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# A Survey of Life Support System Automation and Control

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(NASA-TM-103977) A SURVEY OF LIFE  
SUPPORT SYSTEM AUTOMATION AND  
CONTROL (NASA) 11 P

N93-25085

Unclas

G3/31 0158553

January 1993

**NASA**

National Aeronautics and  
Space Administration



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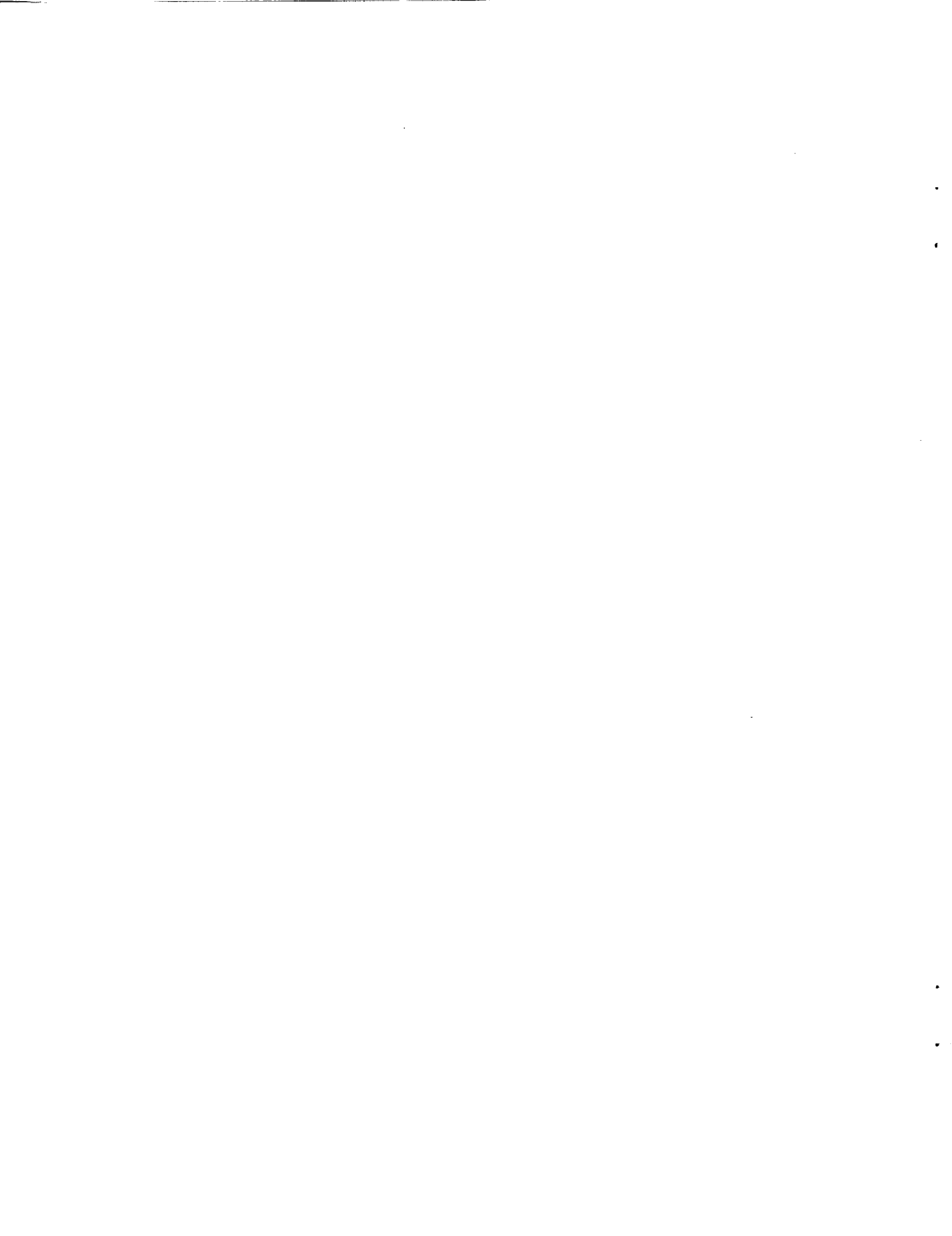
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January 1993



National Aeronautics and  
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## Summary

The level of automation and control necessary to support advanced life support systems for use in the manned space program is steadily increasing. As the length and complexity of manned missions increase, life support systems must be able to meet new space challenges. Longer, more complex missions create new demands for increased automation, improved sensors, and improved control systems. It is imperative that research in these key areas keep pace with current and future developments in regenerative life support technology. This paper provides an overview of past and present research in the areas of sensor development, automation, and control of life support systems for the manned space program, and it discusses the impact continued research in several key areas will have on the feasibility, operation, and design of future life support systems.

## Introduction

In the past, life support systems incorporated relatively simple process technologies, and were not concerned with the regeneration of waste products. Control of these life support systems was primarily carried out in an open-loop fashion, relying on manual adjustments of valves and switches. Consequently, there was little need for continuous measurement of the process, and little need for advanced sensor technology.

More recently there has been increasing interest in longer missions, which will require more complex, regenerative life support systems. The operation and maintenance of these larger, more complex systems will require an excessive amount of crew time unless automated systems can be developed to assist the crew with functions such as monitoring, control, system "health" maintenance, and fault diagnosis. Supervisory controllers will be needed to handle the added complexity and size of these systems, and more advanced sensor technologies will be needed to enable the functioning of autonomous health maintenance, and control systems. Process control algorithms will need to be developed which will be robust enough to handle all the problems associated with regenerative life support systems, including those systems that incorporate bioregenerative technologies. Fortunately, the availability of powerful small computers makes the development of autonomous systems feasible.

At present, progress is being made in several areas, including system modeling, sensor development, knowledge-based systems design, and testbed development. Testbed studies at the subprocess level tend to operate with a limited number of sensors and minimal amount of feedback control. However, if integrated

testbed studies are to provide the quantity, quality, and type of data and range of controlled operating conditions needed for model validation, control system design, and expert system design, then a higher level of monitoring and control will be needed. Other issues such as control architecture, commonality of software and hardware, and fault-free software generation will become increasingly important as regenerative life support projects move forward in the development cycle.

## Control Architectures

It is important that the control architecture for life support systems be defined as early as possible in the design cycle in order to establish a framework for automation and control. It is also important to develop a generic approach to automation and control of life support systems in order to simplify these functions and to facilitate the commonality of hardware and software. Although it may not be possible to adopt a completely generic approach to automation and control at all levels in the system hierarchy, especially at the lower levels where algorithms will need to be process specific, it would be advantageous to develop generic architectures for automation and control at all system levels, as well as to develop generic algorithms at higher levels in the system hierarchy.

A considerable amount of effort has already been given to defining, developing, and demonstrating these generic approaches. For example, Honeywell (Block, 1987) has demonstrated a generic approach to automation and control based on a hierarchical system structure with a distributed control architecture at the lower system levels. They have developed a conceptual design for Space Station Environmental Control and Life Support System (ECLSS) automation and control, and have demonstrated their ideas by monitoring and controlling a representative ECLSS air revitalization system (oxygen generation using a Static Feed Electrolyzer, carbon dioxide concentration using an Electrochemical Carbon Dioxide Depolarizer, and carbon dioxide reduction using a Sabatier Carbon Dioxide Reduction Subsystem). Their Automated Subsystem Control for Life Support System (ASCLSS) demonstrator, sponsored by the Johnson Space Center, includes individual simulators for each air revitalization process (implemented on a personal computer), and a user interface for crew supervisory control. They have developed a layered software architecture, which consists of four layers: (1) the operating system (1750A Assembly Language), (2) the system control software (Pascal), (3) the Input/Output data base, and (4) the process control application software (Pascal). Their conceptual design was demonstrated using the actual air revitalization hardware after having first been demonstrated using the

three process simulators. The simulation software, process control hardware, and air revitalization hardware was provided by Life Systems.

The University of Alabama in Huntsville, in its report to Marshall Space Flight Center (Lukefahr et al., 1989), also advocates the implementation of a hierarchical control system architecture. The report suggests a four-tier structure, where the four tiers are defined as (1) the system-level controller, (2) the ECLSS manager, (3) the element-level controller, and (4) the rack-level controller. The system-level controller would be responsible for station-level functions, including the integration of systems, elements, and payloads. It would handle inter-element functions, performance and trend analysis, system Fault Detection, Isolation, and Recovery (FDIR), and would interface with the station-level operations management system. The ECLSS manager would coordinate the activities of all the ECLSS subsystems across all pressurized modules. Its functions would include monitoring, control, and FDIR. The element-level controller would coordinate and control ECLSS functions across rack boundaries, and would monitor and control ECLSS subsystem health and report status to the ECLSS manager. Its responsibilities would include command and control, FDIR, manual over rides, and displays. The rack-level controller would monitor and control ECLSS functions within each rack.

## Advanced Automation

The development of advanced automation techniques for ECLSS systems will be an important step because ECLSS operation and problem analysis are very time-consuming for crew members (Bishop and Boehm, 1989; Schwartzkopf, 1991). Producing intelligent systems to monitor, control, and diagnose ECLSS systems will be a great technological challenge because of the complexity and highly interactive nature of these systems. Also, the benefits, such as saved crew time and increased safety and reliability, of these autonomous systems must be traded against the extra resources required to install and operate these systems.

To develop these autonomous systems, intelligent control systems must be designed, which will be robust enough to autonomously respond to unexpected situations. Furthermore, automatic FDIR systems and health maintenance systems must be developed to provide failure prediction and prevention. Issues such as resource scheduling, system redundancy, and diagnosibility must also be addressed. To date, little has been done in the area of advanced control algorithm development for integrated ECLSS systems; however, other areas of advanced

automation have been more heavily pursued. For example, expert systems for system health maintenance and fault diagnosis are already being developed for a Mars oxygen production system (Huang et al., 1988).

Boeing's Advanced Automation Project (Boeing, 1990; Dewberry, 1990; Thornton et al., 1991) addresses several aspects of advanced automation, mostly concerned with software tools and techniques for fault diagnosis. The project's main objectives are to demonstrate FDIR for the potable and hygiene water recovery and for the carbon dioxide reduction and removal, as well as for the control, diagnosis, and trend analysis at the ECLSS system level. Boeing's project focuses on the regenerative water recovery and air revitalization subsystems of Marshall Space Flight Center's Core Module Simulator. The authors have modeled the potable and hygiene recovery subsystems and are performing testbed integration, and plan to model the air revitalization subsystem and to incorporate results from the Jet Propulsion Lab on intelligent process monitoring (Voecks and Seshan, 1991). Five packages are under development in support of this project. They are:

1. the Common Model Interface, which coordinates the diagnostic and reasoning packages;
2. the Console Interface, which uses NASA's TAE-plus toolset to conform to the Space Station Workstation Interface;
3. Associational Diagnosis, which uses Boeing's AQUINAS product and NASA's DART product;
4. Model-based Diagnosis, which is prototyped using Gensym's G2 and implemented with NASA's KATE; and
5. Data Acquisition.

Other software that is also being used for this project includes ART/Ada and CLIPS for associational reasoning, and Erasmus for distributed blackboard operations.

Johnson Space Center has developed a pre-prototype expert system, the Shuttle Leak Management Expert System (SLMES), which aids in the selection of flight procedures to handle anomalies such as overboard leakage, onboard leakage, and contamination of the cabin atmosphere (Lafuse, 1991). SLMES integrates rule-based expert system technology with traditional FORTRAN-based software to assist the ECLSS analyst or Subsystem Manager with the analysis of subsystem anomalies.

## Physical/Chemical Life Support System Control

Control of physical/chemical regenerative life support systems has yet to be fully explored in the context of

long-duration Space Exploration Initiative missions. These missions are likely to involve smaller buffers, longer operating times, and increased system closure compared with those of earlier missions. This means tighter control will be needed to meet the requirements for these closed-loop life support systems. Control systems will need to be robust in order to compensate for such things as sensor drift, disturbances to the system, and changes in the system performance, and will also need to demonstrate adequate fault tolerance in order to guarantee crew safety.

Currently, these physical/chemical systems are primarily being tested in an open-loop fashion at a subsystem level (Chang, Craig, and Rousseau, 1986; Colling and Hultman, 1980; Ellis, Wynveen, and Schubert, 1979; Grigger and Schubert, 1988; Heppner, Dahlhausen, and Klimas, 1982; Heppner, Hallick, and Schubert, 1980; Heppner, Hallick, and Schubert, 1977; Heppner, Wynveen, and Schubert, 1977; Kleiner and Birbara, 1981; Koszenski, Schubert, and Burke, 1983; Kovach and Zdankiewicz, 1987; Mallinak, 1987; Noyes, 1985; Rowe, Morando, and Johnson, 1991; Schubert, Wynveen, and Hallick, 1976; Tester et al., 1986; Zdankiewicz and Schubert, 1984). Hence, the nature of the underlying system-level control problem is not yet well defined. However, the development of closed-loop testbeds is underway, and it is hoped that these testbeds will allow researchers to evaluate system control needs and to investigate the use of advanced control algorithms for system-level control.

Control systems for future physical/chemical life support systems are likely to contain a relatively advanced system-level controller, which oversees and gives instructions to conventional controllers, which control the individual processors and other system components. The development of closed-loop testbeds will be necessary to facilitate the development of advanced system-level controllers. These controllers are likely to incorporate both expert systems and modern control techniques (e.g., adaptive control (Ferla and Marchis, 1983; Marchis and Nervegna, 1984), robust control, neural networks, etc.). Unfortunately, little work has been done to date in the application of modern control techniques to closed life support systems; however, this may become an important issue in the development of reliable, automatic control systems for future regenerative life support systems.

### **Controlled Ecological Life Support System (CELSS) Control**

The addition of biological elements to a regenerative life support system will result in some new complications, such as nonlinearities and uncertainties in the dynamic

behavior of the biological species. In order to reduce the level of uncertainty in our understanding of these dynamics and to validate existing models (Averner, 1981; Blackwell and Blackwell, 1989; Blackwell, 1991), carefully designed experiments are needed. These experiments need to be conducted in a closed, controlled environment, and a large number of accurate process measurements must be made. Plant growth experiments are being conducted in a number of places, including many of the NASA centers; however, very few plant growth studies satisfy both of the above criteria. Other control problems in a CELSS system may also arise, such as complications in the system behavior because of closed-loop interactions, long time delays, and limited storage capacities.

Because classical control theories cannot be easily applied to these complex, poorly-understood systems, new approaches must be taken to design robust control schemes for these systems. For example, approaches based on statistical methods are often applied to control of "poorly defined" systems. One such statistical method, sensitivity analysis, has been suggested for control of a CELSS (Hornberger and Rastetter, 1982; Auslander et al., 1983; Stahr et al., 1982; Babcock, 1986; Babcock et al., 1984; Young, 1982). Sensitivity analysis methods can theoretically be applied to CELSS in order to design controllers that have a high probability of adequate performance under a specified set of uncertainties in the process parameters. Performance is generally required to be a binary measure, such as survival/non-survival in the case of CELSS. The best control parameters can then be chosen from a set of possible control parameters for a given control structure using Monte-Carlo simulation techniques.

Control problems associated with closed ecological life support systems become increasingly more difficult when entire ecosystems are considered. For example, the design of a control system for MELISSA (Micro-Ecological Life System Alternative), a project jointly undertaken by the European Space Agency and five independent organizations (CNRS at Gif sur Yvette, Matra Space Branch, University of Clermont Ferrand, University of Ghent, and SCK/CEN at Mol), will be very challenging. To be successful, MELISSA needs to integrate four microbiological compartments with the crew chamber to form a safe, reliable life support system (Lasseur and Binot, 1991). By necessity, fault management systems, redundancy, and automatic calibration technologies are being developed for MELISSA so that continuous, long-term operation of the system will be possible.

## Sensor Development

In the past, sensor needs were limited because monitoring involved little more than measuring fluid temperatures, pressures, and flowrates using relatively simple devices. The increased interest in longer missions will impose added requirements for new and better sensors. These longer missions will require sensors with high reliability and low maintenance requirements, as well as low mass, power, and volume requirements. In addition, there will be a need for detailed air and water composition monitoring because of the potential build-up of contaminants in a closed system over long periods. These measurements will need to be continuous, real-time measurements, and will need to be automated to minimize the need for crew intervention. Fault detection, isolation, and recovery will also become increasingly important, thus increasing the demand for both multifunctional sensors and smart sensors.

In addition to monitoring of fluid temperatures, pressures, and flowrates, there will be a need for monitoring of the air composition (major constituents, trace contaminants, particulates, etc.) and water quality (Total Organic Carbon, or TOC, conductivity, turbidity, pH, iodine concentration, microbial content, etc.), as well as for monitoring for safety reasons such as gas leak detection, fire detection, etc. The future addition of crop growth units will stimulate the need for yet another set of sensors and instrumentation to measure new quantities (nutrient solution parameters, lighting parameters, crop growth measurements, etc.). Many efforts are underway to evaluate these new monitoring needs, and to identify and develop new sensors and instrumentation that will meet these future needs (Diamant et al., 1991; McDonnell Douglas Space Systems Company, 1990; Voecks and Seshan, 1991). In particular, progress in the area of water quality monitoring has been especially well documented (Burchfield et al., 1991; Godec et al., 1991; Highsmith et al., 1991; Jeffers and Jolly, 1991; Jolly and Jeffers, 1991; Niu et al., 1990; Schlager et al., 1976; Schweickart et al., 1991; and Vincze and Sauer, 1990).

In a report prepared by McDonnell Douglas Space Systems Company for Marshall Space Flight Center (1990), results of a life support system technology trade and instrumentation survey are presented. The study involves a technology trade of potential physical/chemical processors for six life support functions. The trade off study is based primarily on technical merit. The report lists the recommended instrumentation for support of the selected air revitalization and water recovery technologies, and it contains a wealth of information, including information on sensors and monitored parameters for past, present, and future spacecraft, and a list of sensors currently in use

with some of the air revitalization and water recovery technologies. More information is available from the McDonnell Douglas ECLSS technology database and computer database of sensor technologies, which were developed using commercial database software. The study is further documented in a paper by Diamant et al. (1990) in which important issues associated with instrumentation technology development for the Space Exploration Initiative are discussed.

The Diamant et al. (1990) study also discusses the advantages and disadvantages of various air and water monitoring technologies that will be considered for use aboard Space Station *Freedom*. Space Station *Freedom* water quality monitoring will likely include on-line monitoring of pH, TOC, conductivity, turbidity, and iodine concentration, as well as off-line monitoring of chemical and microbial composition. Both TOC and microbial monitoring were identified as needing further development. Current TOC monitoring technology has several problems associated with it, including measurement inaccuracies, slow sampling times ( $\geq 15$  min), and use of expendable chemical oxidizing agents. Ultrasound and UV absorption were suggested as possible candidates for future TOC monitoring. Ultrasound uses a simpler gas separation design and does not require expendable oxidizing agents, and may also be useful in the area of trace contaminant control. Fluorescence spectroscopy and biosensors were identified as candidates for microbial monitoring. Fluorescence spectroscopy has limited sensitivity, but can potentially be automated, while biosensors are likely to provide highly sensitive, real-time measurements, but may have limited lifetimes because of sensor instabilities.

Atmospheric monitoring in the past has primarily involved measurement of the major atmospheric constituents: oxygen, nitrogen, carbon dioxide, and water. However, plans for Space Station *Freedom* include the use of a combined Gas Chromatograph/Mass Spectrometer (GC/MS) to measure trace contaminants, a separate MS to measure major constituents, a carbon dioxide monitor, a particle counter, and off-line measurement of airborne microorganisms (Heppner et al., 1990; Diamant et al., 1991). The paper by Diamant et al. (1990) identifies a need for further development of technologies for monitoring of trace contaminants, particulates, and major constituents, as well as for detecting fire and gas leaks. In the area of trace contaminant control, several technologies are targeted for development and/or improvement. The GC/MS is capable of monitoring a multitude of trace contaminants, but suffers from slow response times ( $\geq 30$  min) and high weight and power requirements. The GC/MS needs to be redesigned to detect a wider range of contaminants. The use of a tandem mass spectrometer (MS/MS), which can achieve faster analysis times and



greater accuracy than a conventional MS, would potentially allow the detection of additional compounds. These additional compounds could alternatively be detected using other monitors (GC/MS), but would require the use of additional detectors. Fiber optics is another technology that shows great promise, offering improved sensitivity, precision, and reliability. Particulate monitoring instrumentation is currently well developed, but its size needs to be reduced for future space applications. Major constituent monitoring is another technology area in need of improvement. The MS, in conjunction with a separate carbon monoxide monitor, is targeted for use aboard Space Station *Freedom* to monitor the major atmospheric constituents. Other alternatives for major constituent monitoring include Fourier Transform Infrared (FTIR) Spectroscopy, which is safe, fast, and reliable, and multigas sensors, such as the nonaqueous electrolyte-based amperometric sensor, which is small, lightweight, uses very little power, and has high selectivity, fast response times, and the potential for a long operating-life (Venkatesetty, 1988; Venkatesetty, 1990). One final area identified for further development was the use of acoustic emission detection for gas-leak detection.

The development and implementation of smart sensors will result in a significant improvement in life support monitoring systems. These sensors combine the sensing device, electronics, data processing, and data analysis to speed up control processes and reduce computer loads. Their use of microprocessors allows these systems to analyze combined data received from multiple physical and chemical measurements taken from an array of sensors. These sensor arrays can be placed on a single chip, and can be used for built-in redundancy and self-diagnostics, resulting in increased system reliability.

The addition of plant components to the life support system to create a CELSS will result in a new set of monitoring requirements. Tabacco and Quan (1991) discuss the development of fiber optic sensors, which are suitable for on-line monitoring of atmospheric contaminants and nutrient solution parameters associated with these plant components. The use of fabricated porous glass and porous polymer optical fibers results in a smaller, simpler sensor with improved sensitivity. In addition, interfaces have been developed for these sensors that allow multi-sensor and/or distributed operation. Nishi et al. (1987) discuss the development of a mass spectrometer and computer system for gas monitoring in a CELSS. Their investigation included hamster metabolism and *Spirulina* photosynthesis, but did not include any plant components.

## Conclusions

Defining control architectures and developing generic approaches to automation and control for life support systems are both important steps in designing automatic control systems. It is important to establish a framework for automation and control and to facilitate the commonality of hardware and software. Also, it is important to develop advanced automation techniques for advanced life support systems, because operation and problem analysis of these complex, highly interactive systems can be very time consuming for crew members. The development of autonomous systems requires designing intelligent control systems robust enough to autonomously respond to unexpected situations. Also, automatic FDIR systems and health maintenance systems must be developed to provide failure prediction and prevention, and issues such as resource scheduling, system redundancy, and diagnosability must be addressed.

To date, research in advanced control algorithm development for integrated life support systems has been limited, while other areas of advanced automation have been more heavily pursued. Unfortunately, the system-level control problem is not yet well defined because physical/chemical systems are primarily being tested at the subsystem level in an open-loop fashion. However, it is likely that the development of advanced control algorithms will be a technological challenge because future missions are likely to involve smaller buffers, longer operating times, and increased system closure compared with the requirements of earlier missions. This means that tighter, more robust control will be needed to meet the strict operational requirements for future life support systems. Currently, the development of closed-loop testbeds is underway, and it is hoped that these testbeds will allow researchers to evaluate system control needs as well as investigate the use of advanced control algorithms for these systems.

Regenerative life support systems that incorporate biological components will encounter some new complications, such as increased complexity in the system behavior because of nonlinearities and uncertainties in the dynamic behavior of the biological species, in addition to complications because of closed-loop interactions, long time delays, and limited storage capacities. New approaches may be needed to design robust control schemes for these systems, because classical control theories may not be applicable to these complex, poorly understood systems. In addition, carefully designed experiments will be needed to validate existing models and to reduce the level of uncertainty in our understanding of the dynamics of these systems.

The increased interest in longer missions is likely to result in a need for new and improved sensors with high reliability and low maintenance requirements, as well as low mass, power, and volume requirements. Sensor needs were limited in the past, because monitoring involved little more than measuring fluid temperatures, pressures, and flowrates using relatively simple devices. However, future missions will require detailed air and water composition monitoring because of the potential for build-up of contaminants in a closed system over long periods. Also, these missions will require the development of sensors that produce continuous, real-time measurements, and the development of automated process monitoring systems in order to minimize the need for crew intervention.

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# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE January 1993	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE A Survey of Life Support System Automation and Control			5. FUNDING NUMBERS 199-61-12	
6. AUTHOR(S) Cory K. Finn				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Ames Research Center Moffett Field, CA 94035-1000			8. PERFORMING ORGANIZATION REPORT NUMBER A-92191	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-103977	
11. SUPPLEMENTARY NOTES Point of Contact: Cory K. Finn, Ames Research Center, MS 239-8, Moffett Field, CA 94035-1000; (415) 604-1027				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified — Unlimited Subject Category 31			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  The level of automation and control necessary to support advanced life support systems for use in the manned space program is steadily increasing. As the length and complexity of manned missions increase, life support systems must be able to meet new space challenges. Longer, more complex missions create new demands for increased automation, improved sensors, and improved control systems. It is imperative that research in these key areas keep pace with current and future developments in regenerative life support technology. This paper provides an overview of past and present research in the areas of sensor development, automation, and control of life support systems for the manned space program, and it discusses the impact continued research in several key areas will have on the feasibility, operation, and design of future life support systems.				
14. SUBJECT TERMS Life support systems, Control systems, Automation			15. NUMBER OF PAGES 10	
			16. PRICE CODE A02	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	

