Spatial Planning for International Space Station Crew Operations

Bradley J. Clement*, Javier Barreiro**,
Michael J. Iatauro**, Russell L. Knight*, Jeremy D. Frank**

*Artificial Intelligence Group, Jet Propulsion Laboratory, California Institute of Technology, USA
e-mail: firstname.lastname@jpl.nasa.gov

**Planning and Scheduling Group, NASA Ames Research Center, USA
e-mail: javier.barreiro@nasa.gov, michael.j.iatauro@nasa.gov, jeremy.d.frank@nasa.gov

Abstract

An important aspect of mission planning for NASA's operation of the International Space Station is the allocation and management of space for supplies and equipment. The Stowage, Configuration Analysis, and Operations Planning teams collaborate to perform the bulk of that planning. A peer-to-peer automated planning architecture is proposed to support the three teams in a way that maps naturally to the current organizational structure. Additionally, a Geometric Reasoning Engine is developed to support spatial planning for each of the teams. An initial implementation of the proposed solution has been tested on scenarios taken from actual operations of the International Space Station.

1 Introduction

Planning for NASA's operation of the International Space Station (ISS) is a collaboration among several teams and disciplines at Johnson Space Center. Three of these teams work together to help the crew manage space for supplies and equipment inside the ISS.

Stowage tracks the location of supplies and trash and specifies how to pack items in bags, how to move bags in and out of the visiting vehicle, and where to stow items when unpacked.

Configuration Analysis, Modeling and Mass Properties (CAMMP) defines volumes within the ISS that must be kept clear to ensure mobility of the crew and equipment through modules of the ISS and proper functioning, visibility, and quick access to equipment, controls, sensors, ventilation, and lighting for maintenance and safety reasons. CAMMP also plans where new payload racks and other equipment are placed and determines what activities cannot be performed simultaneously according to the volumetric constraints just described.

Operations Planning plans and manages overall crew activities. With respect to Stowage and CAMMP, this group schedules time for crew members to pack, unpack, and relocate items when needed for vehicle docking, maintenance, science payload requirements, or other crew activities.

Similar to other ground planning systems [1,2,3], automated planning promises to improve the efficiency of these tasks in decision support. Automated ISS crew planning systems have been investigated in the past [4,5] as well as distributed planning systems [6,7,8]. In this paper we describe a distributed planning system specific to spatial planning internal to ISS among the Stowage, CAMMP, and Operations (Ops) planning teams. some of the interactions among these three teams and their implications for ISS operations. We then propose how to use automated planning tools to improve mission planning in a peer-to-peer fashion that maps naturally to the organizational boundaries of the teams. We also specify how a geometric reasoning engine can be architected to meet different needs of the teams' planning tools. Finally, we describe how the proposed solution applies to real scenarios that have arisen in the past during actual operation of the ISS.

Figure 1 depicts the current interactions and exchange of data among the three teams. Ops Planning manages the crew schedule. The Stowage planner maintains constraints and preferences on how supplies are stowed in different racks or elsewhere when the racks are full. Stowage uploads requests to the crew to pack/unpack and relocate items for each vehicle visit. Ops Planners coordinate the timing and crew assignments for those activities. Stowage and Ops Planners exchange information about those activities before the requests are uploaded to the crew. The CAMMP group specifies target locations for new equipment and manages volumetric constraint rules that have to be respected by both the Stowage and Ops Planning groups. The teams informally consult each other on where to move supplies and equipment in the context of the crew schedule.

We start by describing the current planning process for managing item location, the effort to monitor and enforce volumetric ground rules and constraints, and the difficulty in maintaining a continuous flow of information between the teams as requirements change during the planning period leading up to a mission and also during operations when off nominal situations arise. These tasks have greatly increased in complexity with more astronauts onboard ISS, requiring more supplies. To compound this problem, Space Shuttle visits have been less frequent requiring greater amounts of supplies to be sent to bridge the longer time between visits.

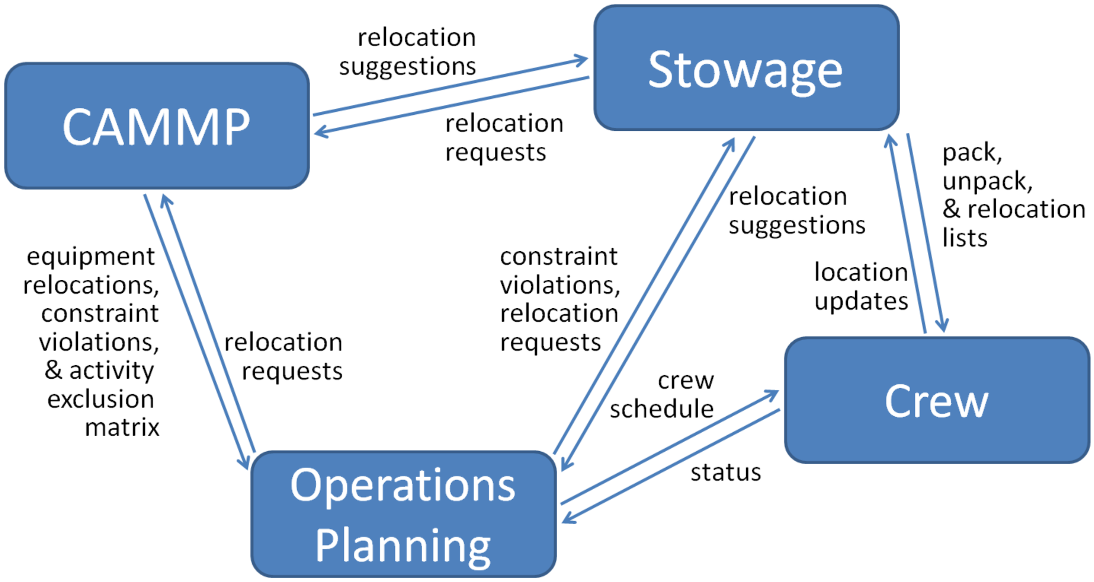

Figure 1. Current interactions of planning teams to manage space for supplies and equipment on the ISS.

Moreover, the tools and databases employed by these different groups are not integrated at all, and since the IVC and Stowage groups are not working with the Operations Planners during real-time operations, the Operations Planners must often handle these issues on their own.

In the context of ISS, the planning problem involves determining

- where new items will be located,
- where existing items must be relocated,
- where items may be stored temporarily until a place has been made available,
- who from the crew will perform these movements, and
- when, respecting time and safety constraints while optimizing preferences.

We describe an approach to automating this planning process. The planning teams currently operate in a decentralized, peer-to-peer manner, thus, our approach is not to provide a centralized solution, instead, we consider customized planning capabilities for each of the teams and propose a flexible architecture to exchange plan information. We also specify how a geometric reasoning engine can be architected to be shared by multiple planning tools and serve their diverse needs

We build a demonstration our proposed solution and apply it to planning scenarios taken from actual ISS operations, such as relocating supplies that block access to equipment needing maintenance or discovering stowage bags blocking an air vent. We then discuss how our solution addresses these scenarios and future operations in general.

2 Current Planning Process

Figure 1 depicts the current interactions and exchange of data among the three teams. Operations Planning manages the crew schedule. The Stowage planner maintains constraints and preferences on how supplies are stowed in different racks or elsewhere when the racks are full. Stowage uploads requests to the crew to pack/unpack and relocate items for each vehicle visit, Ops Planners coordinate the timing and crew assignments for those activities. Stowage and Ops Planners exchange information about those activities before the requests are uploaded to the crew. The CAMMP group specifies target locations for new equipment and manages volumetric constraint rules that have to be respected by both the Stowage and Ops Planning groups. The teams informally consult each other on where to move supplies and equipment in the context of the crew schedule.

2.1 Stowage

The Stowage team supports the ISS crew in the management of all the supplies that are kept on board, it also helps them manage the trash that is generated during each increment. The Stowage group interacts with the crew through messages that are uploaded as part of the daily operations; there are three categories of messages:

- Prepack/Unpack: these communicate to the crew the items and locations that need to be packed to be brought down, or unpacked when a visiting vehicle like the Space Shuttle arrives.
- Stowage Matrix/Daily Notes: these communicate

to the crew in a concise way the location of any supplies needed to perform scheduled tasks

- Trash: these are used to coordinate the staging and translation of trash as it is being generated during operations
- Audit: these are requests to the crew to perform routine location audits to ensure that the Stowage group has an accurate representation of the location of supplies on board.

The Stowage group currently maintains an Inventory Management System (IMS) database, where it keeps track of all the items on board and of the items that will make part of the prepack and unpack messages. It separately maintains a representation of how items are stored onboard. The messages that are uploaded to the crew and other products that are needed during operations are generated through partially manual processes that use data from those two sources.

The Stowage group employs a largely manual process for planning supply bag relocations, integrating and validating CAMMP constraints, and coordinating with Ops planning on activities that affect crew schedule. Automated planning and promises to make each of these tasks more efficient.

2.2 CAMMP

The CAMMP team (previously named Internal Volume Configuration [9]) receives their main input from the Payloads team in the form of planned equipment to deliver to the ISS and inquiries about whether designs can meet volume constraints. The CAMMP team also gets inquiries from the Stowage group about constraints impacting the storage of supplies. For example, the CAMMP team may help Stowage determine whether some supply bags can be safely stacked in a non-standard location. Volume constraints are documented with other constraints, ground rules, and requirements [10].

CAMMP's responses to inquiries often include CAD models of the interior of ISS modules showing the placement of equipment or supplies, constraint volumes, and violations of the constraints. CAD models depicting the interaction of equipment with constraint volumes are a regular output of the group. In addition, the group creates a matrix of crew activities, showing which activities cannot be performed simultaneously. Since lab equipment can be deployed in the aisle way, nearby equipment cannot be deployed simultaneously without violating translation path constraints, minimum passageway areas for crew and equipment to move between hatches through ISS modules. There are many other products of the IVC group that we do not discuss.

Emergency translation path constraints (as depicted in Figure 2) apply to all ISS modules and can only be obstructed by worksites in use by crew members and equipment in-transit. Nominal crew translation paths are a little larger and allow temporary obstructions for equipment protrusions and maintenance activities. For laboratory modules the nominal path is larger to allow movement and manipulation of equipment of standard sizes. Most modules also require a passageway of different shape to allow for equipment translation.

Volume constraints are also specified for worksites and visibility and access to critical equipment and controls, including caution and warning labels and indicator lights, audio terminals, power switches, fire detection indicators, fire extinguishers, gas masks, oxygen ports, and compartment doors. In addition, there are volume constraints for light sources and switches, and air inlets, outlets, valves, ports, and sensors (including smoke detectors).

Some of these volumes must extend to intersect with crew translation paths or work volumes. There are permanent exceptions to volume constraint rules. Other exceptions require a waiver. The volumes vary in shape and may depend on the shape of the object to be accessed. For air vents, specified percentages of obstruction are allowed at different distances from the vent.

2.3 Operations Planning

The Station Ops Planner leads the coordination, development and maintenance of the station's short-term plan, including crew and ground activities. The plan includes the production and uplink of the On-Board Short Term Plan (OSTP) and the coordination and maintenance of the on-board inventory and stowage listings. Planning for an ISS increment (the time period a specific crew remains on the ISS) is done in several iterations with an increasing degree of granularity that starts 8 months before the increment and ends with weekly plans during the increment.

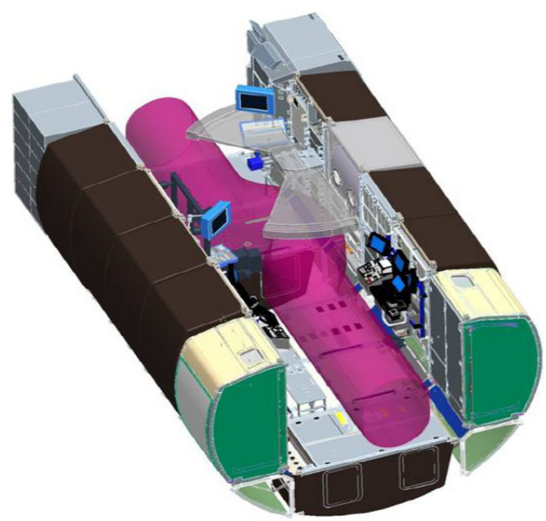

Figure 2. The emergency translation path in this CAMMP CAD model bends around deployed equipment in an ISS module.

The crew will typically stay as close as possible to the OSTP, although unforeseen repairs, medical procedures and other similar urgent conditions normally arise during each increment. Any changes to the OSTP are handled through a Planning Product Change Request (PPCR), which requires approval of at least 3 people.

The nominal plan for the crew has a backbone that repeats every day and consists of sleep (8.5 hrs), post-sleep activities (1.5 hours), Daily Planning Conference (15 minutes), a midday meal (1 hour) and ends with pre-sleep activities (2 hours) . Science payload, maintenance, medical and other kinds of activities are scheduled around this backbone. When there is a visit from the Space Shuttle, the Stowage team uplinks prepack and unpack messages directly to the crew, after some offline coordination with the Ops planning team. The Ops planner must then separately modify the crew schedule so that crew members can execute all the packing, unpacking and item relocation activities that are needed. The Ops planner typically gives the crew members the list of activities to be performed, and time periods available to perform them, the crew members then decide the exact order and physical motions to carry them out.

The Ops Planner also receives volumetric constraints in the form of an exclusion matrix (activities that cannot be performed at the same time) and keep-out zones. These are currently static documents that are generated in advance.

There are a number of issues with the current approach.

- The Ops planner must manually integrate the Stowage-generated activities into the plan.
- The Ops planner must manually integrate and check IVC constraints.
- The Ops planner doesn't have any visibility into geometric restrictions for crew activities, this means that they may generate plans that respect IVC constraints, but that may be inefficient and require the crew to move material back and forth in order to have access to parts or locations.

3 Proposed Planning Process

We propose a customized planning application for each team that supports their domain and respects their current responsibility boundaries in a peer-to-peer fashion. Under this assumption, each planning application has a distinct model; therefore, plan coordination must be performed in a loosely coupled manner, where tasks in one planning application are mapped to tasks in another. We adopt a previously used, straightforward approach for to integration for the proposed architecture [8].

As described in the Current Planning Process section, the Stowage group will mainly be interested in the movement of supplies and how they are stored. The CAMMP team will be more involved in the placement and physical configuration of equipment. With respect to Stowage and CAMMP, the Ops Planners will want to know how the movement and location of these different items affects the crew schedule. The role of automated planning in this setting is to help members of each planning team make decisions about how to manage the location of these items in the context of overall mission planning. In addition to traditional task based planning, geometric reasoning plays an important role in this problem:

- Most of CAMMP's job involves geometric reasoning to define volumetric constraints, determine the location of new equipment or relocation of existing ones, and report known constraint violations.
- Both Stowage and Ops Planning need some degree of geometric reasoning to ensure that constraints specified by CAMMP are respected.
- Stowage can benefit from geometric reasoning in determining where supplies will fit in stowage racks, for example.
- Ops Planning also needs geometric reasoning to ensure that it does not create inefficient plans that cause the crew to spend a lot of time accessing equipment and supplies or perform unnecessary relocations.

Since the model for geometric reasoning is the same for all groups (that is, the ISS geometric model), we propose creating a separate Geometric Reasoning Engine that supports the planning systems for all three groups.

3.1 Geometric Reasoning Engine

The Geometric Reasoning Engine (GRE) uses CAD model abstractions for a fixed point in time to

- check for violations to volume and stowage constraints,
- evaluate preferences for item location, and
- suggest relocating items to resolve conflicts or better meet preferences.

The relocation of items is a simplification of the motion planning problem [11] where only the location is optimized, not the route.

Figure 3 depicts the interactions of the three planning groups through interfaces between automated planners and the GRE. It is the planning systems' responsibility to check for constraint violations over a time horizon, so the GRE must be invoked for different situations. The planners do this by initializing the GRE with an initial state of the ISS and simulating the movements in the current plan while checking for constraint conflicts between each movement. The planner can also incorporate relocation suggestions from the GRE and modify the simulation. We are considering extending the GRE interface to include sequences of move operations in order to gather conflicts for an entire simulation. However, this alone would not be sufficient for conflicts that depend on the concurrent movement of

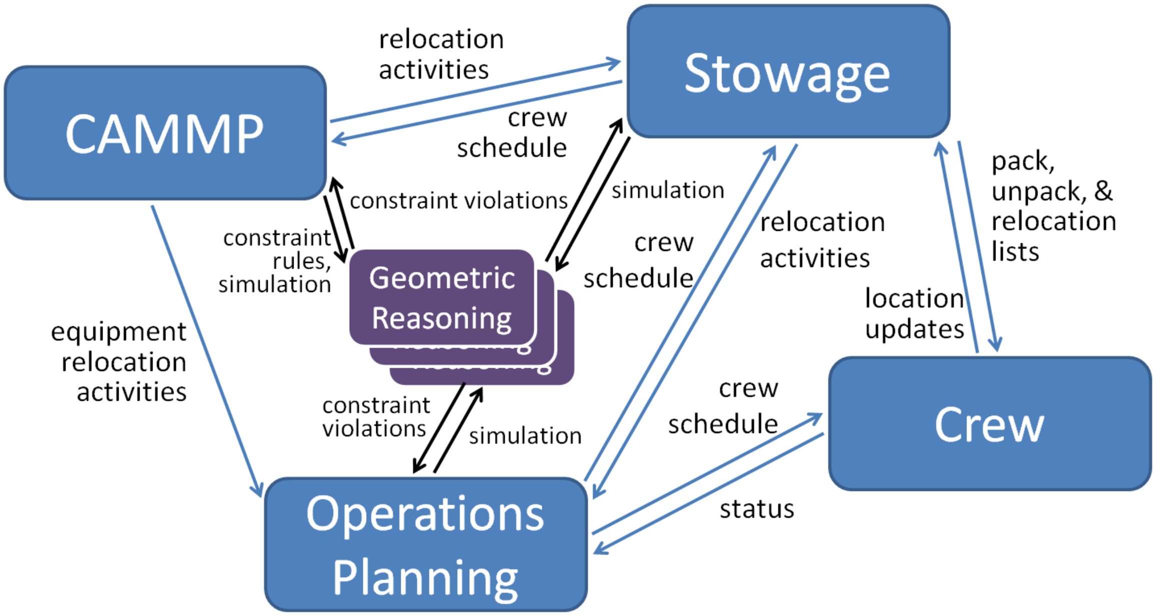

Figure 3. Proposed interactions of planning teams to manage space for supplies and equipment on the ISS.

objects.

The planning interface to the GRE is a set of functions for creating and locating groups of objects of predefined types with predefined constraints:

```
add( objectType, objectName )
delete( objectName )
move( objectName, location )
moveClose( objectName , locationDesired )
getConflicts()
```

Braces indicate optional arguments. Notice that the interface does not use a coordinate system. The ISS has a naming system for interior surface locations in each module. A separate GRE interface is used to map coordinates to location names and define shapes, constraints, and common preferences for the different object types. An object can be a polytope, polygon, line segment, or point. The `moveClose` function specifies a location preference, which the GRE attempts to meet along with other default preferences and constraints.

Constraints include collision avoidance, distance inequalities, containment relations, and Boolean functions of relations. For example, lab equipment may be constrained to be contained by a particular ISS module. Equipment mount points have zero-distance constraints to one of a set of ISS module mount-points. Preference functions can assign values to constraints and include basic arithmetic operations over these values and distances between objects. For example, a preference function for a supply bag could be its distance from crew translation volumes and, if contained in a storage rack, multiplied by two.

3.2 Stowage

The stowage planning system will monitor room available in container racks, determine where supplies will be unloaded from the docked vehicle and where they will be eventually stowed. All the necessary data is already available in the IMS database, therefore much of the work needed to provide better automated support for Stowage consists in using that data to automatically generate the current products (like the onboard stowage map, prepack/unpack and other messages), while ensuring that constraints coming from the CAMMP or Ops Planning groups are respected. Geometric constraint information coming from CAMMP can be ingested by the Stowage planning system by integrating with the GRE. Location constraint information derived from crew schedule coming from Ops Planning can be ingested by direct integration between the Stowage and Ops Planning systems.

3.3 CAMMP Planning

The CAMMP team typically plans new equipment configurations for new payloads, which might be once per vehicle visit to the ISS. In effect, the CAMMP team determines a partial goal state for the mission between vehicle visits. The CAMMP team can benefit from an automated planning system mostly by making some of their products more accessible to other teams, thus, increasing their value. The planning system from the perspective of CAMMP is foremost a server to which their configurations are uploaded.

The GRE could potentially provide other benefits to the CAMMP team in making their CAD models more

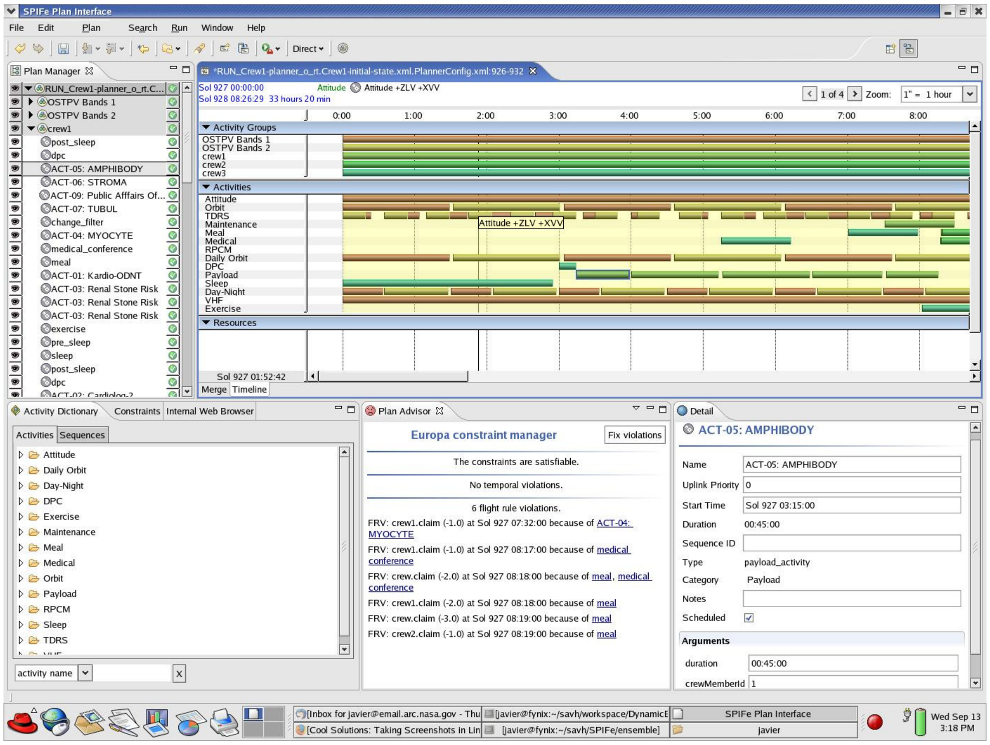

Figure 4. Crew planning system user interface.

accessible. It can be labor intensive to make changes to models using CAD design software, and the models are too large to share more than snapshot images. The GRE could simplify the reconfiguration of equipment in ISS modules through its planning interface. The GRE cannot write out CAD models the format used by the IVC group, but it can produce less detailed renderings of modules, and the resulting smaller files can be accessible to mission operations for better visualization of constraint information. In addition, the GRE can produce animations that may be helpful for instructing the crew.

3.4 Operations Planning

Operations Planning can be supported by a traditional task-based planning application; in fact, such an application is currently under development [3]. Figure 4 shows a screenshot of an early prototype that illustrates the following main concepts.

- There is a timeline for each one of the crew members and for each critical system or resource onboard, Ops planners can see, create and manipulate activities assigned to each crew member during the day.
- Operational constraints are encoded in the planning model that supports the user interface, so that as the Ops Planner interacts with the plan, any constraint violations are immediately flagged.
- The Ops Planner can post new goals, or solve constraint violations either manually or by invoking automated planning modules through the push of a button.

In our proposed architecture, we enrich this application by integrating it with the GRE. The Ops Planning application relies on the GRE for spatial constraint checking and incorporates violations reported by the GRE along with all the other resource and temporal constraint violations it already computes.

4 Scenarios

We have partially implemented the proposed architecture as follows:

- We have implemented the GRE, with the interfaces described above.
- The Ops Planning system was already implemented as part of a different demonstration [8]; we have enhanced that system to interface with the GRE.
- We have implemented one-way communication between the database used by the Stowage team and the GRE and the Ops Planning system.

The scenarios we discuss below are based on actual ISS operations related to us by an ISS Ops Planner. They demonstrate how Ops planners and Stowage can use automated planning to resolve violations of constraints specified by CAMMP. We recreate these scenarios in the context of the proposed automated planning system and our partial implementation to illustrate the concept of operation and the integration of the GRE.

4.1 Blocked Equipment Planned

Initially, Stowage has specified locations for pre-packing bags of supplies to be loaded on a visiting vehicle, and there are no existing constraint conflicts. However, due to changes to the crew work schedule, the Ops planner, O, notices that the worksite for a crew activity is scheduled to be blocked by some of the supplies. O modifies the plan to relocate the supplies to avoid the worksite volume constraint violation. If the violation had been undetected, the crew would have spent needless additional hours moving the supplies a second time.

Now we describe the operation of the planning systems for this scenario. O changes the location of the supplies by editing a pre-pack activity and specifying the new location for the supplies. Upon receiving the change, the Ops planning system (OPS) propagates the effects of the activity, updating future state projections while checking for constraint violations. As part of this propagation, OPS loads the GRE with the ISS objects into their respective states corresponding to the start time of the pre-pack activity. OPS then simulates movement activities over time with move commands to the GRE. For each object move, the GRE translates the object to the destination volume (as specified in a lookup table based on the location name) and invokes a greedy placement algorithm to find a specific translation and rotation within the destination volume that attempts to avoid constraint violations and improve the preference score. Between moves OPS retrieves conflicts from the GRE and displays them in the user interface.

Figure 5 shows a screenshot of an abstract model of the interior of the ISS US Lab output from the GRE. The three blocks of eight small boxes are three placements of supplies visible from the back of the near wall. The supplies on the right are the initial placement from this scenario. Some of the supplies intersect the worksite volume, the highlighted tall box, in front of one of the many lab stations. The small stack of eight boxes to the left are where the Ops planner relocated them, completely overlapping an air vent against the wall of the ISS module. The long box through the interior of the module is a translation constraint volume.

4.2 Blocked Air Vent

The second scenario is an extension of the first. When the Ops planner, O, moves the supplies, an obstructed air vent conflict is reported in the Ops planning system (OPS). A Stowage team member, S, also sees the conflict and offers to help. S moves the bags to a safe location and is successful with the help of the GRE. O is notified of the changes.

The air vent conflict is a violation of the constraint

```
!collision( suppliesX, ventClearanceY ).
```

When O sees the air vent conflict, O decides to let Stowage handle it and adds a preference to avoid the blocked worksite:

```
if collision( suppliesX, worksiteZ )
0 else 1.
```

The new preference is specified over a time interval and is represented as an activity in OPS. This preference is added to the default preference function for pre-packed bags:

```
distance( bag, translationPath ) /
distance( bag, vehicleDock ).
```

Like the location change, the preference change requires OPS to re-simulate objects in the GRE from the start time of the preference. A preference change will not change an object's location, but it could result in a change in the exact coordinates of the object within the location volume because the placement algorithm uses a different preference. In this case the coordinates also will not change since the supplies cannot get near the worksite at their current location, so there is no collision that could change the preference score.

The Stowage planning system (SPS) mimics the same behavior of OPS in re-simulating the future state for the changed location and preference. When Stowage team member, S, sees the air vent conflict, S requests SPS to try and resolve the conflict, and SPS invokes GRE's `moveClose` function to find a good place for the supplies close to its current location. The greedy placement function then explores movements to all

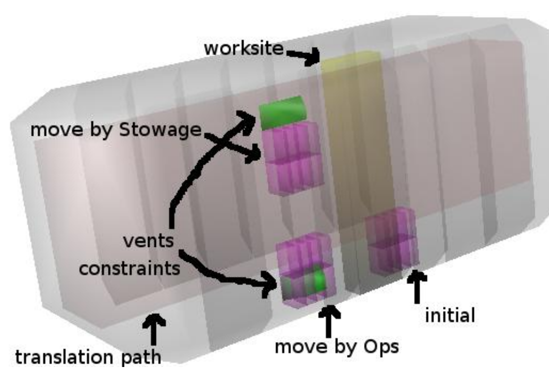

Figure 5. Screenshot of model VRML output from the GRE depicting three placements of supply boxes against the near wall inside the ISS US Lab module.

locations in the module and finds a safe location that maximizes the preference function. SPS updates the location of `suppliesX` in the pre-pack activity, retrieves an empty set of conflicts from the GRE, and S sees the conflict disappear. The location change is also updated in OPS.

Figure 5 shows this last placement of the supplies by Stowage just below the top vent constraint volume up against the module wall, maximizing distance from the translation path.

5 Conclusion

We have described an architecture for integrating task-based planning and geometric reasoning to support the 3 teams that perform spatial-related planning for ISS operations. Our approach is an improvement over current operations in some key aspects:

- Communication among the three teams is automated; the current manual approach is prone to error and time consuming.
- Geometric reasoning is consolidated and shared which eliminates duplication and make it directly accessible to the Stowage and Ops Planning teams instead of from conversations with CAMMP.

We have partially validated the concept with ISS flight controllers and have tested a partial implementation on scenarios taken from actual ISS operations.

There are several avenues that can be pursued to build on this work, some of the most valuable ones that we have identified are:

- Create proper planning applications for the Stowage and CAMMP teams so that they can formally validate constraints and integrate seamlessly with other teams.
- Extend the GRE to perform more complex search operations for relocating groups of items and answering what-if queries from all of the teams.

6 Acknowledgments

This work was carried out at Ames Research Center and at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

We thank the following people at Johnson Space Center for their guidance and feedback: Marc Spicer (Ops Planner), Ursula Stockdale (Stowage), and Michael Collins, Tony Sapp, Jay Weber, and Abigail De Los Reyes (CAMMP).

References

[1] Ai-Chang, M., Bresina, J., Charest, L., Chase, A., Cheng-jung Hsu, J., Jonsson, A. Kanefsky, B, Morris, P., Rajan, K., Yglesias, J., Chafin, B. G., Dias, W. C., Maldague, P. F., "MAPGEN: Mixed-Initiative Planning and Scheduling for the Mars Exploration Rover Mission," *IEEE Intelligent Systems*, vol. 19, no. 1, pp. 8-12, Jan./Feb. 2004.

[2] Knight, R., Chouinard, C., Jones, G., and Tran, D. "Planning and Scheduling Challenges for Orbital Express." In *Proc. International Workshop on Planning and Scheduling for Space* (IWPSS 2009). Pasadena, CA. 2009.

[3] Johnston, M. D., Tran, D., Arroyo, B., Page, C. "Request-Driven Scheduling for NASA's Deep Space Network." In *Proc. International Workshop on Planning and Scheduling for Space* (IWPSS 2009). Pasadena, CA. 2009.

[4] Jaap, J., and Muery, K. "Putting ROSE to Work: A Proposed Application of a Request-Oriented Scheduling Engine for Space Station Operations," In *Proc. of 6th International Conf. on Space Operations* (SpaceOps 2000), Toulouse, France, June 2000.

[5] Kortenkamp, D., "A Day in an Astronaut's Life: Reflections on Advanced Planning and Scheduling Technology," *IEEE Intelligent Systems*, vol. 18, no. 2, pp. 8—11, Mar./Apr. 2003.

[6] Acquisti, A., Sierhuis, M., Clancey, W., and Bradshaw, J. "Agent-based Modeling of Collaboration and Work Practices onboard the International Space Station." In *Proceedings of the 11th Conference on Computer-Generated Forces and Behavior Representation* (CGF 02), pp. 181—188, Orlando, FL, May 2002.

[7] Schauer, C. and Sylver, B. "Misdiagnosed: The Story of How NASA's International Space Station Planning Team Thought They Needed a Collaboration Tool to Solve Their Problems When What They Really Needed was Better Planning Tools." In *Proc. ICAPS 2007 International Workshop on Moving Planning and Scheduling Systems into the Real World*. 2007.

[8] Barreiro, J., Jones, G., and Schaffer, S. "Peer-to-peer planning for Space Mission Control." In *Proc. IEEE Aerospace*, 2009.

[9] Fitts, D. J. "International Space Station (ISS) Internal Volume Configuration (IVC)." In Proc. AIAA Space Architecture Symposium, 2002.

[10] "Generic Groundrules, Requirements, and Constraints Part 1: Strategic and Tactical Planning." International Space Station Program. Revision C, pp. 3-81—104, November 2007.

[11] LaValle, S. M., *Planning Algorithms*. Cambridge University Press, Cambridge, U.K., 2006.