

# An ASPEN Application: Automating Ground Operations for Orbital Express

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## Abstract

We describe the application and adaptation of the ASPEN (Activity Scheduling, Planning Environment) (Chien *et al.* 2000) planning and scheduling/sequencing framework to the OE (Orbital Express) mission. We provide a description of the OE operations, and a characterization of the techniques used to perform planning for operations. These techniques include 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.

## Introduction

Automating spacecraft ground operations using automated planning and scheduling tools has become more popular over the past several years of space

missions. The need to quickly and easily add and delete activities and their respective resources has led to the need to represent spacecraft operations and activities with reusable models. While the domains for each spacecraft model change, the underlying planning tool reading the domains can adapt and evolve to accommodate new technologies needed.

The Orbital Express mission was a Defense Advanced Research Projects Agency (DARPA) led demonstration of in-orbit satellite servicing. The two spacecraft flown on OE were Boeing's Autonomous Space Transport Robotic Operations (ASTRO) vehicle spacecraft, the servicing satellite, and Ball Aerospace's Next Generation Serviceable Satellite (NextSat) spacecraft, whose role was that of the satellite being serviced. The experiments

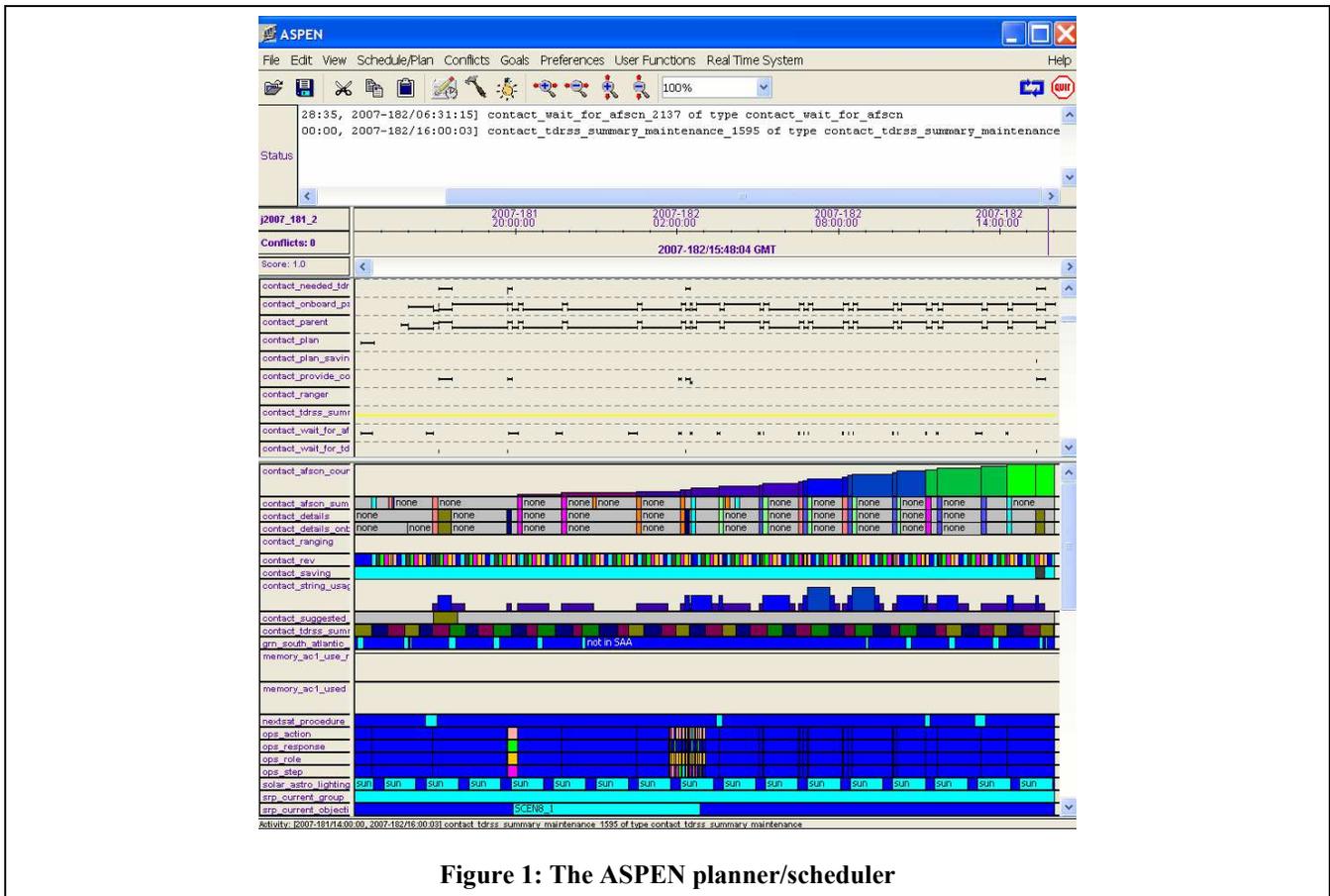
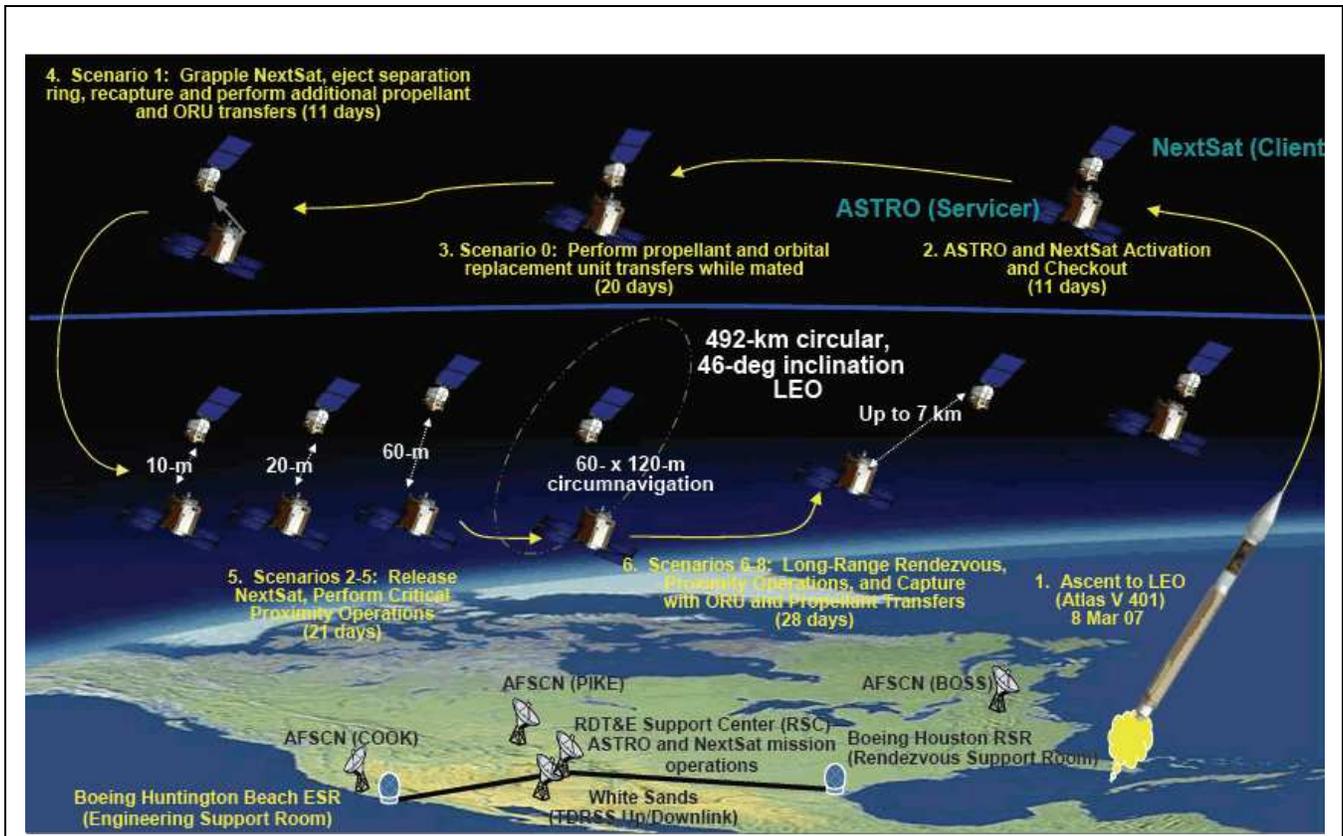


Figure 1: The ASPEN planner/scheduler



**Figure 2: The Orbital Express Scenarios: Increasing Autonomy and Complexity**

conducted included rendezvous and capture, fluid propellant transfer, and in-orbit transfers of equipment (including a battery and a memory device). All mission objectives were met successfully. The ASPEN planner and scheduler (Figure 1), developed at JPL, was used for both long range and daily mission planning of the Orbital Express experiment. (Chien *et al.* 2000)

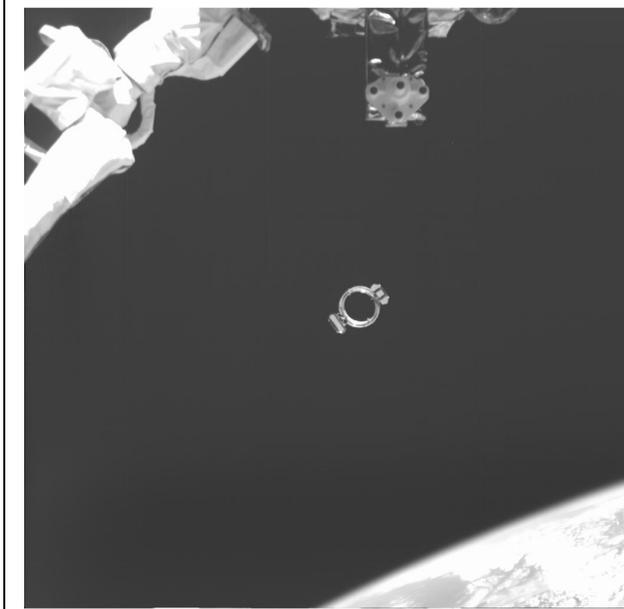
The planning team for the mission was broken up into two units, the Rendezvous Planners who concerned themselves primarily with computing the locations and visibilities of the spacecraft, and the Scenario Resource Planners (SRPs), who were concerned with assignment of communications windows, monitoring 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 discuss the Orbital Express domain written for ASPEN, the technologies added to the planner to accommodate the mission objectives, and we briefly describe the ground operations of long-range and daily planning for the mission.

### Planning Problem

The OE mission domain required fast turn around of heterogeneous, dynamic plans. Every day was a different

scenario, where communication passes could be lost within hours of the daily planning delivery deadline. Operations were conducted in unknown environments: a procedure could change within hours of the delivery deadline. Onboard resources (energy and memory) were limited and needed to be managed. Limited available communications existed using primarily the high-bandwidth ground-based Air Force Satellite Control Network (AFSCN) sites, while the relatively low-bandwidth GEO-Synchronous space-borne Tracking and Data Relay Satellite System (TDRSS) communications could potentially vary by the hour.

A scenario (See Figure 2) typically consisted of a series of procedures, each of which was written by the operations personnel in Microsoft Word table format. Each procedure listed its steps and associated durations and represented the need for a contact and the type of contact desired or required. Several procedures had other embedded procedures and some spanned more than one day. As an example, the “unmated” scenario required an initial setup procedure, then the “unmated” procedure would be kicked off; the de-mate, hold, and re-mate would execute, and then a post-rendezvous and capture transfer procedure would be planned. See Figure 3.B. for



**A. The OE Ring-Eject Procedure**



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

**Figure 3**

an image of the unmated scenario mid-execution in the “de-mated” configuration.

The schedule of each scenario was dependent on what had been accomplished to date, as the goal of each scenario was to become increasingly more autonomous. The planning schedule was also dependent on the state of the flight system, the amount of preparation time needed before execution, and resources available on future dates. Calendar planning was done by a combination of inputs from Flight Directors, Mission Managers, Project Management, and DARPA.

Procedures were delivered to the SRP and copied to Excel. An ASPEN model-generation script was then used to create ASPEN Modeling Language (AML) representations of the procedures. Once the AML model existed for a procedure, the ASPEN tool read the AML description of the procedure and could be used to add any number of different procedures in a plan required to make up the scenario. Scenario-related resources such as total energy consumption and constraints on the number of contacts used per day could then be managed by ASPEN.

### **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. OE required evaluation of

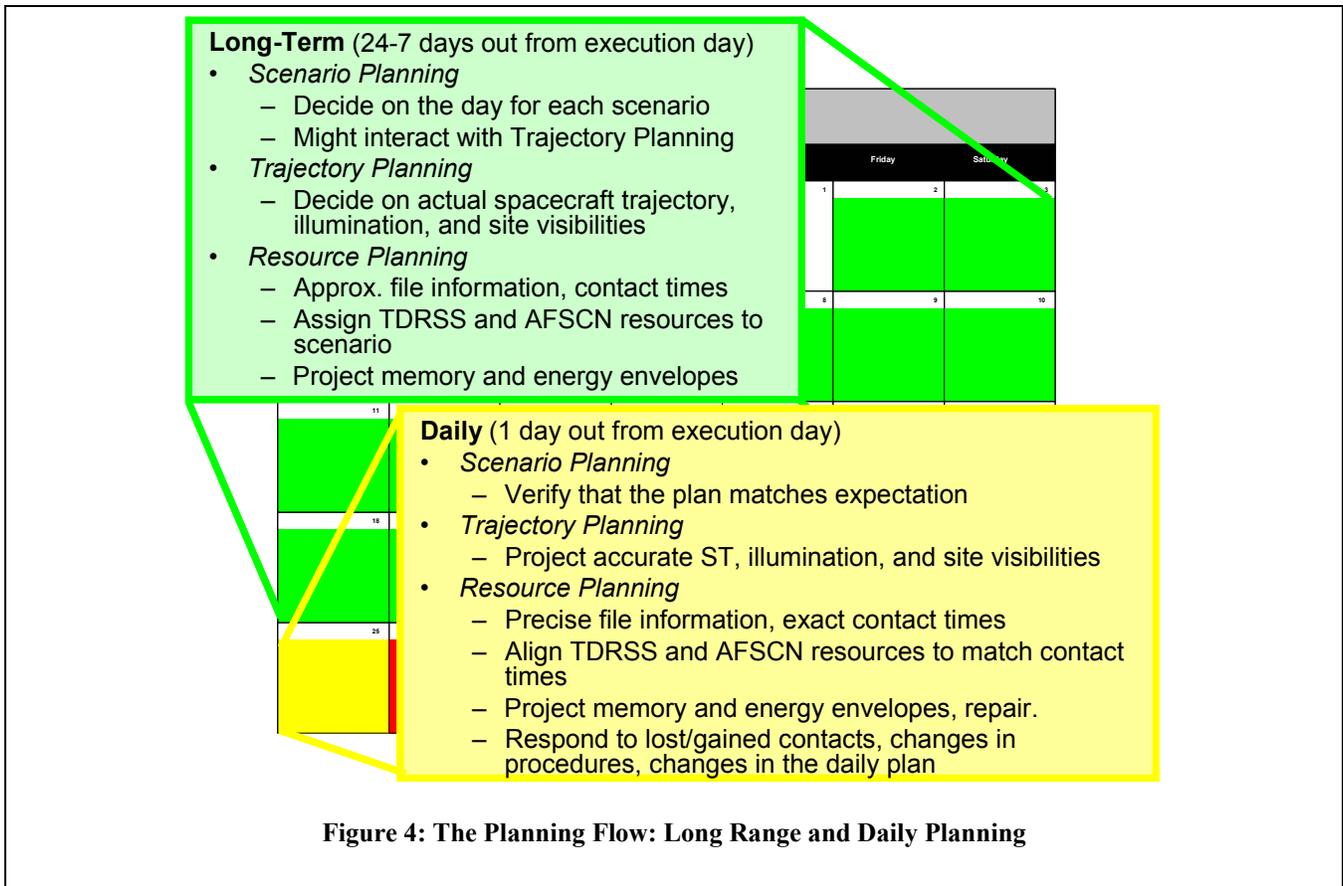
many alternatives, so ASPEN was modified to accommodate reasoning about schema-level uncertainty.

### **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 (i.e., HTNs), 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 time of execution. (For each alternative, we needed enough resources to handle all communications. Each alternative was based on differing execution paths.) 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.

### The Variable Domain

As the mission progressed, unknown variables were adjusted to best estimate reality. A hydrazine propellant transfer became more predictable after several were successfully demonstrated. Any model representing a procedure could need updating over time. There were cases in which the values simply changed, for example the rate of a fuel transfer needed updating. However, there were also cases in which steps in the procedure needed to be removed, or more difficult from a planning perspective, added. To remove a step, the duration of the step could be set very low, or in the worst case, the procedure model could simply be re-generated. To add steps, re-generation was almost always necessary. Depending on the procedure, the re-generation process

could sometimes be more complex than simply running the model generator; if a procedure contained nested procedures, the initial content would need to be hand-verified for correct syntax and then after the model was generated, it was sometimes necessary to hand-edit the procedure to correctly reflect choice points that were not represented in the procedure table. If the representation of a procedure could not be configured to the full extent, the generated model could not encompass the full intent of the procedure either. The long range and daily planning process provided a step-by-step analysis of each plan as verification that the models met expectations.

### **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 requirements 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 drifted slightly per day and had to 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 could mean a loss of several contacts based on any number of reasons (site-specific issues, other satellite conflicts). Losses could require a shift of the procedure to perform the requested objectives. Also, losses were often accompanied by gains, and re-planning could be based on such new additions to the plan.
3. Scoping of the day's long-range plan could 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.

### **Lessons Learned**

With a 100% mission criteria success rate, the Orbital Express project proved that spacecraft servicing is a

reality for space operations. The goals for the JPL ASPEN team were to model the procedures and constraints of the mission and plan the long-term and daily operations. Using ASPEN and the AML for Orbital Express modeling and planning, the planning team was able to represent mission constraints and procedures. The planning tool was flexible and adaptable to changing parameters.

In the long-term plan timeframe, the plan for the execution day often changed or had several alternatives in one day (the nominal plan versus a backup plan). ASPEN's internal activity structure and quick repair algorithm allowed procedures to easily be shifted from one contact to another and to be deleted and replaced by new procedures without major re-working of the plan. Daily planning was adaptable to changes in which procedures and their associated ASPEN models were updated by operations the day of planning. The auto-generation of models allowed the planning team to share new procedure information and process it quickly for use on-orbit. It also allowed the decision of using a procedure on a given day to be made last-minute and not cause delay on the mission schedule. Models could be generated during the daily planning process and used the same day to plan the execution day's contacts.

Originally, NextSat contacts were not going to be scheduled using ASPEN, however, the simplicity of adding objectives to contacts with the planning tool, NextSat's low-maintenance strategy, and the ease of use for the SRPs to add the activities in ASPEN showed the ability to plan for multiple satellites, and account for many real-world factors in planning operations.

### **Related Work**

In June 1997, a docking of a Progress supply ship at the Mir space station was attempted but did not succeed. The Air Force Research Laboratory (AFRL) launched XSS-10 in 2003 and XSS-11, in 2005 with the objectives of advancing autonomous navigation and maneuvering technologies. Orbital Express was the first successful demonstrator of autonomous ORU (Orbital Replacement Unit) transfers in the world and of autonomous refueling in the U.S. While several other missions over the past decade have approached the idea of autonomous satellite servicing with rendezvous and other robotic maneuvers, including NASA's Demonstration of Autonomous Rendezvous Technology (DART) satellite and Japan's National Space Development Agency (Nasda) Engineering Test Satellite 7, OE was the first successful demonstrator of autonomous rendezvous and docking (Dornheim 2006).

Planning operations for the Mars Exploration Rover (MER) mission is aided by the NASA Ames Research Center software tool Mixed Initiative Activity Plan

Generator (MAPGEN) which is similar to ASPEN as an automated planner through the use of activities and temporal constraints. The nature of search for MAPGEN does not allow it to search the infeasible space for plan solutions, i.e., when a constraint violation arises, the planner backtracks. ASPEN admits search in the infeasible space (in fact, threats and constraint violations are rolled up into a single generic entity called a *conflict*) allowing for faster response to off-nominal execution.

Maldague *et al.* have developed a planning framework (APGEN) that automatically generates and validates plans used for commanding spacecraft, but does not perform general planning.

### **Future Work**

Continuous Activity Scheduling Planning Execution and Re-planning (CASPER), an extension to ASPEN, provides a continuous cycle of decision-making capabilities for real-time scheduling, repair and optimization. ASPEN has been successfully used as a ground planning system for earth-orbiting missions on both Orbital Express and EO-1 (Chien *et al.* 2005). On the EO-1 satellite, the embedded use of CASPER allowed flight operations to achieve higher levels of automation as well. While the EO-1 project is on-going, ASTRO and NextSat completed their end-of-life maneuver and were decommissioned on July 22, 2007 (Orbital Express 2007).

Future mission operations goals for ASPEN include the execution of research currently in development and the implementation of models for new missions. The OASIS project uses CASPER to plan and schedule activities for its rover. The rover then executes the plan and uses the optimization cycle in CASPER to monitor science opportunities and repair conflicts that arise (Castano *et al.* 2007). A similar use of CASPER is in development for aerial vehicles, or aero-bots (Gaines *et al.* 2007), and for surface and under-water vessels. ASPEN is also currently being researched and used as a tool to schedule and coordinate resource allocations of ground antennas for over 60 missions of the Deep Space Network (DSN) (Clement *et al.* 2005). Similarly to Orbital Express, continuing work on automating satellite operations is being considered for the DESDynI project using an ASPEN hybrid being built for compressed, large-scale activity planning (DESDynI 2007, Knight *et al.* 2006).

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