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Space Station Freedom ECLSS - A Step Toward Autonomous Regenerative Life Support Systems

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Abstract

The Environmental Control and Life Support System (ECLSS) is a Freedom Station distributed system with inherent applicability to extensive automation primarily due to its comparatively long control system latencies. These allow longer contemplation times in which to form a more intelligent control strategy and to prevent and diagnose faults. The regenerative nature of the Space Station Freedom ECLSS will contribute closed loop complexities never before encountered in life support systems.

A study to determine ECLSS automation approaches has been completed. The ECLSS baseline software and system processes could be augmented with more advanced fault management and regenerative control systems for a more autonomous evolutionary system, as well as serving as a firm foundation for future regenerative life support systems. Emerging advanced software technology and tools can be successfully applied to fault management, but a fully automated life support system will require research and development of regenerative control systems and models.

The baseline Environmental Control and Life Support System utilizes ground tests in development of batch chemical and microbial control processes. Long duration regenerative life support systems will require more active chemical and microbial feedback control systems which, in turn, will require advancements in regenerative life support models and tools. These models can be verified using ground and on orbit life support test and operational data, and used in the engineering analysis of proposed intelligent instrumentation feedback and flexible process control technologies for future autonomous regenerative life support systems, including the evolutionary Space Station Freedom ECLSS.

Introduction

When the baseline Space Station Freedom is completed in 1999, a milestone in regenerative life support systems for human exploration will be achieved. It will be the first complete on-orbit closure of drinking water, wash water, and oxygen loops which is a step along the way to independence from Earth's resources. Long duration interaction of these subsystems and humans in a micro-gravity environment will be a major achievement for the Environmental Control and Life Support System (ECLSS) designers and engineers.

A great deal of knowledge will be gained for development of advanced regenerative life support systems by the lessons learned in ground and on orbit operation of the baseline ECLSS. This knowledge and familiarization with the characteristics of regenerative life support systems will serve as a basis for advanced automation of these systems.

At present, regenerative life support knowledge is contained in the designs and operational data of previous life support systems and tests, the development documentation of the baseline ECLSS, and in the experiences of the systems engineers and medical experts involved. Many of the previously unknown complexities encountered in a long duration regenerative life support system will be manually dealt with in the baseline ECLSS. The underlying causes of these complexities must be understood and modelled in order to build more robust life support systems for long stays in space.

This objective of this report is to clarify approaches to automation of the Environmental Control and Life Support System. In doing so, the report progresses as follows:

- The Baseline ECLSS - an overview of life support system requirements and the Freedom Station's approach to meeting these requirements.

- Autonomous Regenerative Life Support System - methods of building upon the ECLSS for increased near and long term life support knowledge and automation.

Three automation areas will be discussed. The first two, advanced fault detection, isolation, and recovery (FDIR) and intelligent instrumentation are possible augmentations to the baseline ECLSS software with minimal hardware impacts. The third, advanced regenerative life support control systems, is an approach for using the baseline ECLSS as a test bed for development of more autonomous, long duration life support systems including that of the evolutionary Freedom Station.

The Baseline Environmental Control and Life Support System

Life Support Systems are required to provide the habitable environment for the crew and life sciences payloads. This environment includes water for drinking and washing, and atmospheric gasses. Previous life support systems have typically met these requirement by maintaining sufficient supplies of pressurized gases and fluids, though closed loop options have been investigated (5).

Process Description

The Temperature and Humidity Control, Water Recovery Management, and Air Revitalization Subsystems aboard the Space Station combine to meet the water and air supply requirements as in figure 1. These requirements are met by closing the air and water loops to an extent never before implemented in space. Even so, the control system is essentially open loop, a batch filtering process. Little chemical or microbial data is fed back into the control system for use in adjusting flexible processes for maximum efficiency.

The system is tested on the ground for sufficient cleaning and recycling set types and levels of fluids in the air and water, and is periodically verified on orbit using batch laboratory analysis procedures. This alone, the actual integration of these multiple interacting subsystems to meet specified requirements, will be a great achievement. Lessons learned in the on-orbit integration of these batch processing systems will be invaluable in determining micro-gravity interactions and recombinations of chemical and microbial constituents throughout the revitalization systems.

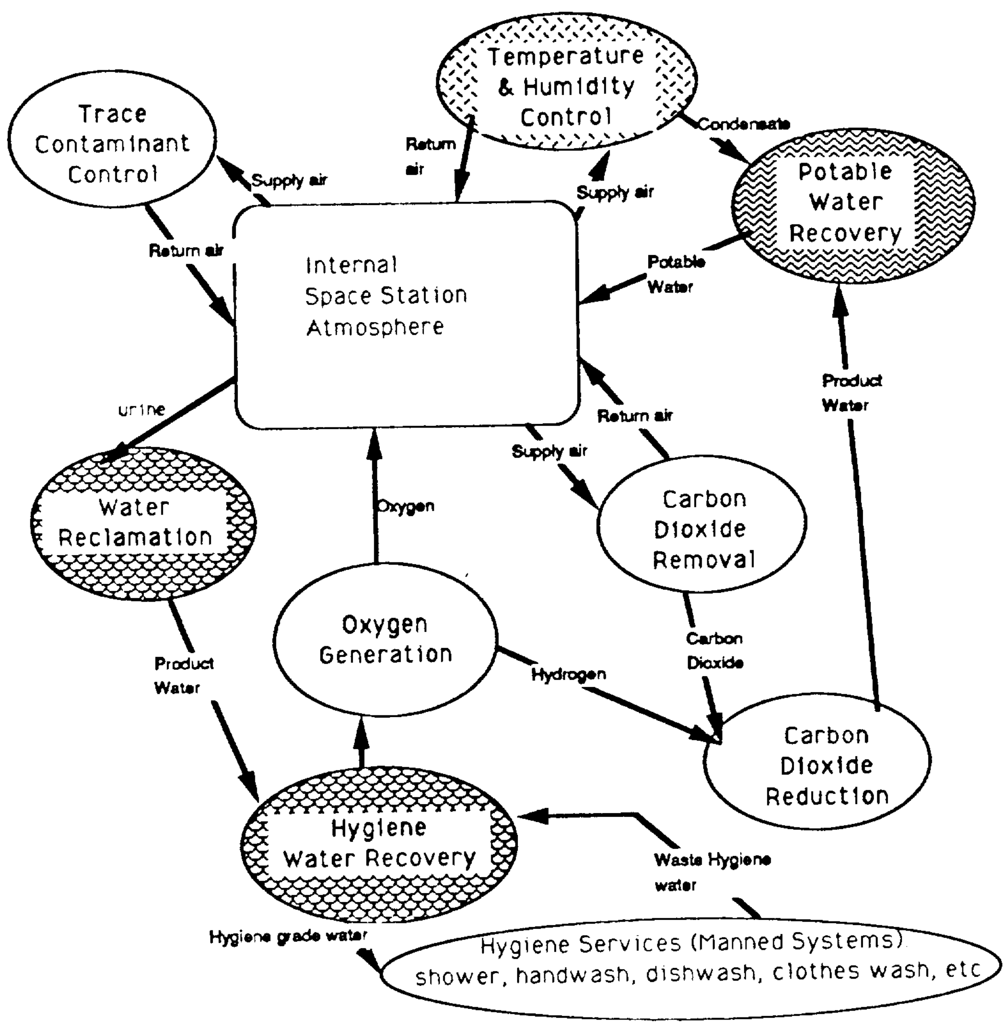

Figure 1 - The ECLSS Functional Interactions

Software Architecture

An overview of the approximate software architecture for the ECLSS is illustrated in figure 2. Two software processes which were determined prime candidates for automation are 2.3 Real-time & Off-line Subsystem FDIR (Fault Detection, Isolation, and Recovery), and 2.4 Component Performance and Trend Analysis. Both of these processes will contain parts initially in the ECLSS Ground Sustaining Engineering, with migration on board when flight data management resources permit.

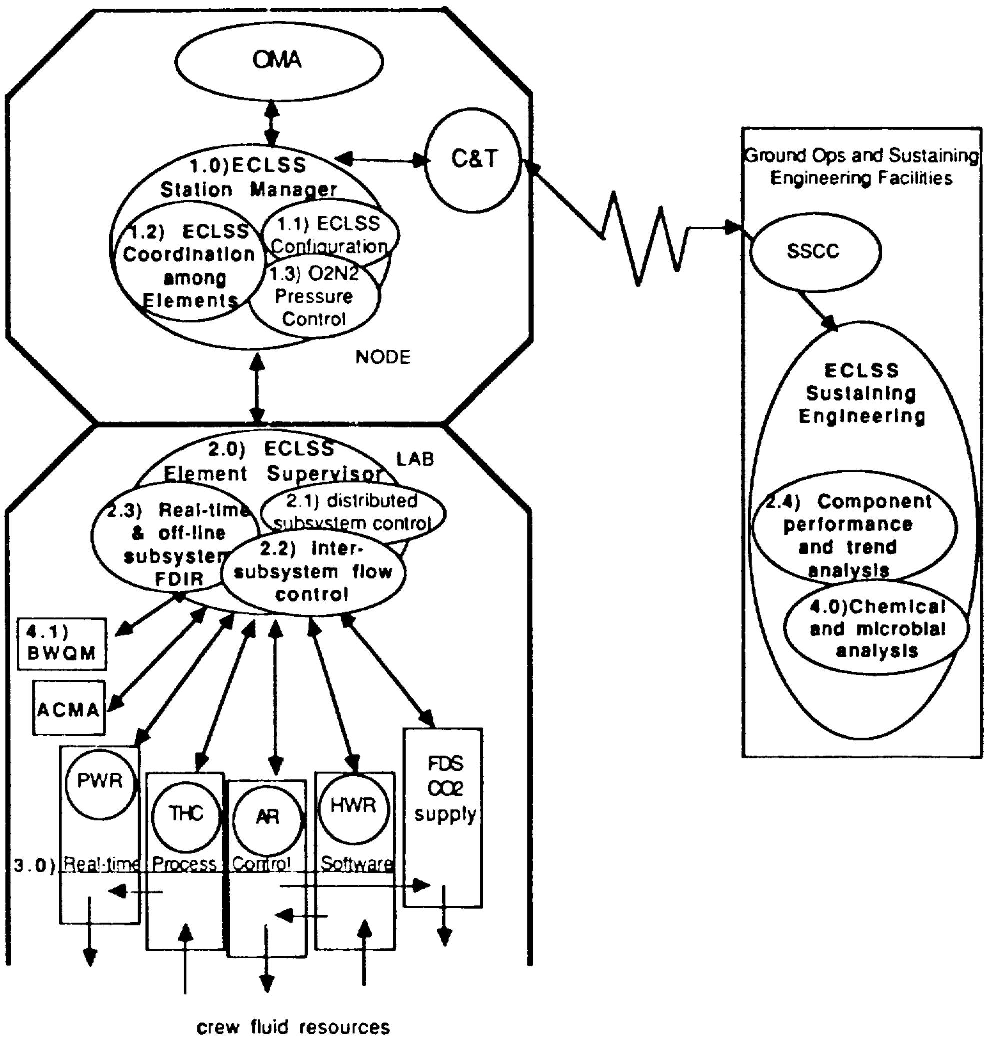

Figure 2 - ECLSS Software Architecture

Baseline Chemical and Microbial Monitoring and Control

Most of the active chemical and microbial monitoring and control of the ECLSS will be a batch manual process involving the crew, ground support labs, and life sciences equipment. There are a few exceptions, confirming that the addition of regeneration technologies introduces requirements for in line chemical and microbial instrumentation and control technologies in the life support system, previously more the domain of life sciences.

The potable recovery, urine pre-treatment, and hygiene recovery processes in the baseline system use some chemical and microbial feedback control. Trace organic carbon levels are monitored on their outputs, and if the measurement violates the required maximum, the water is not released downstream but is cleaned again by the systems' filters. Iodine and pH levels are also monitored at this point for adjustment of the assembly processing. This data will also be available for ground support monitoring and trend analysis. These process control water quality monitors do not provide distinction between organics or their individual levels (4). Also, the viral and inorganic constituents such as metals gathered from the THC slurper or the cabin air ducts are not determined or used by the control system.

More in depth analysis of the chemical constituents of the water is available by manual sampling of the output of the Water Recovery Management processes with on board mass spectroscopy in the Batch Water Quality Monitor (BWQM) and laboratory analysis. Also, extensive ground testing of water samples returned from the Space Station will be used to verify and support the ECLSS. Anomalies require manual replacement of filters or complete flushes and reinitialization of the system, little automatic adjustment of flexible process control subsystems, such as adjustment of chemical additive amounts, flexible filter sizes, or trace contaminant processes, is available.

Autonomous Regenerative Life Support System

In general, future autonomous regenerative life support systems, including the evolutionary ECLSS, will be required to supply water and air, within specific chemical and microbial limits, for extended durations without crew or ground support adjustment. The control system and plant will be intelligent and robust enough to autonomously withstand unexpected crew and payload anomalies. These requirements will be achieved with a minimal set of instrumentation and processing assemblies.

These requirements may be met by augmenting the baseline ECLSS with various technologies. Software hooks, and hardware scars in the baseline will be necessary to minimize the impact of integrating these technologies after Assembly Complete. Increased automation of the ECLSS is possible, but evolution to complete automation, defined as above but requiring some simple unit replacement occasionally, may not be feasible due to the degree of fundamental process adjustments and control strategies required. But the ECLSS can be used to dramatically increase the state-of-the-art in regenerative life support systems.

A block diagram illustrating the components of an Autonomous Regenerative Life Support System is provided in figure 3.

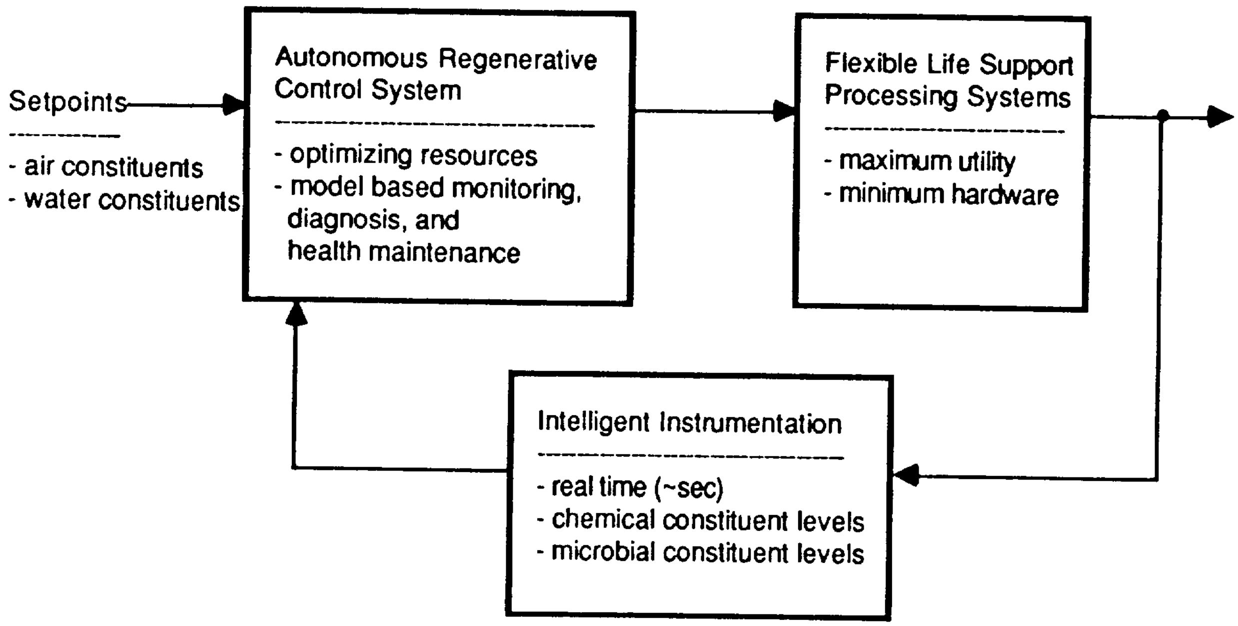

Figure 3 - Advanced ECLSS Block Diagram

The major areas for advanced technology application are:

- Automatic Fault Detection, Isolation, and Recovery (FDIR) and Health Maintenance
- Advanced Intelligent Instrumentation
- Flexible Life Support Processing Systems
- Regenerative Life Support Modelling and Analysis Systems

Automatic Fault Detection, Isolation, and Recovery (FDIR) and Health Maintenance

There are several advantages to beginning ECLSS automation with upgrades in the automatic fault detection, isolation, and recovery (FDIR) and health maintenance (failure prediction and prevention) processes. These processes are software oriented and theoretically, software is the most flexible part of the system and most amenable to upgrades.

FDIR and health maintenance processes require the implementation of emerging software technologies. These processes can be verified in the ground support environment and migrated to the flight ECLSS to increase the Station's flight autonomy. This approach to increasing ECLSS autonomy is described in (2) and (3) and will be the focus of the ECLSS Advanced Automation Project.

Structural and functional models of the ECLSS subsystem processes can be used to diagnose and isolate failures. Model based approaches to diagnosis are computationally intensive but perform autonomous, in-depth diagnosis of faults. The process control nature of the ECLSS allows the use of emerging model based reasoning tools in automating the system, while storing knowledge in component model form (7). The system also may be upgraded for automatic diagnosis of regeneration analysis with the future inclusion of chemical and microbial transfer equations.

Model based fault diagnosis using these models is analogous to the biomedical engineer who notices a trend in the chemical and microbial levels at a certain point and uses a mental model of the behavior of the upstream processes to determine the original anomally. For instance a biological culture in the cabin air duct may cause chemical instabilities in the potable water system, which is downstream (through the THC unit) of this duct. The only way of isolating this fault is through knowledge (a model) of the chemical and microbial behavior of each component, along with knowledge of their structural interconnections.

Advanced Intelligent Instrumentation

Long duration life support systems will be required to monitor a large range of chemical and microbial constituents in real time. This information will be used in advanced feedback control, maximizing the revitalizing effectiveness while minimizing the use of life support processing and resources.

Minimization of system resources implies that chemicals, filters, catalytic gases, and whole subsystem processes can be bypassed or reduced. Maximum revitalizing effectiveness requires adjustment of the life support processes based on the range of chemical and microbial contaminants to be stabilized. The strategic placement of intelligent instrumentation which feeds back chemical and microbial constituents will allow these operations to take place.

Airborne microbial monitoring devices may be needed. The ECLS system uses a trace contaminant monitor which produces gas species data only. Cabin air contaminants and recombination in micro-gravity may need to be known by an advanced control system which could operate to control the contaminants.

Real time, in line chemical and microbial analysis instruments must be developed. This is a tough problem that may be solved by the successful combination of medical, life sciences instrumentation with advanced software technologies. Minimal Space Station Freedom augmentation implies a device which is the same size or smaller than the Process Control Water Quality Monitor.

A modelling system would be necessary in order to optimally design and place these monitors in the subsystem interconnections. The model would allow specific constituent levels to be available to the control system, the optimal placement analysis of feedback pick off points for system microbial stability and other considerations.

Flexible Life Support Processing Systems

Maximization of the range of chemical and microbial effectiveness with minimal system hardware will require process control subsystems which would be able to adjust their processes, for instance the filter type or size, based on the constituent levels of the input and the set point requirements of the output. The filter, or other component for fluid or gas cleanup, would only be used when needed, prolonging its useable life. Multiple, exchangeable component types in the same subsystem would allow a single subsystem to clean a broader range of fluids, minimizing the necessary hardware. The potable and hygiene loops may be able to be combined in this manner.

The amounts of chemicals added, such as urine pre-treatment biocides and iodine, could be adjusted based on intelligent instrumentation feedback. Minimization of these additives would require less supply, and may limit the chemical and microbial combinatorics of the downstream subsystems.

Regenerative Life Support Modelling and Analysis Systems

A high fidelity modelling system would be necessary for optimal placement of feedback instrumentation, engineering analysis of flexible life support processing requirements, and development of biological fault isolation techniques. If the pressure, temperature, chemical, and microbial transfer equations of each regenerative agent, such as a urine processing assembly, biological culture, or crew member, could be developed, the entire system's long duration chemical and microbial stability could also be analyzed.

Verification and upgrades of the models using ground and flight ECLSS configurations would provide an advanced engineering tool for autonomous regenerative life support system engineering. Evolutionary ECLSS, Lunar Base, and Mars Excursion Vehicle life support systems developers could then perform advanced, autonomous, and optimal control system analysis as well as long duration studies using this structured knowledge. Studies could indicate the relative behavior and stability of adding a two bed molecular sieve, CELSS greenhouse module, or Lunar Oxygen mining subsystem.

Gravity constants used throughout the transfer equations would predict changes in subsystem behaviors due to changes in gravity. Biological agents which do not combine due to weight differences in ground tests could produce unexpected results in space. Updating the model transfer equations will increase the fidelity and stored knowledge of variable gravity effects on biological agents in regenerative systems.

Conclusion

The Environmental Control and Life Support System aboard Space Station Freedom will be a step ahead in the implementation of regenerative life support systems. The interactions of its subsystems with each other and the crew will serve to greatly increase our knowledge in low gravity regeneration complexities. The Space Station can be used as a test bed for verification of chemical and microbial, variable gravity transfer models which will prove essential in long duration regenerative life support system engineering and autonomy analysis.

The fully automated regenerative life support system described cannot be built today. Quite a few steps must be taken, and research performed in order to develop systems which can autonomously remain stable for long durations. A first step is to build and deploy the Freedom Station. The actual hands-on knowledge generated from ground and flight tests will allow incremental builds upon the ECLSS toward automation and long term stability. Another step is the inclusion of Life Sciences medical technology in Life Support engineering. Life support systems which use regenerative techniques to meet their supply requirements will have to actively worry about and control microbial recombination, and insure biological stability.

Long term autonomous, robust, and stable regeneration of atmospheric resources require a proportional increase in control system activity and intelligence with the decreased size of the buffer of air and water resources. Stabilizing thimble sized atmospheres for human exploration will require a deeper understanding and active participation than maintaining the integrity of the vast resources of Earth.

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