Demonstrating Automated Planning and Scheduling for Orbital Express

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Introduction

Like a tow truck servicing a car with a dead battery or delivering gas, the DARPA Orbital Express (OE) mission demonstrated such capabilities for orbiting spacecraft, and performed these functions autonomously (Wilson 2007). The cost of building, planning, launching, and monitoring satellites is one of many motivations for the need of in-orbit spacecraft servicing. Decommissioning millions of dollars of robotics simply because there is not enough energy left on board the spacecraft is unfortunate. Alternatively, an "upgrade" to the memory on a highly successful, data-driven satellite could help increase its potential return. The motivating factors for autonomous satellite servicing are still growing, even as the OE mission ends. While automated satellite servicing continues its quest for more and more applications, automated planning and scheduling for mission operations has begun to be successfully demonstrated on many recent missions, including OE. The ASPEN planner and scheduler (Figure 1), developed at JPL, was used for both long range and daily mission planning of the OE experiment (Chien *et al.* 2000)

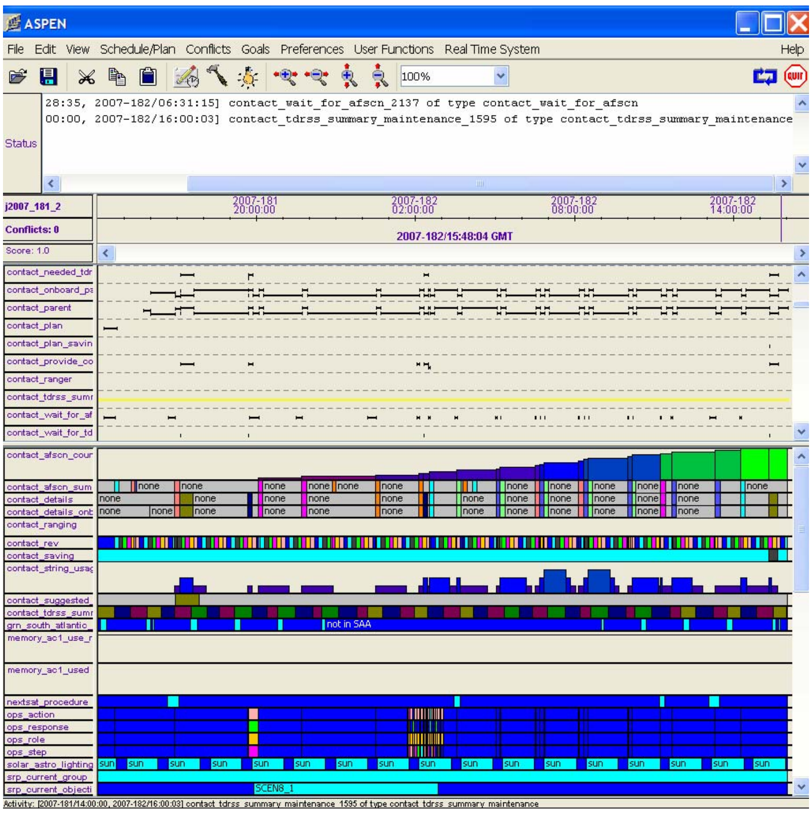


Figure 1: The ASPEN planner/scheduler

The two spacecraft flown on the Orbital Express mission were Boeing's Autonomous Space Transport Robotic Operations (ASTRO) vehicle spacecraft, whose role was that of the "tow truck", and Ball Aerospace's Next Generation Serviceable Satellite (NEXTSat) spacecraft, whose role was that of the satellite "in need of repair". The experiments conducted included rendezvous and capture, fluid propellant transfer, and in-orbit transfers of equipment (including a battery and a memory device). Most of the planning for the mission was performed by the Boeing team, who also serviced requests from Ball Aerospace. The team was broken up into two units, the Rendezvous Planners who concerned themselves primarily with computing the locations and visibilities of the spacecraft, and the Scenario Resource Planners (SRPs), who were concerned with assignment of communications windows, monitoring of resources, and sending commands to the ASTRO spacecraft. The SRP position was staffed by JPL personnel who used the Activity Scheduling and Planning Environment (ASPEN) planner scheduler. We briefly discuss the technologies used and then demonstrate the lifecycle and creation of a plan developed by the SRPs.

Objectives

The JPL team had two primary objectives for Orbital Express: 1) evaluate scenarios for feasibility early in the design of the mission, and 2) provide responsive communications and commanding planning and scheduling during the mission. To satisfy both objectives, we modeled the mission scenarios using the ASPEN planning system. OE required evaluation of many alternatives, so ASPEN was modified to accommodate reasoning about schema-level uncertainty. Rehearsals for operations indicated that the SRP needed to be very responsive to changes in the procedures. To accommodate this, we implemented a system for reading the procedures and interpreting these into ASPEN models.

Research Goals

The research goals we addressed were 1) schema-level uncertainty reasoning, 2) procedure parsing for model generation, and 3) use of recursive decomposition in a hierarchical task network (HTN) to model procedural processes.

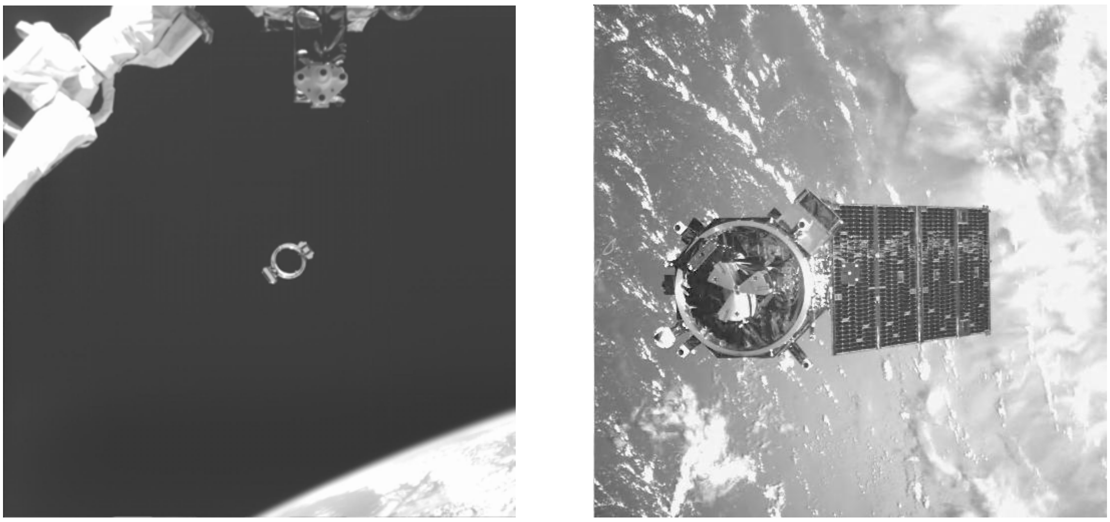
Schema-level uncertainty reasoning has at its core the basic assumption that certain variables are uncertain but not independent. Once any are known, then the others become known. This is important where a variable is uncertain for an action and many actions of the same type exist in the plan. For example, the number of retries to purge the pump lines were unknown (but bounded), and each attempt required a sub-plan. Once we knew the correct number of attempts required for a purge, it would likely be the same for all subsequent purges. This greatly reduces the space of plans that needs to be searched to ensure that all executions are feasible.

To accommodate changing scenario procedures, we ingested the procedures into a tabular format in temporal order, and used a simple natural language parser to read each step and derive the impact of that step on memory, power, and communications. We then produced an ASPEN model based on this analysis. That model was tested and further changed by hand, if necessary, to reflect the actual procedure. This resulted in a great savings in time used for modeling procedures.

Many processes that needed to be modeled in ASPEN (a declarative system) were in fact procedural. ASPEN includes the ability to model activities in a hierarchical fashion, but this representation breaks down if there is a practically unbounded number of subactivities and decomposition topologies. But, if we allow recursive decomposition, we enable HTN-like encodings to represent more procedural phenomena. For example, if a switch requires a variable (but known at the time of the attempt) number of attempts to switch on, we can recurse on the number of remaining switch attempts and decompose into either the same switching activity with one less required attempt, or not decompose at all (or decompose into a dummy task), resulting in the end of the decomposition. In fact, any bounded procedural behavior can be modeled using recursive decompositions assuming that the variables impinging the disjunctive decomposition decision are computable at the time that the decision is made. This enables us to represent tasks that are controlled outside of the scheduler, but that the scheduler must accommodate, without requiring us to give our declarative plan checking and modeling.

Impact

We were able to produce several alternatives for long-term planning so that enough communications resources were available at the



A. The OE Ring-Eject Procedure

B. A Demate/Mate Scenario: NextSAT is 14m away during a departure

Figure 2

time of execution. We also were able to deliver operations plans daily, even in the face of changing procedures and changing resource availability. Together this contributed to the success of the mission.

Long Range Planning

The planning process for the OE procedure execution days began weeks in advance. A plan was built from knowledge of the existing contacts available and an ASPEN-generated and edited model of what the procedure was to do and how the contacts should lay-out across time.

The AFSCN contacts were reserved up to a limit and occasionally with elevated priorities specifically for the unmated scenarios. TDRSS support was originally also scheduled in the long range planning timeframe for all scenarios, however, cost constraints and changes to the plan in the short term dictated the need for a policy change. It was determined more efficient to schedule TDRSS at the daily planning time, except in the case of unmated scenarios, where the timing and the more definite guarantee of contacts was crucial.

Although the essential re-planning generally occurred at the daily planning time, variations on the long range planning occurred from several factors:

1. Our launch delay created the need to re-plan all existing long range plans to shift both AFSCN and TDRSS requests.
2. Changes to models occurred often during the long range process, due to many factors, including updated knowledge of timing, procedure step removals and additions, and general modifications to procedure step times or requirements, etc.
3. Occasionally, maintenance require-ments or site operating hours were learned post-delivery of the long range planning products and a re-plan was necessary.
4. Other factors which required re-planning the long range products were often late enough in the plan timeline that a new “mid-range” plan was created. This usually was done a few days outside of the daily planning.

Daily Planning

In the morning of daily planning, the SRP would receive the list of contacts lost to other spacecraft and any suggested additions to replace these losses, and he or she would also receive the most up-to-date list of TDRSS availabilities. The contact losses would need to be evaluated against the procedure objectives of the day to determine if they could still be met. The ASPEN model of the procedure could be adjusted as needed to reflect any operations updates and the ASPEN activity could be moved around throughout the day to accommodate the contact requirements.

In the nominal case, the planning process would call for the use of the long range plan and simply update necessary timing information to create the daily plan. However, daily planning was based on many variable factors culminating into a need for both simple updating of the plan and/or completely re-planning the long range plan:

1. The visibilities of contacts with the position of the spacecraft drifts slightly per day and must be updated in the short term to make most efficient use of the AFSCN communication times. Even one minute of contact coverage loss was, at times, considered valuable.
2. The daily de-confliction process can mean a loss of several contacts based on any number of reasons (site-specific issues, other satellite conflicts). Losses may require a shift of the procedure to perform the requested objectives. Also, losses are often accompanied by gains, and re-planning can be based on such new additions to the plan.
3. Scoping of the day's long-range plan may change due to both anomalies and new direction from operations. Updating the existing plan at the daily planning time was often required for previously unknown amounts of needed coverage or for real-time failures of contacts pushing into the next day.
4. TDRSS support was originally requested in advance for all long range planning, but as cost became an issue for unused contacts, the requests for TDRSS became part of the daily planning process. This was a major addition to the update of the long range plan.
5. Dealing with the sometimes unpredictable conditions of space and limited mission time, a number of unforeseen events could cause the need to update the long range plan.

Overview of the Demonstration

The demonstration will step through the lifecycle of an OE mission operations plan in ASPEN from 3 weeks out to the day of execution. A number of issues will come up at each stage and be dealt with in real-time. The plan itself will be simple, to keep the time spent on details to a minimum, and the ASPEN models will already be built. There is a possibility of interaction from the audience members to act as "Operations Personnel" and request certain contacts, more time for "uploads", duration changes to certain steps to accommodate sun angles, etc.

The starting products and results from the process of translating a procedure to an ASPEN model will be displayed and discussed, as will the products generated by ASPEN, including the operations summary and tasking file.

There will be several displays of images and movies open from the actual spacecraft execution, showing transfers of equipment, imaging of the two satellites with the arm (endearingly called the "family portrait"), the ring-eject procedure (shown in Figure 2), and a de-mate and mate operation.

Acknowledgements

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