Space Applications for Distributed Constraint Reasoning

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1 Introduction

A potential weakness of any research is its applicability to real problems, and it is often difficult to determine whether a particular application needs a particular technology. Space missions offer a wide variety of multiagent problem domains, but the technology needs of these missions vary. Techniques developed by research in Distributed Constraint Reasoning (DCR) employ representations that can be applied to distributed problems generally (in the same way that many problems can be represented as constraint satisfaction problems). We briefly describe how different motivations for operating spacecraft translate into different multiagent problems and research challenges for DCR.

2 Multi-Spacecraft Missions

The past few years have seen missions with growing numbers of probes. Pathfinder has a lander and rover (Sojourner), Cassini includes an orbiter and the Huygens lander, and Cluster II has 4 spacecraft for multi-point magnetosphere plasma measurements. This trend is expected to continue to progressively larger fleets. For example, one proposed interferometer mission [4] would have 18 spacecraft flying in formation in order to detect earth-sized planets orbiting other stars. Another proposed mission involves 44 to 104 spacecraft in Earth orbit to measure global phenomena within the magnetosphere.

Over 40 multiple platform (multi-spacecraft) missions have been proposed, and they can be grouped into three families depending on why multiple platforms were proposed:

- *Signal space coverage* – multi-point sensing for improved coverage when observing/exploring large areas (like the satellites with passive microwave radiometers for the Global Precipitation Mission and similar sensors on the Global Electrodynamics Mission, Leonardo-BRDF, and the Magnetospheric Constellation)

- *Signal separation* – building large synthetic aperture sensors with many small spatially separated sensors for imaging very remote targets (like Constellation-X, Terrestrial Planet Finder, and TechSat-21); and
- *Signal combination* – specialized probes with explicitly separate science objectives (like coincident Mars Program missions or the PM train within the Earth Observing System).

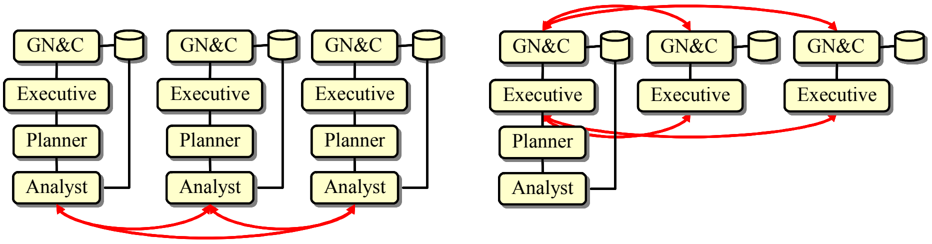
While these reasons for having multiple platforms in a mission are not exclusive, they do have a major impact on how the resulting missions are formulated and managed. These three rationales respectively motivate a single cluster of spacecraft flying in formation around the orbit, a string of spacecraft flying close together on the orbit, and a distribution of spacecraft evenly spread along the orbit.

The main thrusts of autonomy research involve reducing costs and enabling missions that focus on phenomena with high information rates and low information predictabilities. This research can be grouped in terms of three technologies:

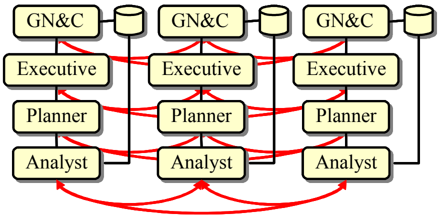
- *Robust execution* includes performing activities with automatic mode estimation & recovery using models of how spacecraft subsystems behave, to broadly cover anomalies within the modeled subsystems;
- *Planning and scheduling* involves determining when to perform which activities as a spacecraft's capabilities and science collection goals evolve; and
- *Science analysis* involves processing observation data onboard a spacecraft to determine both the value of observations as well as new science collection goals.

While the first two technologies focus on raising the level where mission operations commands a spacecraft, the third raises the level of science operations' interaction. Instead of prioritized observation lists and timed command sequences, mission and science operations respectively produce situation dependent activity determination strategies and data dependent observation strategies. The goal of raising the spacecraft commanding level is to reduce latency in responding to anomalies as well as the detection of observation opportunities by closing as many control loops as possible onboard the spacecraft. The ASE project has demonstrated onboard science analysis, replanning, robust execution, and model-based estimation and control [3].

Regardless of whether a standard or autonomous approach to mission management is adopted, several issues need to be addressed before flying a multiple platform mission. For a signal space coverage mission, the main issue is to automate as much of operations as possible to minimize the people-per-spacecraft ratio. However, this requires no special coordination technology. Thus, as shown in Figure 1, a signal coverage spacecraft team may only need to coordinate to distribute measurement goals. In the figure, GN&C refers to guidance, navigation, and control software.



signal coverage   signal separation



signal/mission combination

Figure 1. Autonomy technology interactions

Signal separation missions raise their own unique issues that derive from formation flying and instruments distributed across multiple spacecraft in order to make a single measurement. The main issues include the difficulties of

- anomaly detection and response both within and between formation fliers,
- planning and scheduling to minimize fuel used to reconfigure a formation between observations and during anomaly response, and
- validating data collected by multiple spacecraft.

Signal combination between missions raises extra issues to facilitate collaboration either between operations staffs or autonomous spacecraft. These issues include needs for

- collaboration techniques to merge observation priorities both within and between missions and
- coordination techniques to optimize the planned data gathering activities of multiple spacecraft satisfying these merged priorities.

These multi-spacecraft missions are analyzed in greater detail in an extended report [1].

3 Collaborative/Competitive Mission Planning

While separate missions may need to coordinate planning and scheduling, even within a single mission scientists and operations staff must collaborate over longer-term mission planning and shorter-term command sequence generation. Operations staff must ensure spacecraft safety and health while trying to accommodate scientists' measurement requests. Scientists also compete for use of the spacecraft. There may be several instruments and a group of scientists competing for each one. The use of one instrument may exclude the use of some others because of limited power or geometric constraints on pointing instruments at targets. An extreme case of this is the many scientists that compete for use of a single camera onboard the Hubble Space Telescope. These scientists are often spread around the world making it difficult to communicate effectively and to resolve conflicts in an efficient and timely manner. Thus, software is needed to help automate the coordination of these people.

4 Deep Space Network Resource Allocation

The Deep Space Network (DSN) maintains 16 antennas (26 to 70m in diameter, Figure 1) that provide tracking, navigation, and data transmission services among others. Antenna complexes are located in Goldstone, CA, Madrid, and Canberra and provide services to spacecraft within and beyond the gravitational influence of Earth. While 150 missions are listed as DSN users, about 20 spacecraft are allocated resources in a 4-month schedule.

Schedules are currently manually generated a year into the future with allocations to the minute. These are currently generated a week at a time and average 370 *tracks* (allocation of an antenna to a mission over a time period) per week. These tracks are typically 1 to 8 hours long and must be allocated in a *viewperiod* (i.e. a time period when the spacecraft is visible to the antenna). There are around 1650 of these viewperiods defined per week. The DSN's goal is extend the schedule out to ten years where they are currently just predicting and adjusting resource loading based on coarse requirements. The nearterm schedule (within 8 weeks) additionally considers the allocation of service-specific equipment, personnel controlling the antennas, and some additional geometric constraints on pointing the antenna.

The missions compete over the use of antennas and work out conflicts in meetings and peer-to-peer. To date, there are 27.5 full time employees dedicated to scheduling for different time periods and on behalf of different missions. Like the collaborative mission planning problem, software is needed to automate the coordination of scheduling for the missions without taking away control of their spacecraft. This problem (and a preliminary approach) is described in much greater detail by Clement and Johnston [2].

In the future, NASA plans to extend or replace the DSN with large arrays of smaller 10 meter antennas—as many as 1200 at each of the three complexes. There is the additional problem of partitioning groups of antennas to provide multiple missions varying quality of service. Hardware combiners are configured to combine signals from a group of antennas. These may be hardwired restricting which antennas can be used together. The signals (antennas) may also be switched to different combiners with some degree of flexibility, introducing another difficult problem of how to best configure antennas to a limited number of combiners. Yet another complication of the arrays is some forms of communication are weather sensitive. Weather, the number of allocated antennas, and varied functioning of antennas due to mechanical wear make communication quality much less certain requiring real-time responses to unexpected events.

5 Challenges for DCR

Most of the challenges for applying DCR to these problems are the same as applying CSP and constraint optimization techniques to the underlying single-agent problems. Representations are needed for continuous, vector, and uncertain variables. Constraint translations of models of spacecraft and their environment are needed. These models often include arbitrary functional dependencies between variables (e.g. energy = power • duration). System dynamics can require real-time responses to continual changes in state or goals. The model can change, and objects (such as measurement targets or files) can be added or deleted. Time often must be represented as continuous, and many system variables are functions of time. Computation onboard the spacecraft can be more than a thousand times slower than for a standard office workstation, and this computation is shared with other flight software that is often higher priority for real-time control and safety. Thus, the CPU itself is another resource that must be tracked.

Part of the coordination process is to ensure consistency among agents (spacecraft and people), representable as equals constraints across agents. Because of long delays of transmitting across the solar system, changing (but often foreseeable) network topology due to communication obstructions (planets), and possible relaying of data through orbiters, communication guarantees may range widely, making it difficult to achieve consistency (consensus) in real time.

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