Requirements for Planners for High-level Monitoring and Control of Advanced Life Support Systems*

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1. Introduction

Advanced life support (ALS) systems manage water recovery, air regeneration, environmental temperature regulation, electrical power utilization, and food production. The proper functioning of these systems is essential for producing potable water and clean air. An additional function is the growing, harvesting, and processing of plants for crew consumption.

These systems need both low-level control software to supervise each of the individual systems and high-level planning software to integrate the overall operation of these systems. Intelligent hardware controllers provide the low-level software while the high-level software must supervise groups of these controllers. The goal of the high-level software is to reduce the workload and expertise required from the crew, integrate the

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monitoring and control of all the systems and manage the limited resources that are required by the systems.

This project is investigating requirements for the planning and scheduling functions of the high-level software for monitoring and control of ALS. In this domain, planning is the selection of actions to meet the demands for food, air, and water for the crew and plants while maintaining the temperature and reducing the demand for electrical power. Because of the closed-loop nature of this application, resource management is a major concern for the planner software. The scheduling for this domain must reduce peak demands for electrical power and other resources while efficiently allocating resources and ensuring a safe environment.

2. Background

2.1 NASA's Advanced Life Support Program

NASA's Advanced Life Support (ALS) program is building a testbed to evaluate, characterize, experiment with and verify life support systems to grow, harvest, and process plants for food, purify water for the crew and plants, and regenerate oxygen for the crew and carbon dioxide for the plants. The current focus is on providing physico-chemical and biological regenerative approaches for a planetary base with a stronger emphasis on the biological approach.

The first project in the ALS program is the Lunar-Mars Life Support Test Project (LMLSTP), formerly called the Early Human Test Initiative. This project consists of three phases. Phase I, completed in August, 1995, used one human subject and a wheat crop in a continuous 15-day test sealed in the Variable Pressure Growth Chamber

(VPGC) located at NASA's Johnson Space Center. The wheat crop recycled CO_2 into O_2 for use by the test subject.

Phase II, completed in August, 1996, used 4 test subjects for a continuous 30-day test in the Life Support Systems Integration Facility (LSSIF), shown in Figure 1. This three-story chamber includes sleeping quarters on the top floor and a kitchen and exercise room on the ground floor. The Phase II test focused on water and air recycling systems using physico-chemical methods, rather than the biological methods used for air recycling in the Phase I test.

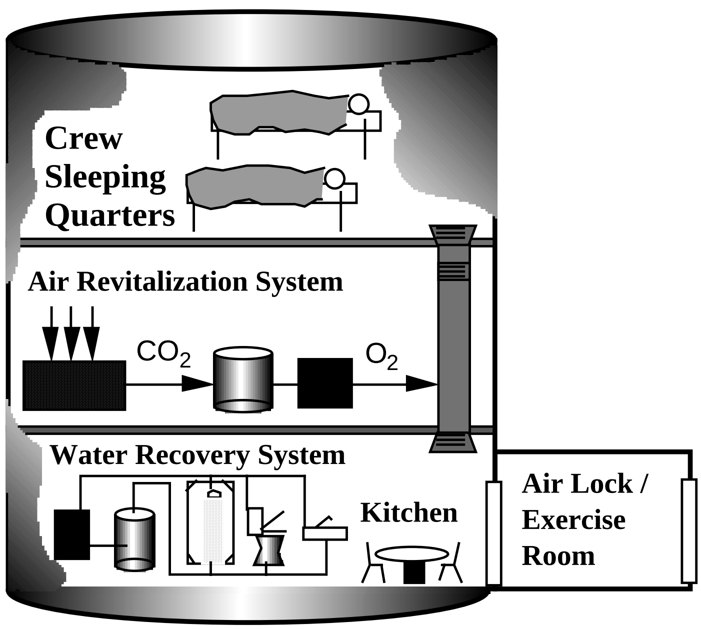

Figure 1: LSSIF Crew Chamber

LMLSTP continues with the Phase III test scheduled to begin in September, 1997. This test combines the air revitalization system (ARS) from Phase II with the crop growth systems from Phase I. An incineration unit to handle solid waste will also be added. This test is for 90 days with 4 human subjects in the LSSIF chamber. The focus of this phase is the development of monitoring and control software for integrating the gas exchange between the two chambers.

The next project in the ALS program is the construction of the **Bio**regenerative Planetary Life Support Systems Test Com**plex** (BioPlex). The BioPlex Test Facility, shown in Figure 2, is starting construction and will be used for tests to begin in the year 2000. These test chambers will be used for tests of 120 to 425 days with up to two crews of 4 occupying the complex concurrently. The BioPlex has subsystems for air, water, and nutrient recycling including crop production and other biological subsystems. The growth chambers for this testbed will be much larger and contain multiple growth bays.

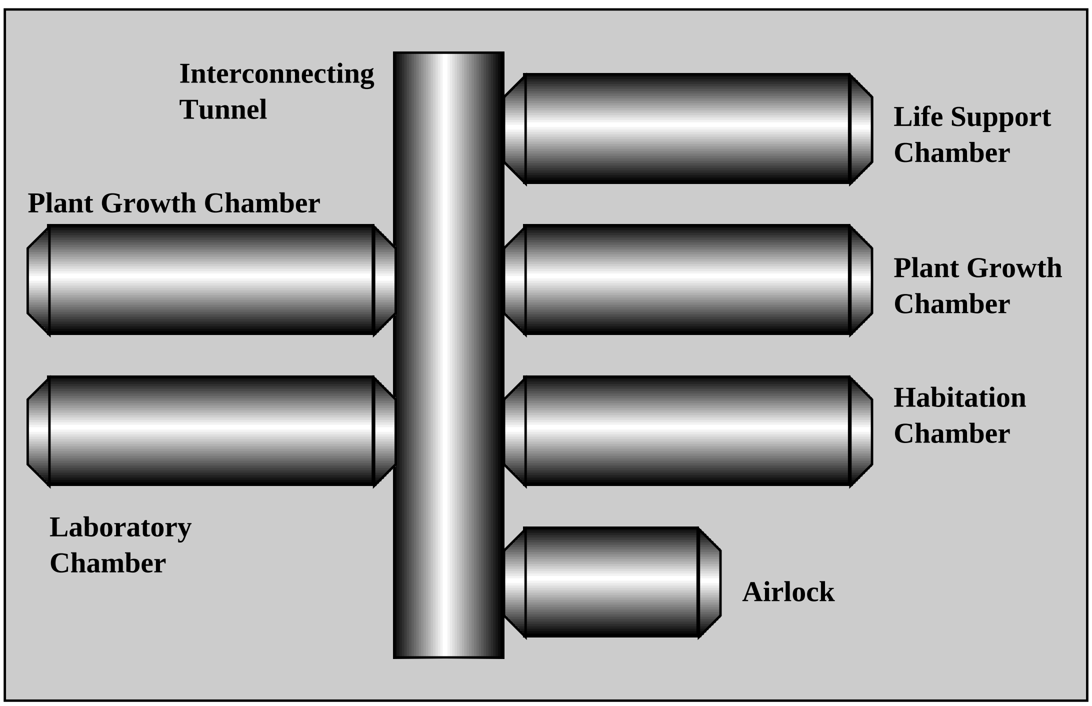

Figure 2: The BioPlex Test Facility

2.2 The 3T Software Architecture

The 3T software architecture has been selected for intelligent monitoring and control for the ALS project. The 3T three-tier architecture was initially designed to combine deliberation and reaction into an architecture for robot control. The three separate tiers, planning, sequencing, and control [2,3], are shown in Figure 3. Each tier of the architecture handles a different part of the control problem. The bottom control tier is a set of reactive skills while the middle tier handles sequencing of routine tasks. The top planner tier focuses on goals, resource utilization, and timing constraints between tasks.

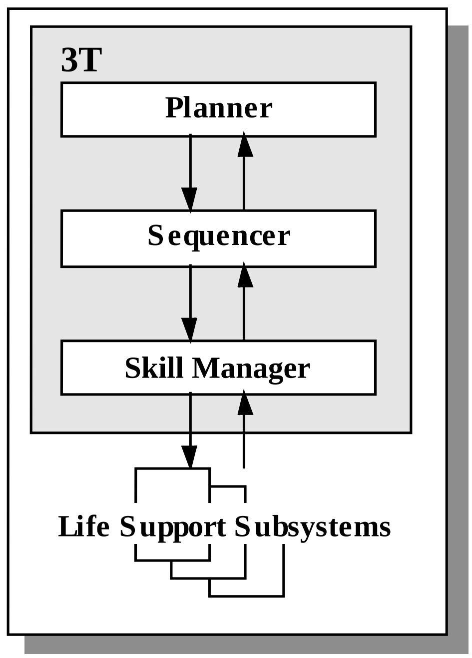

Figure 3: Overview of 3T Architecture

For this problem, the control tier is tightly coupled to the sensors and actuators of the life support systems. This tier consists of a set of skills that are coordinated by a skill manager. These skills send commands to the ALS systems to perform tasks such as opening or closing a valve, turning on/off a heater or fan, and changing a setpoint. Skills can react to dynamically changing status, and make little or no use of past or future environmental states. Special skills, called event skills, act to filter the large amount of data coming from the numerous sensors. For example, there are more than 200 data channels for the variable-pressure growth chamber being used for ALS experiments. These event skills read sensor data channels and alert the sequencing tier only to significant problems or skill completion. In this way, only small amounts of data are passed to the sequencing tier.

The sequencing tier activates sets of skills to accomplish specific tasks. A task consists of success criteria, rules for interpreting the results of the task, and one or more methods for achieving the task. The success criteria define the environmental state accomplished when the task has successfully finished. Each of the task's methods has an associated context that specifies the situations in which the method should be executed. At runtime, the Sequencer selects one of the methods matching the current context and expands it into a sequence of skill activations. Once the skills have been activated, the Sequencer waits for events to signify completion of the skills or events that are not expected for the current context. The current implementation of 3T uses the Reactive Action Package (RAP) system [6] as the sequencing tier. This tier makes use of past state information by maintaining a model of the environment using the RAP system memory.

The planning tier is for deliberating about future implications of actions, detecting and sorting out interactions between multiple goals, creating new sequences of tasks when preexisting methods are inadequate, and solving specific problems when they arise. Plan steps are the tasks executed by the Sequencer. The 3T tool uses the **A**dversarial **P**lanner (AP) for this tier [8,9]. AP has a multiagent planning capability that will be used in operator and agent selection for the multiple ALS systems controlled by 3T. The planner uses the Sequencer's tasks as primitive operators and, thus, plans are synthesized at a high-level of abstraction and the Sequencer handles the details. Furthermore, while plans are partially ordered to accommodate constraints, the Sequencer instantiates the actual order by expanding tasks at execution time. The planner is notified about the success or failure of the tasks, so replanning can be invoked when appropriate.

3. Technical Challenges for Planning Systems

3.1 Requirements for Planning

Planning involves more than simply selecting actions to achieve goals. Often, it involves scheduling when the actions are done. In addition, in the ALS domain, it includes monitoring events, sharing control, and ensuring safety. Each of these topics is discussed in the following sections.

3.1.1 Planning

Planning is the process of selecting a sequence of actions to achieve goals. In this domain, planning also includes selecting a sequence of actions to maintain goals in the face of unexpected events. For example, when a low CO_2 event occurs in the plant chamber, the planner must select one or more actions to increase the amount of CO_2 and maintain the goal of nominal growing conditions. The actions could be simple, increasing the amount of CO_2 flowing into the plant chamber from the crew chamber, or complex, activating the incinerator to produce more CO_2. Therefore, the planner must be able to select a sequence of actions to achieve or maintain goals.

Part of the input to a planner is the current environmental state. In this domain, the environment can change due to *exogenous* events or events outside the direct control of the plan executor [12]. To manage changing environmental states, each action's preconditions are checked prior to the action being taken by the plan executor. An action's preconditions specify the partial environmental state that must hold before the action can be executed. Some of the possible preconditions for ALS include crew availability, equipment status and availability, current configuration, planned configurations, pass/fail criteria, resource status and availability, inventory availability, and potential conflicts [11]. Therefore, any actions used by the planner must define the appropriate preconditions under which it can be executed.

When selecting a sequence of actions, the planner must take into account the reduced performance of ALS systems over time and the fluctuating performance of the plants due to aging and differing germination rates of successive crops. If a predictive model is used by the planner, the model can be adjusted to account for the changing performance of the systems and plants by adjusting parameters based upon errors between the model and data collected from the ALS systems. Without a predictive model, the planner must change or adjust the postconditions or effects of actions. If there is no adjustment for the changing performance of systems and plants, more replanning will be necessary and less optimal plans may be produced. While not a mandatory requirement, adjusting postconditions of actions or the results of a predictive model will decrease replanning and increase plan quality.

Planning for the BioPlex is complicated by the multiple, interacting systems within the testbed. In addition, each of these systems have different goals. For example, turning on lights in the plant chamber produces heat, and this increases the load on the thermal control system. However, the lights enable the plants to produce O_2 and reduce the load on the air recycling system. If planner turns the lights on to achieve the goals of producing O_2 and food it must then turn on the thermal control system to achieve the goal of maintaining an appropriate temperature. The planner must be able to manage different goals for the multiple, interacting systems within the BioPlex testbed.

3.1.2 Scheduling

Scheduling is the process of determining when to carry out actions selected by the planner. Conceptually, there is a clear distinction between scheduling and planning. However, in a real-world problem, deciding which actions to select depends upon when the actions can be executed. Scheduling in the ALS domain must take into account the constraints of crew time, available resources, and system dependencies[11]. The available electrical power for a Mars planetary base is estimated to be an average of 50kW. This constraint will limit the number and type of operations that can be executed concurrently. The ALS planner must take into account these types of restrictions when selecting actions. One of the requirements for the planner is assuming the scheduling task which ensures that the generated plans will meet all the scheduling constraints.

3.1.3 Monitoring

In the current plant chamber alone there are more than 200 data channels. For the most part, the bottom tier of 3T, the skills level, is responsible for filtering the large amount of data and detecting significant events. However, the significance of an event depends upon the context within which the event occurs. For example, a high CO_2 alarm is expected to occur during or just after the incinerator has operated but not during nominal operation. By setting context, the planner can help determine what events and conditions need to be monitored.

In addition, experience from other remote monitoring projects [13] indicates that changing sampling rates can help reduce the amount of data generated. For example, in nominal mode, the environmental conditions change slowly so the overall sampling rate can be reduced. In other contexts, the sampling rates for specific sensors may be adjusted to suit the context. The 3T planner, with its predictive capability, can help decide the sampling rates, based on expected rate of change and significance of the sampled data.

3.1.4 Shared Control and Safety

Shared control and safety are important requirements for monitoring and control systems in the ALS domain. Shared control allows the crew to modify plans and examine the status and control the execution of the current plan. An additional feature provided by a planner, with predictive capability, is the ability to do “what-if” analysis of potential plans.

Safety requires that the overall monitoring and control software ensure the ALS systems function in a safe and robust manner [11]. One example of safe operation is turning off any electrically-powered equipment in a chamber where the total percentage of O_2 in the air is above a predefined limit. In addition, crew interaction and approval is required before proceeding with certain critical tasks [11] such as turning off the ARS for a short time to perform a scheduled maintenance task. A planner must therefore flag certain actions to require crew approval before execution.

3.2 Adapting 3T for ALS

Another challenge for the planner in 3T is adapting it for monitoring and control of the ALS systems of the LMLSTP and BioPlex. AP, the top tier of 3T, was designed and built by MITRE for the battlefield management planning domain [8,9]. The 3T architecture as a whole was initially designed for robot control. The ALS domain is a new application for both the AP and 3T tools.

Monitoring and control of BioPlex encompasses many more systems and a much larger amount of data than any previous application of the 3T tool. Many more event skills must be running concurrently. This may stress the skill manager’s capability to monitor the data for significant events. As discussed earlier, the planner can be used to limit the number of event skills necessary by determining the events and conditions that need to be monitored for each context or group of actions.

The increased number of systems also puts more emphasis on the multiagent planning capability of AP. In the two testbeds, parts of the ALS systems can be viewed as agents with action assignments and resource requirements for each agent. For example, the ARS and the plants both produce O_2 but use different actions and resources. These individual agents do not have the overall view of the testbed environment needed to make optimal choices for selecting actions and allocating resources. An additional requirement for the planner is that it must be able to deal with agent assignments and resource allocation.

An additional characteristic of this domain is the longer time frame involved for the plans. Determining the type and amount of crops to plant depends upon the food required one or more months in advance. This time frame is much longer than the planning needs of any of the previous 3T applications. The planner must be able to balance short-term and long-term goals.

One area of special interest not addressed in previous 3T applications is the use of simulation models for plan prediction and simulation. Other similar architectures, such as the New Millennium Remote Agent architecture [7] and the TouringMachine architecture [4] use models as part of their architecture. Future research will examine how models can be used within the 3T architecture for planning. Model-based prediction is especially important since the effects of many actions within the testbed are brought about very slowly. For example, it can take more than an hour for the results of some control actions to appreciably change the O_2 concentration in the habitation chamber.

4. Summary

This paper presented requirements for planners for high-level monitoring and control of advanced life supports systems. The requirements focus on the current plans for using 3T in the LMLSTP and BioPlex testbeds. The planner must:

- select actions to achieve and/or maintain goals,
- determine when to carry out the selected actions,
- use action preconditions during plan execution to account for exogenous events,
- take into account changing system performance when planning and scheduling actions,
- balance different goals for multiple, interacting systems,

- assign actions to multiple systems (agents) and allocate resources for each agent action,
- assist in reducing the number of events and conditions to monitor concurrently or the sampling rates, and
- provide shared control with the crew.

Acknowledgments

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