Orbital Express Mission Operations Planning and Resource Management using ASPEN

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Introduction

As satellite equipment and mission operations become more costly, the drive to keep working equipment running with less man-power rises. Demonstrating the feasibility of autonomous satellite servicing was the main goal behind the Orbital Express (OE) mission. Like a tow-truck delivering gas to a car on the road, the "servicing" satellite of OE had to find the "client" from several kilometers away, connect directly to the client, and transfer the fluid (or battery), autonomously, while on earth-orbit [1]. The mission met 100% of its success criteria, and proved that autonomous satellite servicing is now a reality for space operations.

Planning the satellite mission operations for OE required the ability to create a plan which could be executed autonomously over variable conditions. As the constraints for execution could change weekly, daily, and even hourly, the tools used create the mission execution plans needed to be flexible and adaptable to many different kinds of changes. At the same time, the hard constraints of the plans needed to be maintained and satisfied. The Automated Scheduling and Planning Environment (ASPEN) tool, developed at the Jet Propulsion Laboratory [2], was used to create the schedule of events in each daily plan for the two satellites of the OE mission.

This paper presents an introduction to the ASPEN tool, the constraints of the OE domain, the variable conditions that were presented within the mission, and the solution to operations that ASPEN provided. ASPEN has been used in several other domains, including research rovers, Deep Space Network scheduling research, and in flight operations for the ASE project's EO1 satellite. Related work is discussed, as are the future of ASPEN and the future of autonomous satellite servicing.

The Orbital Express Mission

The Orbital Express space mission was a Defense Advanced Research Projects Agency (DARPA) lead demonstration of satellite servicing, including on-orbit, autonomous rendezvous and transfer of propellant and of Orbital Replacement Unit (ORU) components. Boeing's Autonomous Space Transport Robotic Operations (ASTRO) vehicle provided the servicing to the Ball Aerospace's Next Generation Serviceable Satellite (NextSAT) client. For communication opportunities, operations used the high-bandwidth ground-based AFSCN network along with the relatively low-bandwidth GEO-Synchronous space-borne TDRSS network. Mission operations were conducted primarily at the Kirtland Air Force Base. All mission objectives were met successfully:

- The first of several autonomous rendezvous was demonstrated on May 5, 2007: http://www.darpa.mil/orbitalexpress/mission_updates.html,
- Autonomous free-flyer capture was demonstrated on June 22, 2007
- The fluid and ORU transfers throughout the mission were successful.

Planning operations and accepting daily procedures for the mission were conducted by a team of personnel including the Flight Directors, who were responsible for verifying the steps and contacts within the procedures, the Rendezvous Planners who concerned themselves primarily with computing the locations and visibilities of the spacecraft, and the Scenario Resource Planners (SRP), who were concerned with assignment of communications windows, monitoring of resources, and sending commands to the ASTRO spacecraft. ASPEN was used daily by the SRP to model and enforce mission and satellite constraints.

ASPEN Introduction

ASPEN is a planning and scheduling tool which reads in text Aspen Modeling Language (AML) files representing a particular domain and its activities and analyzes the properties and constraints in the domain while managing and solving any existing conflicts of the activities as they are placed and moved along a timeline. The types of constraints that can be represented in ASPEN are temporal constraints (an activity must occur at time T, or an action A must occur before an action B), resource constraints (step 5 of an activity must use X amount of energy), and state constraints (the satellite must be in eclipse during an image).

Resources can be defined as depletable/non-depletable or atomic, where either the resource may rise and may fall in value (like memory being used and being downloaded), or the resource is in-use or not in-use (like an antennae) which may not be used by two activities at the same time. Within the non-atomic resources, a capacity must be defined. Atomic resources have a unit capacity, and so do not need a value.

As a domain description is written, activity descriptions are also modeled. Once the model exists, the user can add as many activities to the plan as desired. If there are limits to the resources in the plan, as defined by the domain, ASPEN will identify the conflicts that exist. The iterative repair algorithm in ASPEN will then choose to move, add, and/or delete activities to resolve the conflicts. Generic heuristics are used to make better choices, and a user can create their own heuristic functions to make more specific choices.

The OE Domain Constraints

During operations of the OE mission, ASPEN was used to create models of the procedures, which represent data and timing information about the spacecraft and the contacts needed for each step. ASPEN was also used to monitor energy and memory usage per day. Limited resources on the spacecraft and on the ground translated to the use of ASPEN's depletable resource construct.

Hardware and software limitations constrained the domain: on the spacecraft, a limited number of contacts could be handled each day by the onboard software, while on the ground, a unique number of "strings" (hardware configurations available to personnel to support the satellites) required monitoring the number of and start and end times of contacts.

The String Problem

At the mission operations site in Albuquerque, New Mexico, a limited number of strings were available at any one time. The following set of hard rules, which developed over previous experience and rehearsals, applied to string usage of both AFSCN and TDRSS contacts:

- Each AFSCN contact used one string.
- AFSCN contacts needed at least 1 hour before the AOS of a contact to bring the string up.
- Up to three TDRSS contacts could use one string if AOS of the first TDRSS contact to LOS of the third contact was less than or equal to 90 minutes.
- For TDRSS support, the three contacts did not necessarily need to occur consecutively (AFSCN contacts could exist in between the TDRSS contacts).
- For each group of three or less TDRSS contacts within 90 minutes, only the first contact needed at least 1 hour before the AOS of the contact to bring the string up.
- All other cases of TDRSS contacts needed at least 1 hour before AOS to bring the string up and used one string.
- A string could not be re-used for at least one hour after its use.

From this set of rules, imagine the following set of tightly connected contacts:

Contact Type:	AOS	LOS
TDRSS	00:00:00	00:30:00
AFSCN	00:30:00	00:40:00
AFSCN	00:40:00	00:50:00
AFSCN	00:50:00	01:00:00
TDRSS	01:00:00	01:30:00
TDRSS	01:30:00	02:00:00

Table 1: A Complex String Usage Scenario

On a timeline, one configuration of this scenario might look like:

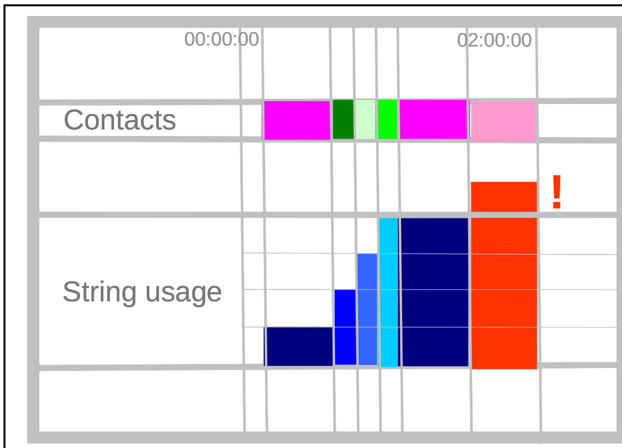

Figure 1: AFSCN and TDRSS String Usage

Pink shaded boxes are the three TDRSS contacts in Table 1 and green shaded boxes represent the three AFSCN contacts. For the TDRSS contacts, the "string usage" is one for up to 90 minutes (AOS of 1st to LOS of 3rd, 2nd, or 1st), and for each AFSCN contact, the "string usage" increases by one. In this scenario, the 3rd TDRSS over-subscribes the string usage by 30 minutes. This particular scenario is impossible to achieve with the rule set and the limited strings. In most cases, the String Problem was solvable. The problem created another set of resource constraints on the domain, which can actually be compared to the Job-Shop Scheduling problem: a classical programming problem with an NP-hard classification [3].

For operations, ASPEN modeled the string usage of contacts and the 60 minutes of time required after each string's usage. The SRP hand-corrected any over-subscriptions to best cover the contact times that were needed in tightly connected scenarios as shown above. As an example, in the given scenario, the 1st AFSCN contact uses its required string for 10 minutes. The string is free again 1 hour after the LOS of the AFSCN contact, so the last TDRSS could use or "re-cycle" that same string if its AOS was 10 minutes later at 01:40:00.

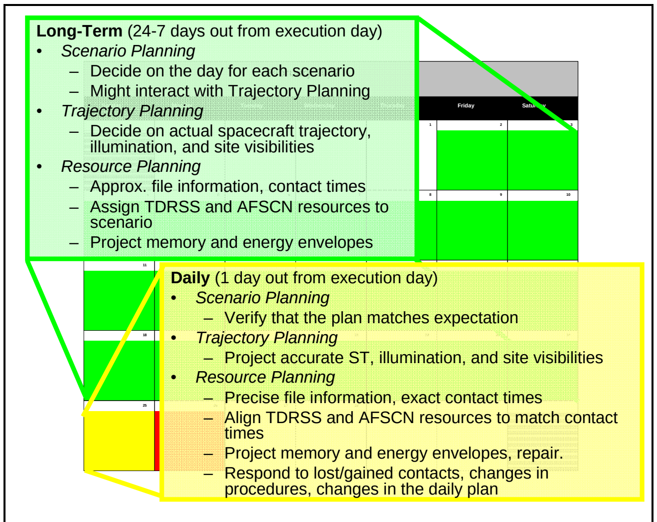

Figure 2: Monthly, Weekly, and Daily Planning Cycle of OE Mission Operations

Mission Operations: The Planning Timeline

The mission timeline also defined the temporal constraints of the domain. As the long term plan became the daily plan, any changes to contacts and/or activities needed to be reflected into the new plan. Several of the unmated operations scenarios needed a longer time-span than the typical 24 hour plan. ASPEN is generally capable of accepting any plan duration and the OE activity models were created to fit across several days as needed.

In Figure 2, a calendar of the planning cycle is shown, where green days represent the long-term planning timeframe of 24 to 7 days out from execution, and the yellow day is the daily planning timeframe: one day out from execution. The red day is execution day, also referred to in operations as the real-time planning timeframe.

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 drifted slightly per day and were 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.

Mission Operations: The Solution

The re-planning capabilities in ASPEN allowed activities to be deleted, moved and added as needed in a matter of seconds, or less. The daily timeframe and delivery deadlines were the driving force behind the ASPEN modeling. Activities that were the most variable were separated into their own models to be easily added and deleted as needed. Scenario models took advantage of automated planning and anchoring steps to particular times or contacts. Scenario activity models also took advantage of the AML use of decompositions and auto-generated sets of required sub-activities where appropriate.

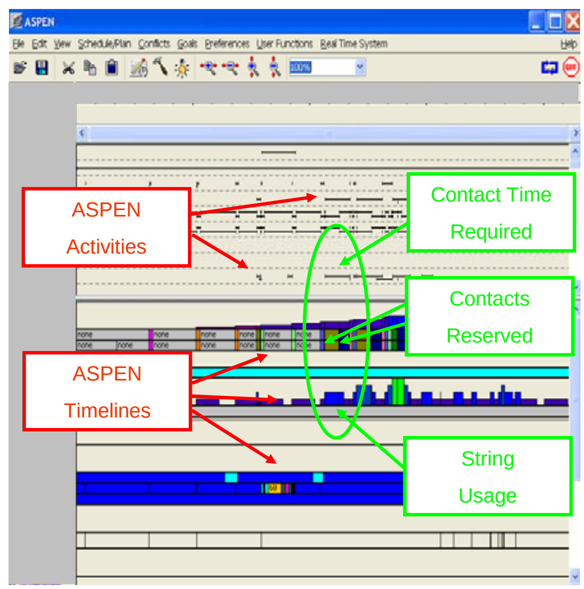

Figure 3: ASPEN Activities in a Plan Making Reservations on a Timeline

Many parameters in the activities could be altered to accommodate different kinds of decompositions or to set different values to variable parameters within an activity while keeping key parameters consistent. For instance, if the name of a file and the number of files to be uploaded changed from one day's plan to the next, a filename parameter in an upload activity could be easily changed with a simple "set parameter" function call in ASPEN. The duration required of contact time would need to be derived from the number of files to be uploaded. A user could set the number of files to be uploaded in the upload activity's ASPEN parameter and this value would propagate to other parameters and functions to determine the duration of contact time needed. The reservation on the ASPEN timeline for contact time could then be manipulated further if needed by the user, or the default reservation could be accepted and requested.

In Figure 3, a modified version of the ASPEN GUI is shown. The screenshot is at the one day resolution. When a user is working with a particular activity in the GUI, generally it is more zoomed in. The top half of the GUI contains activities, and the lower half contains timelines (as indicated in red). Several examples of ASPEN contact activities with varying durations make reservations on the contact timeline and reserve both AFSCN and TDRSS time. As indicated in the green oval, the long, black activities request contact time; below the activity row in the timelines section, two types of contacts are reserved; and below the contact reservations, their string usage profile is shown to increase. A more detailed version of the same is shown in Figure 4.

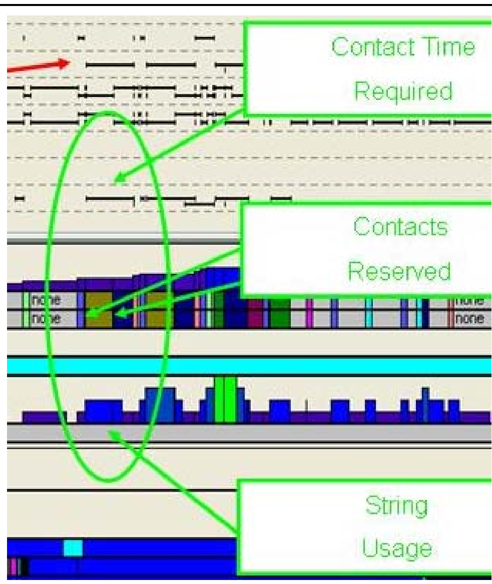

Figure 4: ASPEN Activities and Timelines

Once the plan was edited in the daily planning process, satellite tasking files were then generated for commanding, and operations summaries were used by the flight and planning team.

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 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 [4].

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. Where ASPEN mainly differs from MAPGEN is in the core capabilities of repair and optimization of a plan and in the representations of resources and their effective reservations and constraints on timelines. ASPEN has been successfully used as a ground planning system for earth-orbiting missions on both Orbital Express and EO-1 [5]. While the EO-1 project is on-going, ASTRO and NextSAT completed their end-of-life maneuver and were decommissioned on July 22, 2007 [6].

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. On the EO-1 satellite, the embedded use of CASPER allowed flight operations to achieve higher levels of automation as well.

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 [7]. A similar use of CASPER is in development for aerial vehicles, or aero-bots [8], 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) [9]. 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 [10, 11].

Conclusions

The flexibility of the ASPEN tool to accommodate changes to procedures and to the daily and long-range plans contributed to the success of the Orbital Express mission. Through the use of automated planning and scheduling, human errors can be averted, and the manpower needed each day for planning is arguably reduced. The SRP role was staffed at one person per day with an overlapping day at the start and end of each shift. Auto-generated activity models and ASPEN's use of iterative repair helped the SRP create plans quickly and repetitively and alter existing plans in an efficient timeframe. Automated analysis of the temporal constraints on contact availability and the reservation requirements of procedures for contact time trigger the identification of conflicts with the constraints. Automatic conflict identification is just one of the major benefits of using ASPEN. Using the AML, many highly complex domain and activity descriptions can be written and used for operations. ASPEN has been shown to be a useful tool for automated planning of mission operations in the Orbital Express demonstration domain.

Acknowledgements

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