Activity Planning for Long Duration Space Missions

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Abstract

For long duration, manned exploration to be cost-effective, it is necessary to automate routine manual operations. To enable such automated control, activity plans must coordinate the activities of the crew with other automated "agents" including robots, life support systems, and vehicle systems. An important challenge is assisting the crew in using automated planning software to construct and monitor the execution of these multi-agent control plans. In this paper we describe how humans and automated planners will work together for activity planning.

Introduction

A significant task in Shuttle and Space Station operations is the planning of crew activities. For these programs, activity plans are constructed prior to a mission and updated daily by ground flight controllers. Because control and malfunction procedures are executed manually, activity plans focus on the tasks the crew will perform. For future manned missions to be cost-effective, however, it is necessary to automate many of the routine operating procedures that are currently manual. To enable such automated control, activity plans will need to coordinate the activities of the crew with other automated "agents" including robots, life support systems, and vehicle systems. A necessary precursor is that automated control be able to integrate with the crew activity plan.

We have demonstrated that the Three Tier (3T) robotic control architecture (Bonasso, et al., 1997) can be used to control life support systems (Schreckenghost, et al., 1998). 3T includes autonomous planning software. Such planners should be deployed into manned space operations by keeping a human in the loop for plan construction and execution. The next step in fielding this technology is addressing how the crew or flight controllers can make effective use of automated planners. We have begun a project to integrate an existing planning engine with intelligent user interface software that assists the crew in using the planner. This intelligent interface software will mediate crew interaction with the planning software.

This approach enables the crew to do their own activity planning at the remote site, instead of relying on ground controllers to generate and update plans. It makes the crew more independent of ground operations, which reduces operation costs and accommodates the communication delays and blackouts common in space exploration. It also makes the planning process more robust by taking advantage of the human ability to adapt to novel situations.

In this paper we discuss how humans will work with autonomous planners for manned space operations. We give background on activity planning, describe our approach to autonomous control for life support, and characterize the information exchange and interaction between the crew and autonomous planner.

Planning Space Operations

In this section we provide background on what an activity plan is and how it will be used in long duration space habitats, such as a manned mission to Mars. This background information is a synthesis of planning operations for the BIOPlex, the Space Station, and a manned Mars mission. For the sake of clarity, we have defined a consistent terminology derived from these projects. A *task* corresponds to a goal or objective to be achieved and an *activity* corresponds to the actions taken to achieve the objective. For hierarchical planners, tasks correspond to the high-level nodes in the plan and activities correspond to the lowest level nodes.

The Mission Plan

The mission plan defines the tasks, resources, and constraints for the entire mission (up to 2 years duration). The mission plan consists of the following objectives:

- *Science Objectives.* Prioritized exploration tasks and experiments. Tasks have rough allocations to a time window and approximate resource estimates, although exact timing or resource constraints can be identified. A range of automation is expected (autonomous to manual)
- *Operations Objectives.* Facility operation & maintenance including environmental control, food growth and processing, air/water recycling, solid waste processing, and robotics. Many tasks are routine and periodic, with a high level of automation expected.
- *Crew Personal Objectives.* Training, programmatics, and crew health tasks (exercise, eat, sleep);includes *crew discretionary time* (time not assigned to operations).

Each task in the mission plan has a goal related to these objectives. Tasks are allocated to time windows that specify timing constraints such as earliest start time, latest stop time, or frequency for periodic tasks. Plans include resource estimates and task allocations to types of agents. The mission plan can be evaluated by reviewing resource estimates & agent workload for the plan. Resource models used for this level of planning are coarse and conservative.

Significant human involvement, including Earth-based operations, is expected in defining the mission. Mission planning tasks are directly related to mission objectives and usually will not include the detailed steps to accomplish them. Instead, tasks represent producers or consumers of resources over a time period. Constraints are related to crew and mission safety and task priorities arising from mission objectives.

The Activity Plan

The activity plan takes the abstracted tasks from the mission plan and determines the actual activities and resources needed to perform these tasks (decomposition of high-level goals into an action hierarchy). The time period of the activity plan can cover a week to a few months, depending upon the mission (e.g., operations concepts for human exploration of Mars define a 10-day activity plan). The first step in building the activity plan is to determine the goals and constraints that apply for the time period of the plan. To do this, the crew reviews tasks from the mission plan. Proposed experiments and exploration activities are revisited. Some may be delayed beyond the time period of the activity plan, which affects the mission plan. Those retained may be re-prioritized. The loss of system capabilities or significant differences between the predicted and actual usage of consumables can result in constraint changes affecting the activity plan, and possibly the mission plan. The effectiveness and efficiency of routine operations are reviewed with the goal of improving system performance and crew satisfaction. Public relations commitments are defined.

When the final set of goals have been determined and the changes to constraints and resources made, the planning software identifies the activities that will achieve these goals and allocates these activities to be performed by specific agents during well-defined time periods. The crew evaluates the resulting plan with respect to agent workload and resource production and usage. Significant changes in resources or constraints (e.g., subsystem loss) or task delays outside the time period of the activity plan may require modifying the mission plan.

The activity plan will be re-evaluated routinely to determine that it is still valid (i.e., goals and constraints used to generate the plan still hold), to update goals based on operational changes from Earth, and to make selections among plan alternatives. For example, the activity plan for the Lunar/Mars Life Support Test Project (LMLSTP) Phase II test was evaluated every Sunday to build a weekly schedule. This routine evaluation produces the following:

- Changes to crew schedule
- Plan updates for automated control operations (stand-alone experiment controllers; integrated life support and facility control; robotic operations)
- Downlink of plan changes to Earth-based operations

The activity plan includes the operation of autonomous systems (robots, life support systems) because the crew must be cognizant of autonomous operations to ensure mission objectives are met.

Control of Life Support Systems

Life support systems are the hardware and software used to manage consumables required to sustain human life. For a remote space habitat, life support systems are needed for air revitalization, trace contaminant removal, plant growth, food production, water recovery, thermal control, and solid waste processing. We have developed 3T control software for air revitalization, plant growth, and water recovery.

3T Control Architecture

We use the 3T control architecture for autonomous control of life support systems. It consists of the following tiers of parallel control processing:

- *Planner*: The planning tier performs deliberative control. It plans activities to achieve control objectives. The planning software used in 3T is the Adversarial Planner (AP; Elsaesser and MacMillan, 1991). AP is a non-linear hierarchical task net (HTN) planner. It represents and assigns tasks to multiple agents. It monitors the execution of a plan, detects plan execution failure, and replans dynamically at failure. AP was developed for military planning. It was selected for 3T because its approach to plan monitoring with quick plan repair is needed in space applications. The optional capability to model an adversary's plans is not used for space.
- *Sequencer*: The sequencing tier performs procedural control. It selects and orders tasks using a hierarchical task decomposition predicated on the current world state. Thus, task selection is dynamic and reactive to changes in control conditions. Sequencing software is the Reactive Action Package System (RAPS; Firby, 1989).
- *Skill Manager*: The skill manager implements closed loop control. The activation of a skill corresponds to starting closed loop control to change the state of control hardware. Events can also be activated to monitor for specific feedback from control instrumentation. The skill manager software is written in the C language.

The parallel tiers of control processing represent different control abstractions and response times. In general, the control task becomes more abstracted and the response time becomes larger as control moves up the tiers.

The 3T architecture operates with a top-down flow of control and a bottom-up flow of control feedback. Leaf activities in the plan hierarchy are mapped to top-level RAPs by unifying the purpose of the planned activity with a succeed clause in a RAP. The planner installs the selected RAP on the task agenda for execution. The top-level RAP is further decomposed into a hierarchy of control tasks. Leaf tasks (primitives) in the RAPs task hierarchy activate skills in the skill manager. The skills pass commands to the control hardware. Feedback from control instrumentation is passed from monitoring events in the skill manager to the sequencer. The sequencer uses these events to determine if the task executed successfully. Once the task terminates, RAPs memory is modified to reflect the new state. The planner monitors RAPs memory for state changes related to activity execution status.

Product Gas Transfer Application

We developed life support planning software as part of a 3T system managing plant growth (Schreckenghost, et al., 1998). This system was developed for the LMLSTP Phase III test. During this test, a four-member crew lived in an enclosed chamber for 90 days to simulate many of the conditions of a remote planetary habitat. A primary test objective was to demonstrate air revitalization using plants. We built a 3T application to control the gas concentrations in the plant chamber to ensure healthy plants and to transfer recycled O2 to the crew. We also managed O2 buffering for use in solid waste incineration.

There was a typical 4-day planning cycle for production and consumption of O2 and CO2. For 2 days, CO2 from the crew was converted by the plants to O2 and the O2 was returned to the crew chamber. For 1 day, O2 was buffered in a tank for solid waste incineration. For the remaining day, we circulated incineration effluent over the plants to remove the high concentrations of CO2.

There was also a16-20 day planning cycle corresponding to the planting and harvesting of the wheat used for air revitalization. Since the O2 production of wheat varies by a factor of 2 over the lifetime of a plant (~90 days), the wheat crops were planted in stages during the test. At any time there was a mix of crops in the chamber planted at 4 different times, separated by about 20 days. Crop staging damped fluctuation in O2 production to an average level sufficient for 1 person. The planner managed the planting and harvesting of crop stages, including scheduling an airlock for plant germination and scheduling humans for the manual task of planting and harvesting. The airlock also was used to buffer incineration effluent that was hazardous to young plants.

Humans Working with Autonomous Planners

Autonomous control of routine operations for life support and robots is an important enabler for long duration habitation at remote space sites. Such autonomy frees the crew from mundane operations, giving them more time for exploration and experimentation. It reduces the workload of Earth-based flight controllers, which is a significant cost reduction for multi-month missions. And it avoids the impacts of long communication delays on real-time control. Yet these operations must be conducted safely and with a high rate of success in achieving mission objectives.

We have demonstrated that safe autonomous operations can be achieved by control software that supports adjustable autonomy (Dorais, et al., 1998). By adjustable autonomy we mean that the humans and the autonomous control software share responsibility for control of life support and achieve control objectives by shifting control initiative among them (mixed initiative interaction). Our applications of 3T include both automated and manual tasks at all tiers of the control hierarchy. Control authority is allocated by the planner and can be altered by the user during plan execution. We have used these features to investigate the following models of mixed-initiative interaction: human supervision of autonomous control, traded control between humans and autonomous systems, and manual override without shutting down autonomy. In this section we describe essential features of a control architecture that deploys autonomous planners into manned space operations. We identify representational issues and describe work in progress to address some of these issues.

Plans for manned space operations should include both manual and autonomous control activities

An activity plan for a remote space habitat should include activities executed by both the crew and the autonomous control software. These activities should be integrated into a single plan that manages expendables and resources of the facility. The activity plan will include manual tasks in many different circumstances. First, the plan should specify *activities that are performed jointly* by humans and autonomous systems. For example, robots may assist humans in food production, requiring coordinated actions among all agents involved. Or a human may interact with an autonomous life control system to diagnose and repair the hardware system being controlled. Second, the plan should specify *activities that require cooperation* among humans and autonomous systems. Cooperation is needed when activities (1) use the same equipment (e.g., a tool), (2) produce/consume the same expendables (e.g., water, O2, etc.), or (3) require a constrained resource (e.g., power budget, physical space). For a space habitat, the crew produces and consumes the expendables (water, O2, CO2) managed by life support systems, which requires that control of life support systems be coordinated with crew activities. The crew occupies the same physical space as robots in a space habitat, which requires that robotic activities be coordinated with crew activities to ensure crew safety and to avoid accidents damaging robots. This integrated activity plan should be (1) executable by the autonomous control software, (2) translatable to a crew schedule, (3) verifiable through direct or indirect feedback, and (4) traceable to the underlying mission objectives.

The following issues arise when representing both human and autonomous agent activities in one plan:

- Level of abstraction for coordinated activities. Some activities may be described with minimum detail in the plan (e.g., crew free time), effectively representing low-level constraints. Such activities do not require modeling how the task is performed, but their effect on resources and agent availability must be considered when building and monitoring the plan.

- Representation of plans with flexible crew activities (manual tasks cannot be regulated too tightly) that allow sufficient commitment for reliable autonomous control
- Information passed from the integrated plan to crew personal schedulers and autonomous control systems

We have developed prototypical 3T control applications that include both joint task performance and cooperation among agents. Our planning application for product gas transfer achieved its goals by selecting a control strategy that was used as context by the sequencer when selecting tasks to execute. In this domain, manual activities affect the autonomous control software in the following ways:

- Manual activities, like crop planting and harvesting, constrain how autonomous control activities executed in parallel with these activities are performed. For example, as the coordinator of control agents, the planner informs the sequencer when humans are in the plant chamber. The sequencer then suspends O_2 removal and CO_2 injection in the chamber due to safety considerations.
- Manual activities, like a gas contaminant test, require cooperative interaction with the planner since the plan execution cannot proceed to the next activity until the test result is provided by the human. This result serves as an event indicating the current activity is complete and as a context determining how to perform the next activity (i.e., if contaminated, vent gas; else use gas).

Plan construction is a joint human-autonomous system task

For Shuttle and Space Station operations, plan construction is a manual task performed with scheduling software tools. Using this software requires considerable training and expert knowledge. Even with such experience, plan construction takes time (e.g., Shuttle plans are generated months prior to a mission and during the mission 8 hours daily is allocated to replanning). More capable planning software is needed to reduce the cost of Earth-based planning operations and to enable future operations where the crew participates in plan construction. Such advanced planning software exists (Pell, et al., 1998; Bonasso, et al, 1997), but has not been applied to manned space operation.

We do not propose that plan construction for space operations be a purely autonomous activity, however. There are a number of advantages to human involvement in plan construction. Humans are very good at adapting to unusual situations beyond the scope of the knowledge encoded in the planning software, which adds flexibility and adaptability to the planning process. Such adaptability is important in the space environment, which is dynamic, complex, and unpredictable. Having the crew involved in plan construction educates them about the planning process, which prepares them to adjust plans when novel or anomalous situations require near-real-time replanning. If replanning requires changing goals or constraints, humans should be in the loop to ascertain that these changes don’t compromise crew safety or mission objectives. Finally, there are important psychological benefits for the crew to have some control over their personal schedules during long duration missions.

Thus, we recommend that humans and autonomous systems work together to construct plans. Most automated planners require humans to specify planning goals. There also has been important work on considering human advice and preferences when planning (Myers, 1996). For manned space operations, humans should be able to interact with the automated planner during plan construction as follows:

- defer a goal (e.g., do not consider the goal in the current plan, but retain it for later plans)
- change a parameter value in a constraint or precondition (for unique situations where the usual value is not right)
- specify the task start or stop time (e.g., tasks can be moved forward or delayed anywhere within the planner-allocated window of opportunity)
- select the order in which parallel tasks are performed (for situations where default ordering must be altered)
- exclude or assign a qualified agent to an activity
- change the availability of resources or consumables (e.g., permits overriding the typical resource allocations and consumables usage and production rates)
- specify preferred features of the plan (crew preferences)

These capabilities provide humans with the flexibility to adjust the plan to unique situations that occur infrequently and so do not cause permanent changes in the planner’s knowledge. User modification of planner knowledge must be pursued cautiously due to the high cost of errors in space applications.

Work on mixed initiative planning (Ferguson and Allen, 1998) seems a good match for many of these requirements for plan construction during manned space operations. In mixed initiative planning, the control of planning initiative is traded between the human and the autonomous planner. Issues associated with mixed initiative plan construction for space operations include the following:

- Representation of crew preferences in the plan (e.g., soft goals/constraints that can be relaxed when replanning
- Information and capability needed by a human to respond to an inability to construct a plan autonomously.
  - Interim planner states during plan construction
  - Information clarifying the circumstances when plan construction fails; what goals could (and could not) be met, what activities were selected to meet goals, and what activities were considered but rejected (including why these activities were rejected).
  - Final plan state, even if only partially complete
- Aspects of the plan that can be deferred until plan execution time, such as agent assignment, task ordering, and activity initiation or termination times. For example, the planner could designate that task initiation be specified by the human during plan execution. The task would be scheduled to a window of opportunity but would not be automatically started. This accommodates

tasks where initiation conditions are difficult to specify prior to execution. It also accommodates "fitting in" less constrained tasks opportunistically instead of arbitrarily placing them during plan construction.

Based on our investigation of crew activity planning, we discovered that the selection of the appropriate plan construction tasks depended upon what had already been done (i.e., the context of the plan construction task). Thus, the control of the plan construction process can be viewed as a type of *situated action*. The actions of interest for activity planning are the tasks required to generate and update an activity plan. The situation context includes the intent of the interaction, the status of plan construction so far, and the information produced during plan construction. We have just initiated a project to develop intelligent software that assists a human in using automated planners for activity planning in manned space operations. This software will mediate changes in control initiative between the human and the planner during plan construction and automate routine interaction with the planner. It will support iterative plan construction with interim plan evaluation and comparison (Rich and Sidner, 1998). This capability will orient the user about what changed during plan construction and what resulted from those changes.

Plan construction includes developing contingency plans and the evaluation of alternative plans

Activity plans for long duration habitats have the primary goal of achieving mission objectives safely. They have a secondary goal of maintaining crew satisfaction during extended periods of isolation from Earth. Thus, plans developed for these facilities will require flexibility and crew autonomy in activity execution (i.e., independence from Earth-based operations) without increasing crew and mission hazards. Such independence is particularly important for remote planetary sites with constrained communications. Flexible crew plans include more crew discretionary time and permit delayed commitment to specific timing or ordering of activities. As a result, these plans are less tightly constrained than Shuttle plans and multiple valid plans are a possibility. Methods for evaluating and comparing alternative plans are important in making such flexible plans operationally viable. Possible metrics for plan evaluation include the following:

- *Resource Utilization*: quantities such as robot hours, gas/water consumption rate, and energy usage. The plan builder can use these metrics to identify irregularities in resource usage (e.g., periods with exceptionally high or low usage). These irregularities can be smoothed by adjusting activities to change resource utilization.
- *Resource Production*: quantities such as crops ready to harvest, O2 produced, potable water recovered. These metrics can be used to identify and change sub-optimal production patterns (e.g., slow depletion of reserves)
- *Crew Workload:* quantities such as total hours worked, the number of activities, how activities are distributed throughout the day, and how long they last. The plan builder can use these metrics to change crew allocations or to delay activities if no one is available.
- *Robot Workload*: similar to crew metrics. Also, measures of performance and efficiency (e.g., change scanning pattern to reduce activity time). Reviewing such metrics educates the crew about how the robots behave, making it easier to identify and repair degrading behavior early.
- *Plan Flexibility:* quantities such as the number and importance of crew preferences satisfied

During certain critical operations, however, activities will be scheduled much more tightly and monitored much more closely. This also may include active involvement of Earth-based operations. Critical activities are activities where the risks are high or the objective of the activity is very important. Examples of critical activities include:

- EVA: crew is outside the facility or vehicle
- Joint activities: activities where multiple agents must coordinate their efforts. This includes human-robot joint activities, multi-robot activities (e.g., robots deployed for sample collection), and multi-vehicle activities

As a result, the activity plan during critical activities will include more detail and will be more constrained with respect to agents, resources, and time. In addition to the nominal plan, plan variations that address plausible failure situations will be developed. These *contingency plans* are developed by postulating that a high impact failure has occurred, and determining the activities in response that achieve as many of the mission objectives as possible.

Some issues that arise in developing and evaluating alternative plans include the following:

- Information needed to evaluate and compare alternative plans resulting from variations in planning conditions
- Representation of crew discretionary time for plan construction and plan execution monitoring
- Management of contingency plans, including their use when replanning during plan execution

Since most automated planners cannot manipulate multiple plans simultaneously, we are developing software to assist users in constructing plan variations and managing the results of these planning efforts. This assistance includes support for collecting and managing sets of goals, constraints, and initial conditions, and for comparing the plans produced under these different conditions.

Humans should be aware of autonomous activities and may participate in plan execution

Plan execution is the accomplishment of planned activities by humans and autonomous control systems. It is expected that routine control activities will not require human participation and will require only infrequent monitoring to maintain awareness of autonomous activities. To assist the crew in supervisory monitoring, the autonomous planner should export information describing planned activities and assessing how well these activities achieve objectives (Schreckenghost & Thronesbery, 1998).

There are a variety of circumstances where the crew will participate in plan execution. During nominal operations, the crew may need to perform manual tasks or provide information not available from instrumentation. To provide flexibility in how the plan is executed, the assignment of an agent to perform a task, the initiation of a task, or the circumstances when a task is designated complete might be deferred to the human at plan execution.

The crew may take a more active role if anomalies in plan execution occur. The crew will monitor autonomous activities more closely during hazardous or critical tasks, to enable quick anomaly response. Crew intervention at an anomaly can be as simple as approving a diagnostic activity or as complex as working with the automated planner to construct a new plan. It even may be necessary to suspend nominal operations while the crew performs low-level corrective actions. Such low-level interaction is expected to occur infrequently and should be performed without shutting down the autonomous control system.

Human participation in plan execution also can occur when novel opportunities arise requiring activities different from encoded operations. To illustrate, during the Phase III test we had an unanticipated opportunity to experiment with new control algorithms for an air fan in the plant chamber. We designed the control software with adjustable autonomy, permitting the human to perform the experiment without shutting down the autonomous system. The planner should work cooperatively with the crew during such opportunistic operations by determining a good time for such operations, suspending nominal operations while the crew is in control, reminding the crew when important suspended operations are threatened by delay, and reconfiguring to resume nominal operations.

Some issues associated with plan execution include:

- Provision for crew feedback about manual activities. This becomes particularly important when actual events do not follow planned activities. The planner must determine which goals were achieved and which remain, even if activities were not executed as expected.
- Autonomous monitoring of manual activities. Possible alternatives include using computer vision to observe manual tasks, or inferring success until evidence of failure is observed. In some situations it is more useful to detect when a task fails than to confirm task success.
- Human awareness of autonomous replanning. Includes notification that replanning has occurred, with conditions that initiated the replan and plan changes that resulted.
- Response to plan failure during critical or time-limited activities. During such activities, there may not be time for the human to assist in replanning. Or actual events may diverge so significantly from planned activities that it is not viable to replan until after-the-fact, when the plan is brought up-to-date on these events.

During the Phase III test, the plan executed by the autonomous control software included both autonomous and manual tasks. Test engineers were notified when a manual task was needed, such as planting a crop. The autonomous software also requested the engineer to inform it of task completion or results, such as gas sample quality.

Future Work

We are developing intelligent software to mediate the interaction between the crew and automated planning software for activity planning. This software will provide a uniform interface to a suite of software tools including a planning engine, a database, and personal calendar software. The intelligent software will be implemented using an action representation language that can model the procedures, rules, and protocols (i.e., the work process) for working with an activity plan. It will support mixed initiative interaction with the planner during the construction and execution of plans.

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