ICKEPS 2012 Challenge Domain:

Planning Solar Array Operations on the International Space Station

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Abstract

Flight controllers manage the orientation and modes of the eight 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. This document provides the specification of the planning problem of solar array operations on ISS.

1 Introduction

The International Space Station (ISS) solar arrays are designed to automatically track the sun as the station orbits the earth, in order to maximize power production. However, normal ISS operations such as water dumps, docking spacecraft, attitude changes, thruster firings, and extra vehicular activities (EVAs) can increase structural loads, environmental contamination, and thermal stresses on the arrays. A variety of operational safety constraints known as “Flight Rules” prescribe the correct operation of the arrays in order to ensure safety of crew, systems and vehicle, while other rules express preferences for vehicle longevity and mission effectiveness. Ultimately, the flight rules define acceptable array orientations and operational modes, which in turn limit power generation. The operational safety constraints include context-dependent constraints on legal configurations, temporal constraints limiting allowed transitions between configurations, and preferences on the order in which to satisfy the constraints under contingency operations. It normally takes about four weeks of calendar time to manually produce a solar array plan for a four week planning horizon.

This domain involves generating solar array operations plans to optimize ISS solar array configurations subject to these constraints and user-configurable solution preferences. This document describes the planning problem and the requirements for the International Competition on Knowledge

Engineering for Planning and Scheduling (ICKEPS). The rest of this document is organized as follows. Section 2 describes the problem, including the inputs, constraints, the actions available in the array operations, the goals and preferences on ISS solar array plans. Section 3 describes some characteristics of three classes of sample problem (Easy, Medium, and Hard). Finally, section 4 provides some discussion about the modeling language required for the competition.

2 Problem Description

2.1 The Solar Arrays

The ISS has eight solar arrays, 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. Figure 1 shows the ISS solar array arrangement. In addition to the angle of orientation, the state of each rotary joint (SARJ and BGA) is determined by its mode, which can be one of the following:

- ***Autotrack***, ***Park***, or ***Lock*** for each SARJ, and
- ***Autotrack***, ***Park***, or ***Latch*** for each BGA

In the *Autotrack* mode, on-board software automatically rotates the solar arrays so that the array surface is pointing directly at the sun. In the *Park* mode, a drive motor is engaged to maintain the current array angle facing (in the reference frame of the vehicle). In the *Lock* or *Latch* modes, a physical barrier is engaged to maintain the current array facing. In both Park and Lock-Latch, the angle is constrained relative to the rest of the vehicle (but not relative to the sun since the vehicle is still in motion).

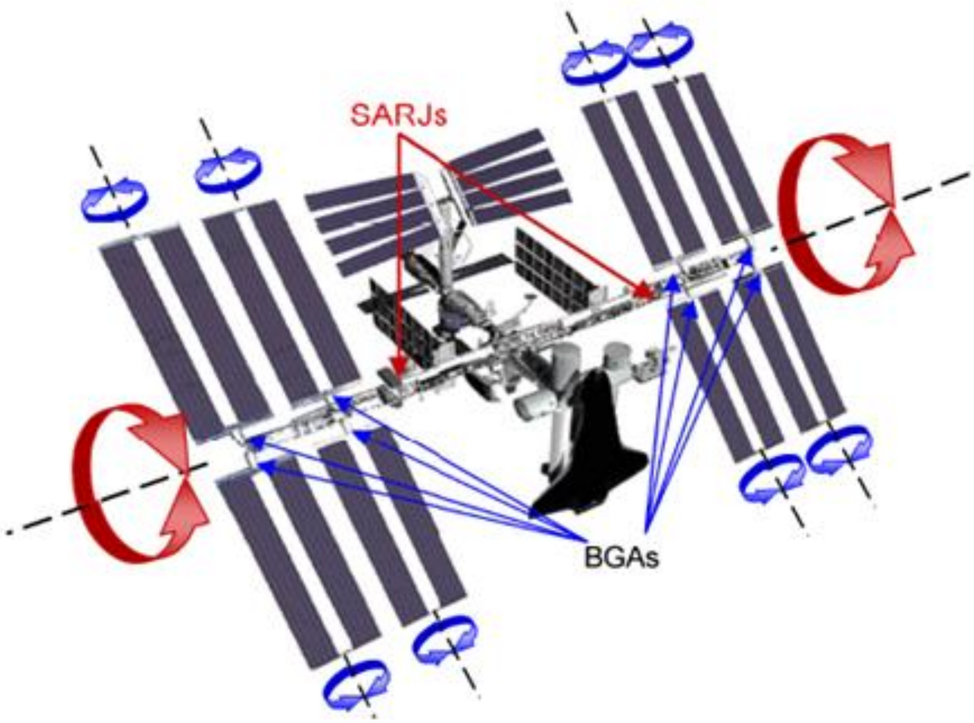

Figure 1. The ISS schematic shows the port and starboard assemblies of 4 solar arrays each, and locations of the SARJs and BGAs. The axes of rotation of the SARJs and the BGAs are also indicated.

2.2 Input: ISS Configurations

The state of ISS relevant to solar array planning is determined by a combination of input timelines. Some input timelines may have flexible start and/or end times and durations. Figure 2 shows a sample solar array planning problem consisting of several input timelines. In Figure 2, we see four events each of which is associated with a start and optional end time, solar beta angle, attitude type, reference frame, and yaw, pitch and roll (YPR). Events 1 and 2 have fixed start and end times, but events 3 and 4 have only the start time specified; this is interpreted as the latest start time, and thus event 3 has a flexible end time and event 4 has a flexible start and end time. An event, in this case, refers to a planned activity that influences solar array planning. The Solar Beta angle describes the position of the sun relative to the ISS. Since ISS orbits the Earth, which in turn orbits the sun, this position changes in a complex way throughout the year, but is essentially unchanged over the course of a week, which is a common planning horizon. A Thruster Configuration timeline (Figure 3) is also provided, and lists thrusters that are allowed to fire during various events. Finally, ISS can be in a 'contingency' state, meaning that something has gone wrong and that some constraints on solar array plans are temporarily lifted. The combination of all of these inputs determines a *configuration*.

#	Start-Stop (GMT)	Event	Solar Beta	YPR	Attitude Name /Reference frame	Contingency	SARJ turn rate
1	170/06:00 170/08:30	Attitude Hold	-27	355.0 357.3 358.0	XVV /LVLH	N	9
2	170/08:30 170/13:30	Prop Purge (DC1)	-27	355.0 357.3 358.0	XVV/ LVLH	N	9
3	170/13:30	Reboost	-27	5.1 357.2 0.0	XVV/ LVLH	N	9
4	171/5:00	Attitude Hold	-27	355.0 357.3 358.0	XVV/ LVLH	N	9

Figure 2. Solar array problem input showing a sequence of configurations, each with a start time and parameters - solar beta, attitude, reference frame, yaw-pitch-roll (YPR), and event - that determine the applicable constraints.

An attitude name, reference frame (attitude and reference frame pair determine the position and orientation of the ISS relative to the sun), the YPR of the station with respect to that attitude, a contingency mode indicator, and the SARJ turn rate. In combination with the solar beta (angle between the solar vector, which points from the sun to the center of the Earth, and the ISS orbital plane) and the array orientation, this determines the shadowing on the arrays as well as the loads and forces on the arrays and their joints. Of course, the array facing relative to the sun, coupled with shadowing, influences power generation. Specific events (e.g., docking, EVA, water dump), the port to be used for docking, and the attitude control thruster selections determine additional loads, environmental contamination (e.g., from thrusters) that can damage the solar arrays, and shadowing of the arrays. Other parameters that influence both the loads and contamination include the alternate jet selects used in case of thruster failure. The input timelines will have no gaps.

2.2.1 Input: Event Names

The list of event names and parameters is as follows:

- Approach (Spacecraft:{ATV, Orbiter, Soyuz, Progress})
- Docking (Spacecraft:{ATV, Orbiter, Soyuz, Progress}, Port:{SM, DC1, FGB})
- Undocking(Spacecraft:{ATV, Orbiter, Soyuz, Progress})
- Reboost

- Maneuver(Type:{debris-avoidance, attitude})
- Prop purge (Location:{SM, DC1})
- Water dump(Location:{Lab, Orbiter})
- Attitude hold

2.2.2 Input: Configuration information

Additional configuration information describing a planning problem is as follows:

- Solar beta:{integer [-60 60]}
- Attitude name {XVV, XPH, YVV}
- Reference Frame:{XPOP, LVLH}
- YPR:{integer.decile [0.0,359.9] x integer.decile [0.0,359.9] x integer.decile [0.0,359.0]}
- SARJ turn rate:{integer [9 30]}
- Contingency mode:{boolean}

2.2.3 Input: Thruster Configuration

#	Start-Stop (GMT)	Attitude	Thruster	Spacecraft	Port
1	170/08:30	R	ISS-SM	N/A	N/A
2	170/08:30	P	Docked	Prog	DC1
3	170/08:30	Y	Docked	Prog	DC1

Figure 3. Solar array problem thruster configuration showing start/stop time, attitude being controlled, and additional information on the thruster controlling that attitude.

Figure 3 provides an example of thruster configurations in the solar array problem. Thruster configuration start and end times are in mission *day / hours : minutes*. A spacecraft thruster configuration is a vector of three pairs. Each pair specifies:

- What attitude variable being controlled:{Y,P,R}
- Spacecraft thruster controlling that axis:
  - ISS-SM, ISS-CMG
  - Docked spacecraft

- Spacecraft:{ATV, Orbiter, Soyuz,Progress}
- Port:{SM, DC1, FGB}

2.3 Input: Constraint Tables

There are four classes of constraints that limit the angle orientations: power generation (denoted P), structural load (L), environmental contamination due to particulate accumulation on array surfaces (E), and longeron[1] shadowing (S). These constraints are represented in tables (denoted *t*) mapping an orientation of a single array to a color from the set red (R), yellow (Y), and green (G). The set of colors is denoted *Col*. In most cases, red indicates 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 result in a reduction of vehicle longevity or achievable mission objectives, and green is optimal. A visual representation of a 360x360 table is shown in Figure 4.

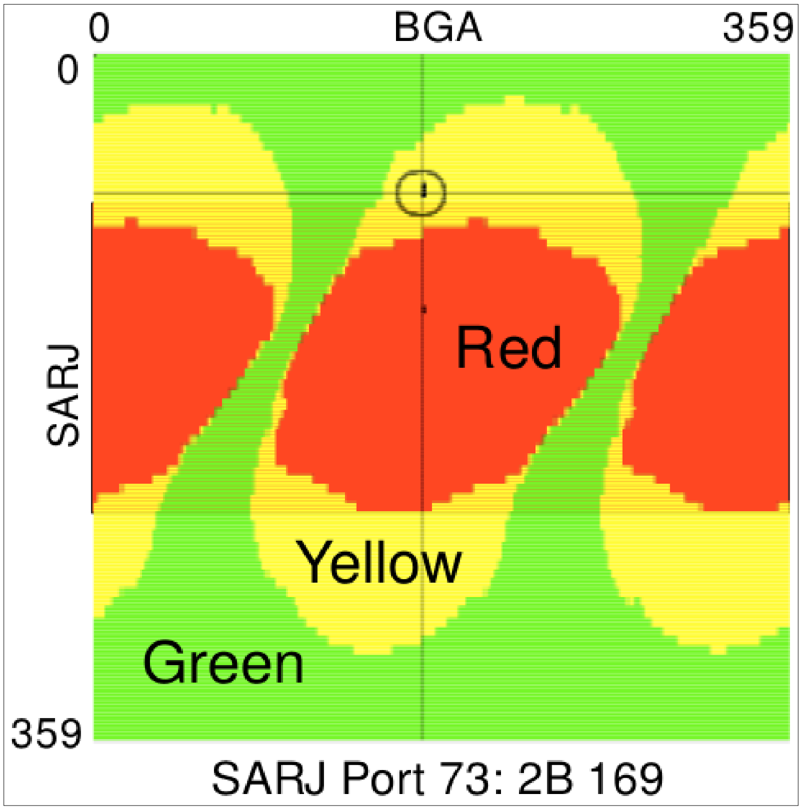

Figure 4. A representative table indicating, for one SARJ and one BGA, the safety of setting the solar array orientations; the y-axis is the SARJ orientation and the x-axis is the BGA orientation; green is preferred, yellow is acceptable, and red is (most of the time) infeasible.

1 Longerons are structural elements that keep solar array blankets in tension. Differential shadowing among the longerons can, over time, damage the structures that hold them together.

Tables apply under specific circumstances. A single table *t* applies not only to a single array, but also for a designated value of solar beta, attitude, reference frame, YPR, event, thruster configuration, and contingency state. Thus, in addition to the input timelines, a planning problem also has as input a large set of constraint tables, as the one showed in Figure 4. Moreover, exactly one of each class of table (P,L,S,E) applies at any instant of time in the planning horizon.

The complete specification of a table is as follows:

Header

- Array angle pair:{P,S} x {1,2,3,4}
- Table type:{P,L,S,E}
- Solar beta:{integer [-60 60]} see 2.2.2 above
- Attitude name {XVV, XPH, YVV} see 2.2.2 above
- Reference Frame:{XPOP, LVLH} see 2.2.2 above
- Roll:{integer.decile [0.0,359.9]} see 2.2.2 above
- Pitch:{integer.decile [0.0,359.9]} see 2.2.2 above
- Yaw:{integer.decile [0.0,359.9]} see 2.2.2 above
- Event Name: see 2.2.1 above
- Roll Thruster: see 2.2.3 above
- Pitch Thruster: see 2.2.3 above
- Yaw Thruster: see 2.2.3 above

Data

- 360 x 360 table; each entry is {R,Y,G} (red, yellow, green)
- SARJ (Port or Starboard) angle indicated in the row, BGA (1,2,3,4) angle indicated in the column

2.4 Constraints on Solar Array Plans

2.4.1 Array Angles

The orientation of a single array is defined by the pair of values of the SARJ and BGA. Orientations are expressed in single digit degrees, that is, each array can be in one of 360 positions. The degrees of freedom of four BGAs and one SARJ are linked; thus, for one side of the ISS, the total number of distinct assignments of positions to the arrays is 360^5.

2.4.2 Constraint Table Values

The arrays cannot be assigned orientations such that the value of any applicable power table, longeron shadowing table, or loads table is red. It is permissible for the value of an environment table value to be red.

When considering the values in tables, it is important to distinguish *Autotrack* from the other modes. Consider the table in Figure 4. When both arrays are in a fixed position the applicable color is easily found. When, for example, the SARJ is in *Autotrack* and the BGA is in either *Park* or *Latch*, then the array in question transits through all the colors in a column of the table; when the SARJ is parked or locked and the BGA is in *Autotrack*, then the array transits through all of the colors in a row of the table. Finally, when both arrays are autotracking, in general it is assumed that every cell of the table is visited. So, when determining the color value from a table for an array mode, use the worst color in the applicable row/column/table depending on whether one or both arrays are autotracking.

2.4.3 Array Rotation Rate and Mode Duration

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 slew rate $d\alpha_i$ defaults to 9°/min but is adjustable up to 30°/min (however it is constant over the planning horizon, and thus is a problem input). These rates govern both turn rate and *Autotrack* rate.

2.4.4 Lock Latch constraints

These constraints are basically described as the following: If the current orientations are safe (green zone), 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. The modes cannot be independently determined for each joint, because four BGAs are mounted on each SARJ, and the legitimate modes for the SARJ depend on the behavior of the BGAs mounted on it. The two following tables provide a complete specification of the lock-latch constraints:

Array Modes	Loads	Env.	Cont.	Lock/Latch
Neither autotracking	Yellow cell, Row has red			SARJ=Lock BGA=Latch
Neither autotracking	Green cell, Col has red			SARJ=Lock BGA=Park
Neither autotracking	Green cell, Col has no red			SARJ=Park BGA=Park
Neither autotracking	Green cell, Col has red			SARJ=Lock BGA=Latch
Neither autotracking	Green cell	Col has red		SARJ=Park BGA=Park
SARJ autotracking BGA not autotracking	Col all green	Col all green		BGA=Park
SARJ autotracking BGA not autotracking	Col has no red	Col has red or yellow	Y	BGA=Park

Table 1. Lock Latch constraints indicating whether the SARJ must be latched.

Array Modes	Loads	Env.	Cont.	Lock/Latch
SARJ autotracking BGA autotracking	Table all green	Table has no red		
Neither autotracking	Green cell, Row has red			SARJ=Park BGA=Latch
Neither autotracking	Green cell, Row has no red			SARJ=Park BGA=Park
Neither autotracking	Green cell	Row has red		SARJ=Park BGA=Park
SARJ not autotracking BGA autotracking	Row all green	Row has red or yellow	Y	SARJ=Park
SARJ not autotracking BGA autotracking	Row all green	Row all green		SARJ=Park

Table 2. Lock Latch constraints indicating whether the BGA must be locked.

It is possible that two entries provide conflicting guidance on whether an array mode should be *Autotrack, Park, or Lock/Latch*. In the event of a conflict, the resolution is to choose the most constraining mode, where *Autotrack,* is least*, Park* is next*, and Lock/Latch* is most constraining.

2.4.5 Well Formed Plans

In a legal plan, each array joint is either *Turning* or in one of the modes, *Autotrack, Park, or Lock/Latch*. Each configuration requires the arrays to be in one of the modes, or turning, continuously while the configuration holds. If the array angle must change between configuratoins, then the turns must begin early enough so that the new array modes start when the later event starts. The array angles do not change during *Park* or *Lock/Latch*. The array angle may only be changed by *Turn* or *Autotrack*.

Consecutive events can be "covered" by a long interval during which one or more arrays remain in the same modes. The following constraints and preferences hold: if a plan requires 'park-lock-park' at the same angle, then it is preferred to 'lock' over the entire interval. Similarly, if a plan requires 'park-latch-park' at the same angle, then it is preferred to 'latch' over the entire interval. Finally, all SARJ turns should complete before all BGA turns start.

If an event has only one time, this is its latest start-time; otherwise the times define fixed start and end times of an event. The time of turns, autotrack and lock-unlock times can propagate, but must obey the temporal constraints imposed by the input event timeline.

Finally, joints must be in position before setting the mode to *Lock* or *Latch*, and turns are executed when it is safe to do so. An array must be in the planned position and mode at the beginning of the configuration. This final constraint can be relaxed in an "attitude hold" configuration, as no safety-critical events take place during this configuration.

2.5 The Goal

The goal of the planning problem is to find a set of actions (change modes and turns), states, and their extents that (1) are consistent, (2) do not violate the constraints, and (3) are optimal with respect to the solution preferences. For a given configuration of the ISS, the objective is to find orientations and modes for the different arrays that maximize the power availability, but at the same time keep them in a feasible space with respect to the various constraints.

2.6 Preferences

Further preferences and objectives during planning are, in priority order:

- Preferences on the color values in the applicable tables that correspond to the array orientation;

- Preferences on the mode minimizing turns of the rotary joints once sufficient power is available to meet critical needs (power is in the green zone);
- Minimizing the change in direction of rotation of the joints, and;
- Minimize turn distances.

2.6.1 Preferences on Orientation

The preference on the orientation of the arrays has two components. The first of these components is the preference on the colors for the set of tables applicable to a single array. Recall that only one table of each constraint class (Power, Load, Longeron Shadowing and Environments) will apply to a single array.

The preferences on orientation have two parts. The first part is a complete specification on the preferences for a single SARJ and BGA pair. This is shown in Figure 5 (Grey in Figure 5 indicates “don’t care”). Every possible color combination is either totally ordered (show at the top of the figure) or invalid (shown at bottom). The second part is an additional set of preferences that show how to trade one color of a very important table (e.g. power) for worse colors of less important tables (e.g. environment). These trades are shown in Figure 6 (Grey in Figure 6 means “don’t care”, but the table values for grey cells must be the same on both sides of the inequality.)

This set of preferences is ‘incomplete’ in the sense that the preferences don’t necessarily result in a total order of all color combinations of the 5 array angles (1 SARJ and 4 BGAs) on one side of the ISS. In order to complete the total order, if two configurations of the 5 arrays are not otherwise comparable, then treat each of the legal configurations of any 2 arrays as having a numerical score between 1 and 24, sum the four values, and prefer the configuration with the minimum sum. Examples are shown in Figure 7. A similar means of determining preferences should be used to combine the solutions for the two halves of the vehicle. Note it may take some effort to determine whether two configurations are ranked according to the preferences.

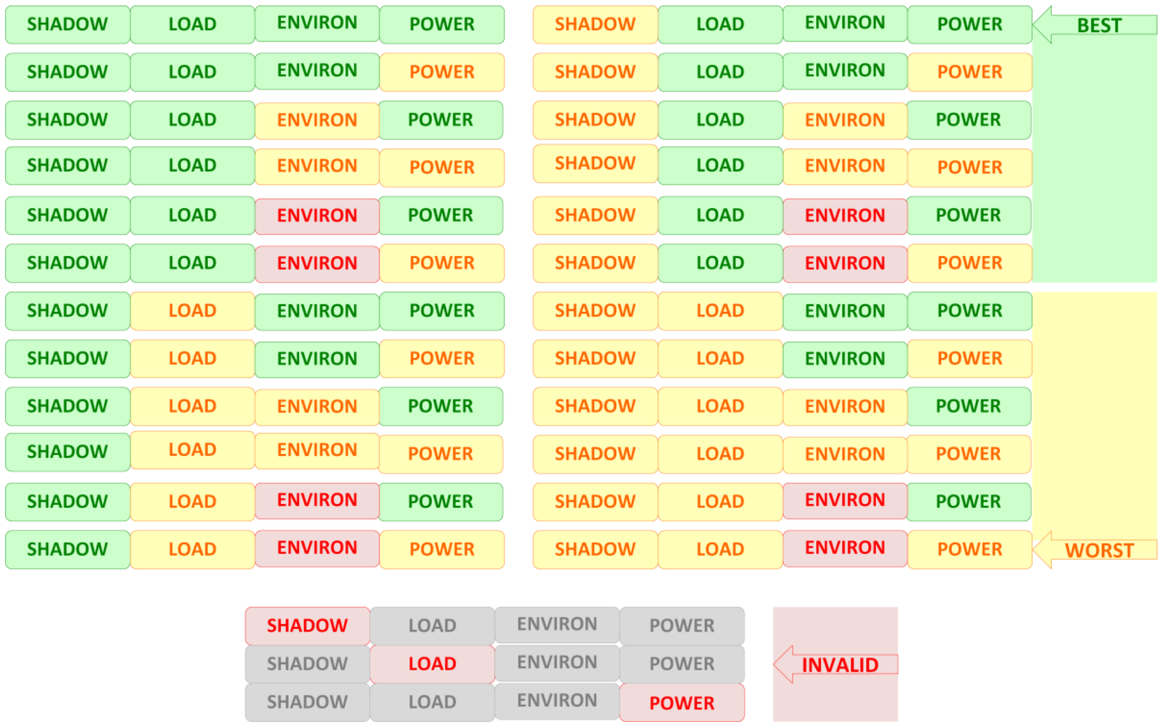

Figure 5. Preferences on the colors from applicable tables on a single array. (Note that Yellow Shadow is permitted is worse than green Shadow.)

Notice that, in some cases, the Lock Latch constraints allow the arrays to autotrack through a color other than green (e.g. through yellow power or shadow, or when in contingency mode it is possible to autotrack through red Environment cells). In these cases the preferences still apply, but the worst cell in the row or column is used to determine the preferences. So if contingency applies, and the planner can autotrack through different sets of Environment cells, if it is possible to only autotrack through green environment cells, this is preferred.

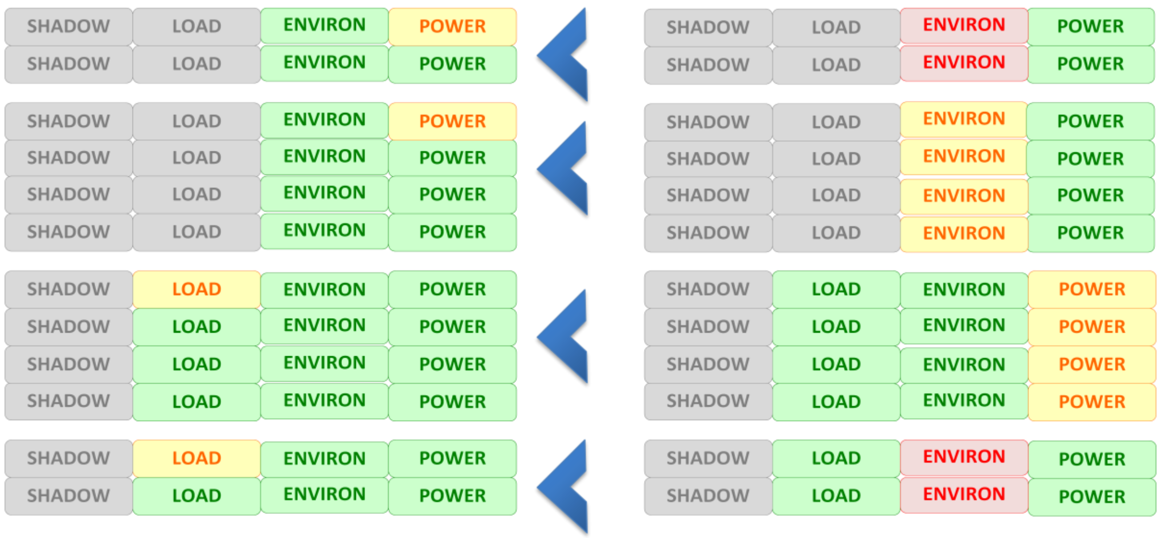

Figure 6. Preferences on the colors from applicable tables on all four BGAs associated with one SARJ.

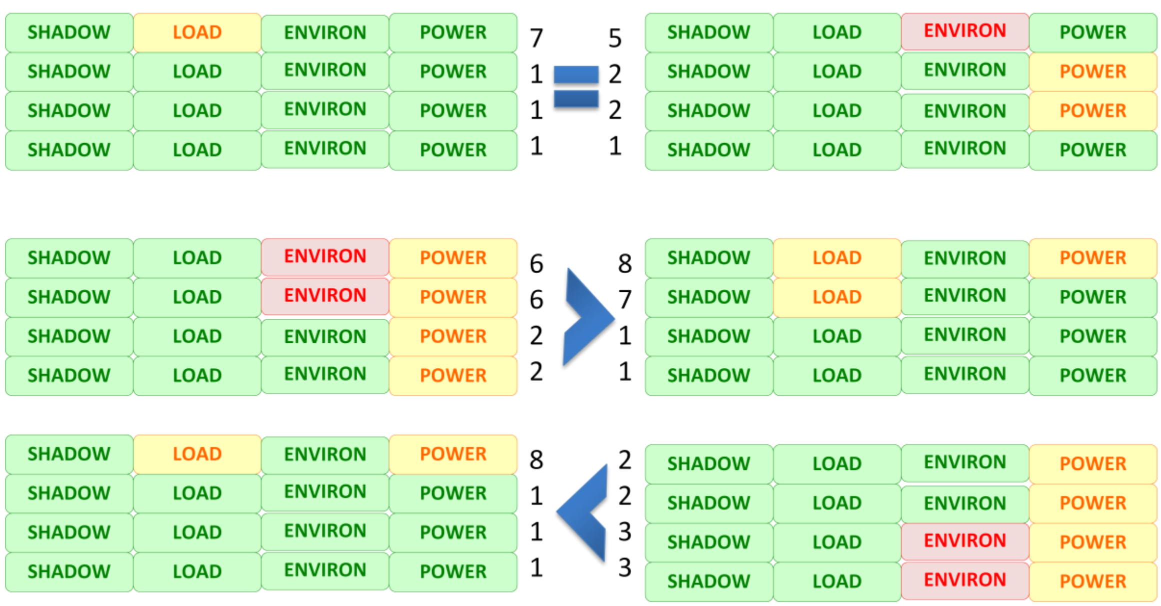

Figure 7. Inferred preferences on the colors from applicable tables on all four BGAs associated with one SARJ. (Note the '>' signs may appear to go the wrong way, but lower total scores are preferred!)

2.6.2 Preferences on Mode

In determining a mode, prefer *Autotrack* to *Park*, and *Park* to *Latch* or *Lock*.

2.6.3 Ordering Mode and Color Preferences

In some cases mode and color preferences may conflict. For example, if some environment tables contain yellow cells, it may still be possible to Park an array to avoid Autotracking through those yellow cells. Optimizing the color is preferred to optimizing mode.

2.6.4 Minimizing Change in Direction

Given that an array must turn, it is always preferable to continue turning in the same direction rather than reverse direction.

2.6.5 Minimizing Turn Duration

Given that an array must turn, it is always preferable to turn the arrays the shortest distance possible. Notice, though, that if an array is already turning that the preference to continue turning in the same direction, which is more important, may lead to a larger turn distance.

2.6.6 Optimizing over the plan

There is no explicit criterion for optimizing over a complete plan. While the preferences for a single configuration do lead to a well-defined Pareto frontier, for the purposes of the competition it is no necessary to guarantee that a plan is Pareto-optimal.

2.7 The Actions

The actions apply to the 10 ISS solar array angles. The possible actions are the following:

- *mode changes* (*Park*, *Lock* or *Latch*, *Autotrack*) of the 8 different BGAs and 2 SARJs; and
- *turn* or *slew* to change the orientation of the arrays.

Both the state and the action take time. Actions do not have flexible duration.

2.7.1 Mode change: Park

Parks the array at the angle defined by the end state of the previous array mode. No duration constraint, but transitioning out of *Lock* or *Latch* into *Park* takes 20 minutes.

2.7.2 Mode change: Lock / Latch

Locks (SARJ) or latches (BGA) to the angle defined by the end state of the previous array mode. Transitioning into *Lock* or *Latch* takes 20 minutes.

2.7.3 Mode change: Autotrack

Autotracks the array (follows the sun). Refer to 2.4.3 for array rotation rates, which coupled with duration, define ending array position. *Autotrack* mode must last at least 90 minutes. Transitioning out of *Lock* or *Latch* into *Autotrack* takes 20 minutes. When the arrays autotrack the angle increases, both for the SARJ and the BGAs.

2.7.4 Turn or Slew

This action changes the angle of the array. The angle can be changed in the positive or negative direction. Refer to 2.4.3 for array rotation rates, which in turn dictate duration. It is not permissible to turn any arrays during docking or undocking, re-boost events, or station maneuver events.

2.7.5 Docking and Undocking events

For the purposes of this problem, docking and undocking of spacecraft to ISS are not considered actions that can be planned, but events that constrain the solar array plan. The consequences of docking a spacecraft to a particular docking port will influence the thruster configuration and thus what thrusters may be used for reboosts or maneuvers, but this is accounted for as part of the plan input. The planner should not attempt to reason about the consequences. (The planner may adjust the times of events for which there is some flexibility.)

2.7.6 Thruster Configuration and events

The thruster configuration timeline will fully specify what thrusters are to be used during any event. The planner should not search over thruster configurations in order to optimize the selected tables.

2.8 The Problem

Generating a solar array plan requires finding feasible and optimal values for the orientations and modes of the eight BGAs and the two SARJs in each input event, as well as actions to change the modes and orientations of the arrays from one event to the next. The problem state is composed of the orientations, modes, and the (sequence of) events and other relevant information (solar beta angle, SARJ speed, contingency specification).

3 Scenarios

3.1 Easy

An easy problem is one for which every applicable table is green. Table color preferences need not be considered at all, and no lock-latch constraints apply since it will be possible to autotrack all of the arrays. Nevertheless, this provides a nice test case to ensure that inputs and tables are parsed.

The preferences apply when either power or longeron shadowing tables have yellow cells, but the lock latch constraints do not apply. Combinations of power or shadow tables with yellow power and shadowing force the planner to reason about preferences and introduce the need to actually plan actions like turns to hit the sweet spots where both applicable power and shadow tables are green. Also notice that it does not matter how many yellow cells there are, but it matters how many tables have yellow cells; so the planning problem will be to find a SARJ angle where the fewest BGAs autotrack through yellow, or to find a set of BGA angles where autotracking the SARJ leads to the fewest yellows.

This set of problems can have a small number of applicable tables. We can, for instance, omit contingency, SARJ rate, and multiple attitudes from this problem set.

3.2 Medium

The Lock Latch constraints apply and the preferences become more difficult to manage when Load and Environment tables have yellow cells.

This set of problems can have more applicable tables and thus require more aggressive optimization of modeling and internal data representation.

3.3 Hard

The whole enchilada! This set of problems has a very large number of tables.

4 Data

We provide examples of input data for the three scenarios. The inputs for each problem instance will consist of the following:

- An Event Timeline

- A Thruster Configuration Timeline
- A table header file. This is an Excel file containing on each line a header specification and a file name.
- A set of constraints tables. Each table is a PNG file. A PNG-to-TXT converter is included in order to provide a txt representation of the png tables; given a png table, the converter maps the 360x360 pixels to 360x360 characters in a txt file, in which R is red, G is green, and Y is yellow.

The Event and Thruster Configuration timelines are consolidated in a single PDF file, while the Excel and .png files are in separate directories.

The data can be found at:
http://icaps12.poli.usp.br/icaps12/sites/default/files/ickeps/sacedomain/Input.zip

5 Modeling Language Requirements

There is no restriction on the modeling language to be used while modeling the problem. However, we encourage competitor to use declarative languages widely used in the AI Planning community.

References

REDDY, S., FRANK, J., IATAURO, M., BOYCE, M., KURKLU, E., AI CHANG, M., JÓNSSON, A. 2011. Planning Solar Array Operations for the International Space Station. In ACM Transactions on Intelligent Systems and Technology (TIST) Volume 2 Issue 4.