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Planning Solar Array Operations on the International Space Station

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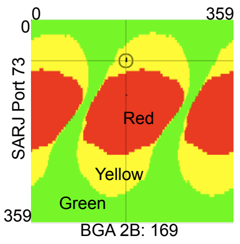
Introduction

Flight controllers manage the orientation and modes of eight large solar arrays that power the International Space Station (ISS). The task requires generating plans that balance complex constraints and preferences. These considerations include context-dependent constraints on viable solar array configurations, temporal limits on transitions between configurations, and preferences on which considerations have priority. The Solar Array Constraint Engine (SACE) treats this operations planning problem as a sequence of tractable constrained optimization problems. SACE uses constraint management and automated planning capabilities to reason about the constraints, to find optimal array configurations subject to these constraints and solution preferences, and to automatically generate solar array operations plans.

SACE is built on the Extensible Universal Remote Operations Planning Architecture (EUROPA) model-based planning system. EUROPA facilitated SACE development by providing model-based planning, built-in constraint reasoning capability, and extensibility. EUROPAs built-in functionality was used to model some constraints, while EUROPAs modular and extensible framework enabled the addition of custom code for modeling other constraints and optimizations, as well as the addition of custom planning algorithms to generate solar array plans.

SACE is currently in use at the NASA Johnson Space Center (JSC) for monitoring ISS solar arrays; the planning functionality is being certified for operational use. SACE reduces a highly manual process that takes weeks to an automated process that takes tens of minutes. In addition, SACE provides flight controllers with a real-time situational awareness capability by monitoring the status of the various constraints as the plans are executed. Flight controllers can also perform what-if analysis in SACE to address unplanned events that may cause station configuration changes. This article formulates the planning problem, explains how EUROPA solves the problem, and provides performance statistics from several planning scenarios. This paper summarizes the key aspects of the problem and its solution; for more information please refer to (Reddy et al. 2011).



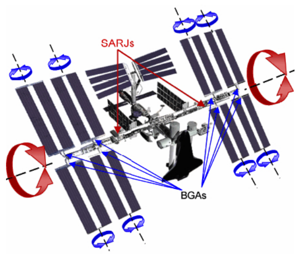


Figure 1: (L) A sample table; (R) The ISS Solar Arrays.

The Solar Array Planning Problem

The ISS has eight solar arrays (Fig. 1 L), each of which is mounted on a rotary joint called the Beta Gimbal Assembly (BGA, denoted β_{ij}). A set of four BGAs is mounted on a truss attached to a Solar Alpha Rotary Joint (SARJ, denoted α_i), with one SARJ on each of the starboard and the port sides of the ISS. Therefore, each solar array has two degrees of rotational freedom, though some degrees of freedom are constrained by the shared SARJs. Array orientations are the integers $[0, 359]$) and are denoted Deg. (If an array is Autotracking, the orientation denotes the final array position.) Each joint can be in one of three modes: Autotrack (A), Park (P), or Lock (for each SARJ) and Latch (for each BGA) (denoted L) and denoted M. In the Autotrack mode, on-board software automatically points the arrays directly at the sun. In the Park mode, the array maintains the current array orientation. In the Lock or Latch modes, a physical barrier is engaged to maintain the current orientation.

The input to the solar array planning problem consists of a sequence of configurations, denoted C_k, such that the start time of $C_k$equals the end time of C_{k-1}. Configurations are defined by properties including events (e.g. EVA, docking spacecraft), solar beta angle (relative sun position), attitude type, attitude reference frame, and ISS Yaw, Pitch, and Roll (YPR), and thruster configuration. The decision variables for a configuration are the 10 array orientations $\alpha_i o^k, \beta_{ij} o^k$ and the 10 array modes $\alpha_i s^k, \beta_{ij} s^k$. The orientation of a single array in configuration C_k is defined by the pair of values $(v(\alpha_i o^k), v(\beta_{ij} o^k))$. The problem is to choose orientations and modes for all arrays for all configurations.

Constraints

There are four classes of constraints that limit orientations: power generation (denoted P), structural load (L), environmental contamination due to particulate accumulation on array surfaces (E), and longeron shadowing (S). These constraints are represented by tables (denoted t) mapping an orientation to a color from the set red (R), yellow (Y), and green (G) (Fig 1 R). One table of each type constrains the orientation and mode in each configuration. The class of table t is denoted $Y(t)$. A separate row, column and cell maintain entries in the event the SARJ is autotracking, the BGA is autotracking, or both arrays are autotracking, respectively. Thus, a table $t : Deg^2 \rightarrow Col$ (the set of colors). In most cases, red indicates infeasibility, for example, insufficient power to run life support or forces strong enough to cause structural damage to the station; yellow values are acceptable but may result in a reduction of vehicle longevity or achievable mission objectives, and green is optimal.

The tables contain headers that specify the properties of the configurations required for the tables to apply. Thus, each table is a conditional constraint. Denote by $T(C_k)$ the set of applicable tables in configuration C_k. Each configuration C_k identifies one of each class of table constraint.

The tables $T(C_k)$ constrain the mode variables $\alpha_i s^k, \beta_{ij} s^k$ by means of a set of Lock-Latch constraints denoted LLC. A fragment of the LLC logic follows: "In determining a mode, prefer Autotrack to Park, and Park to Latch or Lock. If the current orientations are safe, but if there is a possibility of the loads on any joint getting into yellow zone (as per constraint table L) during autotracking, park that joint, and if there is possibility of loads getting into red zone (as per L), lock or latch that joint. Further, if there is a possibility of the contamination constraints getting into the red zone (as per E) during Autotracking, avoid Autotrack, except during contingency operations." Since the tables are uniquely determined by the configuration, $LLC_k(\alpha_i o^k, \beta_{ij} o^k \alpha_i s^k, \beta_{ij} s^k)$ constrains all the modes and orientations on one side of ISS for configuration C_k.

During configuration C_k arrays must be in one of the modes, or transitioning between modes, both by commanding (e.g. Parking or Unlocking) or by turning the arrays. Each array type (SARJ and BGA) has a maximum rate at which the different joints can be slewed or turned. The BGA slew rate $d\beta_{ij}$ is 18°/min while the SARJ rate $d\alpha_i$ defaults to 9° /min but is adjustable up to 30°/min (the SARJ rate is fixed over the course of a plan).

Optimization Criteria

The optimization criteria for a solar array plan is $L(C_k, \alpha_i) = \sum_{v \in c,m,d,t,p} w_v L_v(C_k, \alpha_i o^k, \beta_{ij} o^k \alpha_i s^k, \beta_{ij} s^k)$ where c is the color cost, m is the mode cost, d is the direction change cost, t is the array angular distance cost, and p is the power cost, in order of decreasing importance. We describe the color cost in more detail in this section. Table color tradeoffs are permitted; for instance, an orientation that sacrifices green power for green environment is preferred. These preferences were transformed into a Linear Program and solved offline. The 12 LP variables arise from the three colors (R,Y,G) combined with the four table types (P,L,S,E). The LP constraint enforcing the trade preferring green environment for no worse than yellow power is written $w_{GP} + w_{YE} \geq w_{YP} + w_{GE} + 1$. The sum of these variables is minimized in the LP (lower color costs are preferred.) The color cost $L_c(C_k, v(\alpha_i o^k), v(\beta_{ij} o^k))$ reduces to $\sum_{t \in T(C_k)} w_{r,s} | r = t(v(\alpha_i o^k) v(\beta_{ij} o^k)), s = Y(t)$. We omit discussion of the other optimization critiera.

Planning and Optimization

SACE optimizes configurations sequentially, constraining the solution of subsequent configurations based on the solution of previous configurations. Conflicts may arise because there is insufficient time for actions to switch between optimal solutions for the adjacent configurations. There is no backtracking, and hence there is no guarantee that a feasible solution is found even if one exists. However, SACE users find that most conflicts can be resolved by *merging* conflicting configurations, and finding a single solution that works for all merged configurations. Optimization of a merged configuration requires selecting the *worst* color from all tables that apply to any 'parent' configuration for the purposes of computing color cost, mode cost, and evaluating LLC. While optimizing each array orientation and mode requires searching a complex optimization landscape over the domain of 360×360 possibilities, this cost is constant for a single configuration. The planning algorithm is:

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for each configuration $C_k$ in increasing start time order
  Optimize array orientation (for each SARJ separately)
  Compute Array Modes
  if Optimal solution for $C_k$ conflicts with $C_{k-1}$
    Merge configurations $C_k$ and $C_{k-1}$
    Optimize array orientation for new configuration
    Compute Array Modes
  Prune array positions for $C_{k+1}$ using slew rates and orientation
for each configuration $C_k$ in increasing start time order
  Eliminate Re-Lock / Re-Latch
  Insert Turns and Mode Change States
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Implementation

SACE is built on top of the EUROPA planning system. Each configuration is modeled as a state on a configuration timeline. Each array has a timeline of states including Autotrack, Park, Lock or Latch, Turning, and model change states. Compatibilities describe allowed state transitions. EUROPA's customizable constraint engine was extended to represent the table constraints, the lock latch constraints, propagation algorithms, and the optimizing search algorithms required by the application.

References

Reddy, S.; Frank, J.; Iatauro, M.; Kurklu, E.; Boyce, M. E.; Frank, J.; Ai-Chaing, M.; and Jónsson, A. 2011. Planning solar array operations on the international space station. *ACM Transactions on Intelligent Systems* 2(4).