Planning and Monitoring International Space Station Solar Array Operations

Sudhakar Y. Reddy, *The Boeing Company*
Michael J. Iatauro, *Perot Systems*
Jeremy D. Frank, *Ames Research Center*
Matthew E. Boyce, *MCT, Inc.*
Jeffery P. Radigan, *Johnson Space Center*
Elif Kürklü, *SGT, Inc.*

International Space Station (ISS) solar arrays are designed to automatically track the sun to maximize power production as the station orbits the Earth. However, normal ISS operations such as water dumps, docking spacecraft, attitude changes through firing thrusters, and extravehicular activities (EVAs) can increase structural loads, environment contamination, and thermal stresses on the arrays, leading to the imposition of a variety of operational safety constraints known as Flight Rules. These rules not only prescribe the correct operation of the arrays, ensuring the safety of crew, vehicle, and mission; they also express preferences for vehicle longevity and mission effectiveness.

Managing the solar arrays on the ISS requires flight controllers to generate plans changing the orientations and modes of the arrays while balancing the complex constraints and preferences defined by the Flight Rules. These constraints include context-dependent constraints on legal configurations, temporal constraints limiting allowed transitions between configurations, as well as preferences for constraints. Satisfying all these constraints often limits power generation, and flight controllers need to balance the competing requirements of maximizing power availability and maintaining operational safety.

Over the past 3 years, researchers at NASA Ames Research Center (ARC), developed the Solar Array Constraint Engine (SACE) to assist the ISS flight controllers with planning and executing solar array operations safely and effectively. SACE provides automated solar array planning, what-if analysis, and real-time monitoring capabilities. It traditionally takes about 4 weeks to manually produce a solar array plan for a 4-week planning horizon. SACE has reduced this time to a few hours.

Problem

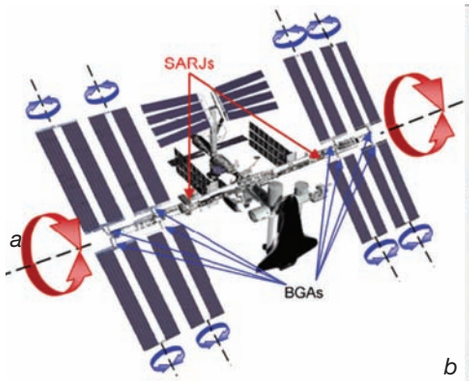
The ISS has eight solar arrays, each mounted on a rotary joint called the beta gimbal assembly (BGA). Sets of four BGAs on both the starboard and the port sides of the ISS are mounted on a truss attached to a solar alpha rotary joint (SARJ). Each solar array thus has 2 deg of rotational freedom, though some degrees of freedom are constrained by the shared SARJs.

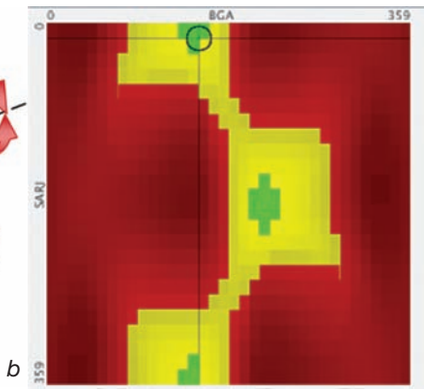
Figure 1(a) shows the ISS solar array arrangement. Each SARJ and BGA has three modes: (1) Autotrack mode, where on-board software automatically rotates the solar arrays so the array surface is pointing directly at the sun; (2) Parked mode, where a drive motor is engaged to maintain the current array facing; and (3) Locked (for SARJ) or Latched (for BGA) modes, where a physical barrier is engaged to maintain current array facing.

The ISS impacts solar array safety by combining: an attitude reference frame; the yaw, pitch, and roll (YPR) of the station with respect to the attitude reference frame; the solar beta (angle between solar vector, pointing from the sun to the center of the Earth, and ISS orbital plane); which ground system is in control of ISS (U.S. or Russian); a list of events (e.g., docking, EVA, water dump); the port to be used for docking; the attitude control and reboost jet selects (configuration-specific combinations of thrusters fired, for attitude control and orbit maintenance, respectively); and the alternate jet selects used in case of thruster failure. This combination of information collectively defines the station's unique configuration. An operating plan for ISS consists of a sequence of configurations, such that the start time of one configuration equals the end time of the preceding configuration.

Four classes of constraints apply to pairs of SARJ and BGA angles: (1) power generation, (2) structural load, (3) environmental contamination due to particulate accumulation on array surfaces, and (4) longeron shadowing. These constraints are tables mapping an SARJ-BGA angle value pair to a color from the set red, yellow, and green. In most cases, red is infeasibility, e.g., insufficient power to run life support or forces strong enough to cause structural damage to the station; yellow values are acceptable but may reduce vehicle longevity or achievable mission objectives; and green is preferred. A representative table is shown in figure 1(b).

Figure 1(c) shows a sample solar array planning problem with two main events broken down into sub-events, each of which is associated with a time, a solar beta angle, an attitude type, a reference frame, and YPR. Events 5 and 6 have fixed start and end times, but other events have flexible end times. A thruster timeline (not shown) lists thrusters that are allowed to fire during various events, both during normal and contingency operations.





c

#	Start-Stop GMT	Beta Angle	Attitude Name	Ref Frame	YPR	Event
ATV_Propellant_Line_Purge (M08_170_A_04.UAF)						
1	170/08:30 --	-27	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover US to RS for Prop Purge (SM)
3	170/10:00 --	-27	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover RS to US Momentum Management
ATV_Reboost (M08_171_A_03.UAF)						
4	171/05:00 --	-28	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover USS to RUS
5	171/05:05 171/05:10	-28	+XVV +ZLV	LVLH	5.1 357.2 0.0	Mnvr to Reboost Attitude (ATV on SM Aft)
6	171/06:56 171/07:01	-28	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Mnvr to LVLH TEA
7	171/07:30 --	-28	+XVV +ZLV TEA	LVLH	355.0 357.3 358.0	Handover RUS to USS Momentum Management

Fig. 1. *(a) The ISS, showing the port and starboard assemblies of solar arrays and locations of the SARJs and BGAs. (b) A representative table indicating, for one SARJ and one BGA, the safety of setting the solar array orientations; the Y axis is the SARJ orientation and the X axis is the BGA orientation; green is preferred, yellow is acceptable, and red is (most of the time) infeasible. (c) A representative sequence of configurations for which a solar array plan must be generated. Each configuration has a start time or start time range, a solar beta angle, an attitude type, a reference frame, YPR, and events dictating which tables apply.*

Approach

SACE uses the extensible universal remote operations planning architecture (EUROPA) framework for automated planning (figure 2). EUROPA, a model-based artificial intelligence planning system, has been in continuing development at ARC over the past decade. It accepts a declarative description of a planning problem consisting of a list of timelines (concurrent threads of a plan), a list of states that may hold on each timeline over an interval, and compatibilities describing the relationships that must hold between timelines for a plan to be valid.

SACE represents the sequence of configurations and states for each array joint as EUROPA timelines. The configuration states are values of the configuration variables. For a given configuration of the ISS, SACE finds orientations and modes for different arrays that maximize the power availability while keeping them in a feasible space with respect to the various constraints. For a sequence of configurations, after each successive orientation and mode selection, SACE ensures the temporal constraints on mode changes and those imposed by the angular rotation rates are satisfied. The ideal solar array plan optimizes the orientations and modes in each configuration. However, there may be insufficient time to turn the arrays to a new orientation or command mode changes, especially from short configurations. Under these circumstances, SACE merges adjacent configurations and optimizes the new configuration.

Optimizing orientation for a single configuration is posed as an unconstrained optimization problem. Optimization problems for the starboard and the port sides of station are independent. The overall cost function is split into two independent functions, one for each SARJ. We calculate the cost of each orientation independently for each solar array. In designing the cost function, we ensure every infeasible orientation has worse cost than any feasible solution. An orientation is feasible if its power table entry is not red, its load entries (SARJ and BGA) are not red, and its longeron entry is not red.

The component cost functions refer to the color cost (due to different constraints being in the red, yellow, or green zones), mode cost (due to modes of the BGA and the SARJ), distance cost (due to the distance between orientations of arrays), direction change cost (due to change in direction of trajectory of arrays), and power cost (due to incremental differences in power within a constrained power zone). Weights on the different component cost functions are designed such that mode cost only matters when colors are equal, distance cost only matters when modes are equal, direction change cost only matters when distances are equal, and power output cost only matters when all other components are equal.

Planning and Monitoring International Space Station Solar Array Operations

continued

Summary

The SACE tool provides an end-to-end solution that starts with a timeline of ISS attitudes and events and automatically produces a solar array plan as well as a timeline of power availability. By using automated optimization and planning, SACE has dramatically reduced the time required for ISS solar array planning from several weeks to a few hours. It has a "telemetry view" for situational awareness, a "sandbox view" for what-if analysis and optimization, and a "plan view" for automated planning. The monitoring and optimization portion of SACE has been certified for flight operations, and the planning component is currently undergoing certification testing.

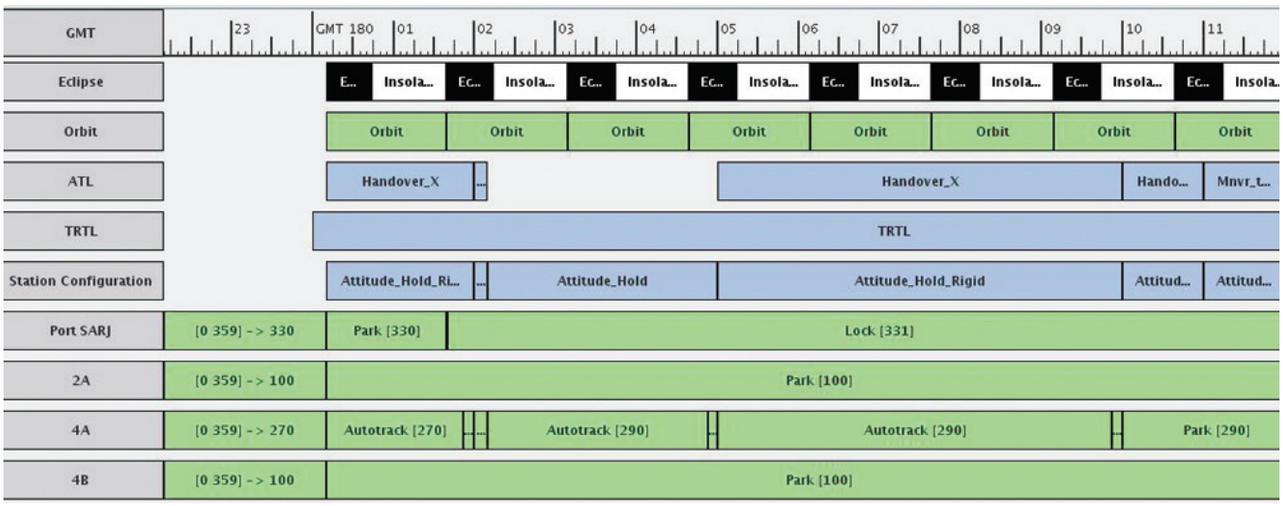


Fig. 2. *The SACE planning window shows timelines for attitude changes (ATL), thruster choices (TRTL), the configurations, and the different SARJs and BGAs, among other things.*

Click here for next report