MISSION SUPPORT

A problem-solving architecture for space mission support must be able to elaborate a description of the problem(s) where the context of the problem(s) can be referred to in the follow-on, problem-solving process(2). But first, an assessment must be made to determine if a problem(s) situation exists. Once a problem(s) situation exists, the architecture must support determining goals to deal with the existing problems and creating plans that are consistent with the goals. The problems, goals, and plans must be constructed with the dynamic context of the domain’s problem(s) situation. As the domain’s problem(s) situation evolves, goals and plans can be appropriately refined.

Figure 2 displays the Space Mission Support problem-solving architecture. The large “K” represents the knowledge of each IS (domain, reasoning, roles, and responsibilities of itself and the other ISs). The problem-solving processes are problems construction, goals construction, plans construction, and plans execution. Sharing during (global) problem solving occurs in all four problem-solving processes between ISs and is represented by the dotted lines. The questions presented in the left column are intended to provide an understanding of each process and the issues it must address. The processes operate concurrently while problem solving evolves and the intelligent systems converge to problem(s) solution. Figure 3 is a snapshot of the problem-solving process, with plans construction as the example. Each IS develops local plans from its local goals and knowledge and, through exchanging information, goals, and plans, is able to produce coherent, local plans that are globally sound.

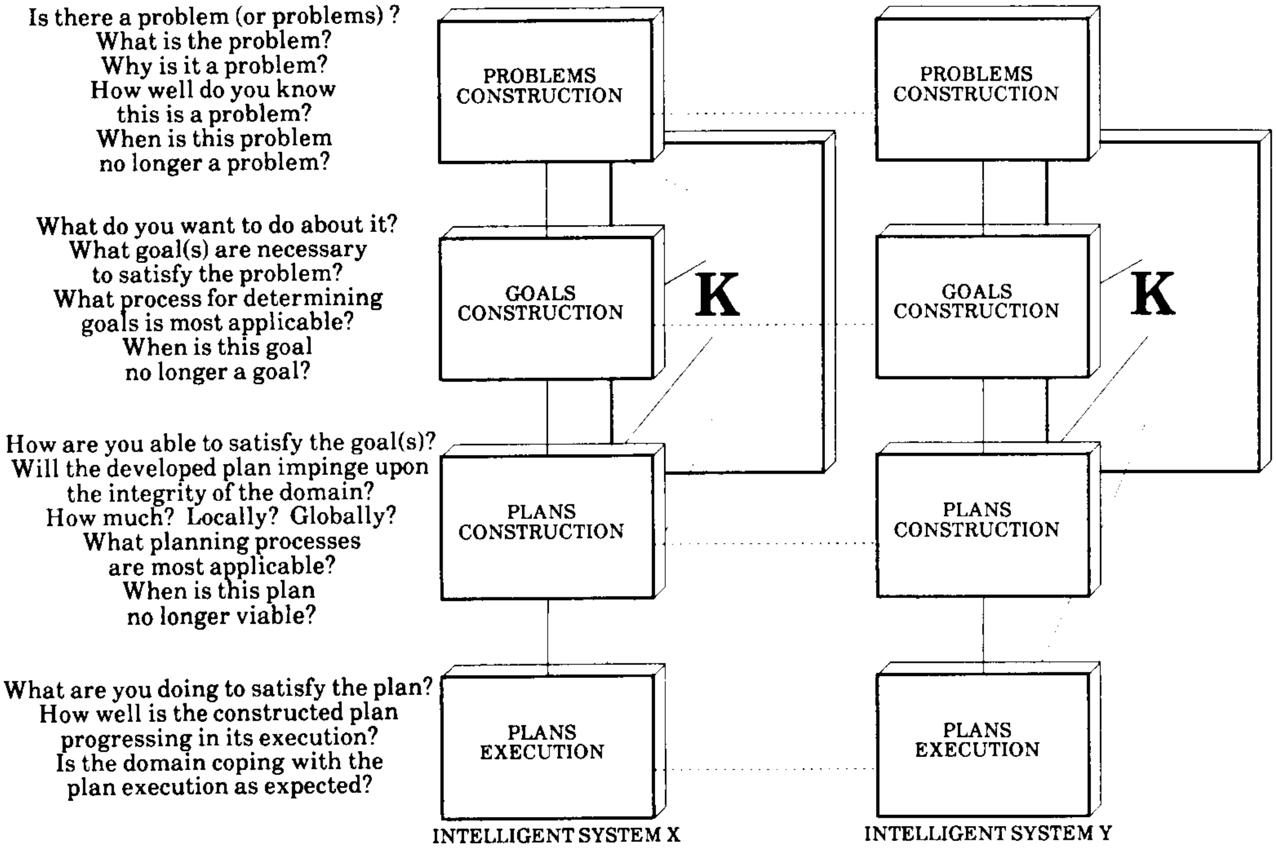

Figure 2. Space Mission Support problem-solving architecture.

SPACE MISSION SCENARIO

To illustrate the problem-solving architecture, we have chosen a power management scenario. The scenario involves three intelligent systems cooperating to solve several system problems that result from a satellite component failure. The sun sensor on one of the satellite's solar wings fails so that the wing is no longer able to track the sun and produce maximum power. The three ISs involved are 1) spacecraft H&S, 2) surveillance payload H&S and data analysis, and 3) mission planning. Each intelligent system is responsible for maintaining local and global system functionality within its domain of influence. For example, the spacecraft IS is responsible for maintaining the spacecraft's state of health during all aspects of mission operations. The payload IS is responsible for maintaining payload state of health, proper calibration, and correct data processing during mission operations. The mission planning IS is responsible for maintaining mission objectives, capabilities, and plans for mission operations.

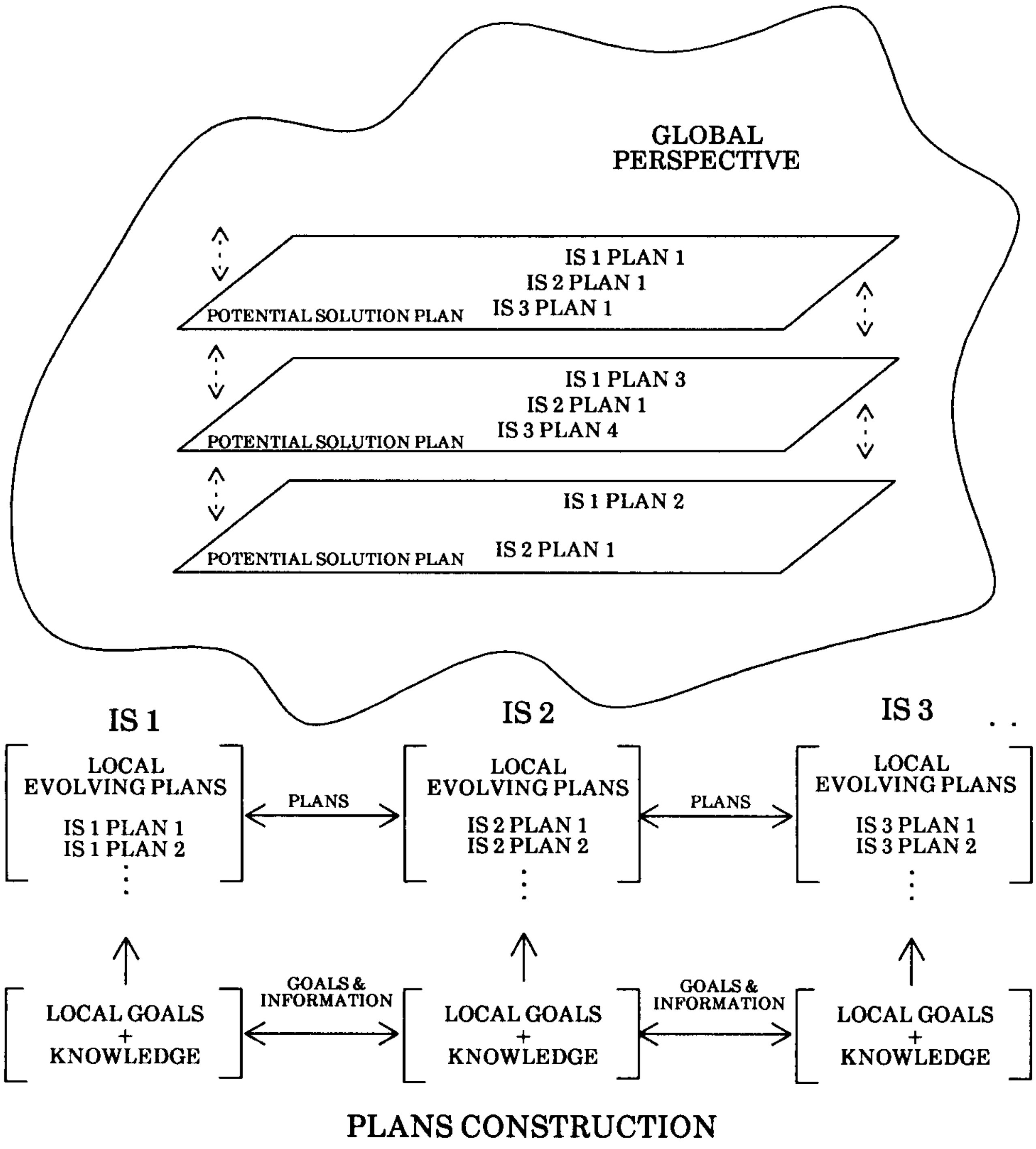

Figure 3. **Local and global perspectives during problem solving evolve dynamically as the Intelligent Systems (ISs) converge to the most acceptable plans through cooperation.**

The scenario begins with Satellite 1 having been out of contact with the ground station for a couple of hours. Satellite 1 is contacted and its telemetry exhibits anomalous Electrical Power Subsystem (EPS) behavior (due to the failed sun sensor which occurred when the satellite was not in contact with the ground station). The batteries are in discharge and one solar wing is supplying less power than expected. The batteries should not be discharging since the vehicle is not in eclipse and both solar wings should be producing equal power.

Satellite 1 is part of a constellation of surveillance satellites. The present mission objectives for the surveillance system include the observing of a particular place on the earth at a particular time. Satellite 1 and Satellite 2 are the only two vehicles capable of the desired surveillance at the desired time. Included in the mission objectives is a corroboration requirement; that is, two satellites (e.g., their surveillance sensors, part of their payloads) observing the desired location during a specified time interval.

For Satellite 1, a failed (solar wing) sun sensor causes several system problems. In particular, three problems stand out and are listed here:

1. Power imbalance: batteries discharging.

2. Payload to be turned off in ten minutes: an automatic spacecraft load shed response to stop possible damage to the batteries.

3. Wings misaligned: present wing operation and future wing operation are suspect.

Problems Construction has the task of determining these system problems (as well as others not discussed here) using the telemetry symptoms and the domain model of the spacecraft. Several telemetry measurements in the EPS are exhibiting unexpected behavior and a few measurements are exhibiting inconsistent behavior. Goals Construction has the task of determining goals for continued system performance, given the problems that presently exist within the system and the overall system state. Plans Construction has the task of determining plans for accomplishing the goals. As the IS reasoning continues, problems, goals, and plans evolve through dynamic interaction with the domain (spacecraft) and the domain model (knowledge base models) with the end result being the most acceptable plan(s) for dealing with the (constructed) problems.

The spacecraft IS is able to determine that the payload and mission planning are affected by the present spacecraft anomalous behavior because each IS contains knowledge about the roles, responsibilities, and domain of the other ISs. Thus, the payload IS and mission planning IS become involved in the problem solving. Goals and plans are exchanged as the three ISs cooperate to determine an acceptable global solution plan. Each IS reasons within its domain of influence to determine local plans for potential and/or partial problem solution.

Figure 4a displays a subset of the problems, goals, and plans that can develop within each IS. Plans are eliminated (from the global perspective) when they do not satisfy or contribute to desired system performance. For example, “turning off the payload” would be undesirable (in this scenario) to both the mission planning IS and the payload IS. Figure 4b displays a (potential) global solution plan. Of course, as IS plans are executed (commands sent to the satellite, mission planning modified, etc.), they may not work (as desired), and the ISs continue problem solving until an acceptable level of system performance is achieved. The term “acceptable” depends upon many variables, such as seriousness of component failures, limitations in satellite design, etc.

CONCLUSION

Many future space missions will be supported with either modular transportable or mobile transportable ground stations. These new ground stations will be limited in size, but must still provide the functional capabilities of today’s larger, fixed facilities. Therefore, many of the functions performed by humans will be augmented by intelligent systems. The intelligent systems will have to cooperate as elements of the larger system, just as humans (or teams of humans) do today. This cooperation will include exchanging information, goals, and plans so that each intelligent system performs its tasks with knowledge of the impacts and benefits it has on other elements within the larger system.

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Spacecraft IS

Problems	**Goals**	**Plans**
- Batteries discharging	- Increase solar power - Shed unnecessary loads	- Rotate wing toward sun - Turn off payload - Turn off components (to low power mode)
- Automatic load sheds to occur in 10 minutes (including payload)	- Stop unwanted load sheds	- Reconfigure components Circuitry
- Wings misaligned	- Realign wing	- Rotate wing

Payload IS

Problems	**Goals**	**Plans**
- Spacecraft solar power is below anticipated level	- Reduce load to spacecraft	- Turn payload off - Configure sensors to low power mode
- Surveillance requirement exists	- Support the surveillance mission	- Calibrate sensors

Mission Planning IS

Problems	**Goals**	**Plans**
- Double satellite surveillance not achievable	- Achieve two satellite surveillance	- Reconfigure constellation - Delete corroboration requirement - Adjust surveillance time interval

Figure 4a. IS Problems, Goals and Plans

Spacecraft IS	**Payload IS**	Mission Planning IS
1. Rotate wing	1. Configure sensors to low power mode	1. Adjust surveillance time interval
2. Reconfigure load shed circuitry	2. Calibrate sensors	

Figure 4b. Global Plan