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Controls and Automation Research in Space Life Support

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A highly controlled and automated life support system has long been a NASA goal. It is usually assumed that life support for future long duration missions will use physical/chemical recycling systems that substantially close the oxygen and water circulation loops. Such a tightly coupled life support system has been thought to require an overall supervisory control system to minimize crew operation and maintenance activities. The International Space Station (ISS) Environmental Control and Life Support System (ECLSS) was at first expected to have supervisory control and automation. After this was found infeasible during the design of the ISS ECLSS in the early 1990's, it was then expected that the ISS or future mission systems would be upgraded to meet the original expectations. Since then NASA has extensively researched life support system controls and automation. Automation and Artificial Intelligence (AI) have gone through several cycles of enthusiasm and neglect before their recent great achievements, and NASA life support interest has similarly varied. Since the ISS ECLSS was launched, its on-board operational problems have led NASA to deemphasize system level controls and automation in favor of improving subsystem reliability and maintainability. Recent work has investigated supervisory control for a system similar to the ISS ECLSS. This paper reviews past planning and work on the supervisory control of closed, integrated physical/chemical life support systems similar to the ISS ECLSS and its precursors dating back to the 1960's.

Nomenclature

AI = Artificial Intelligence
AILSS = Advanced Integrated Life Support Systems
BIO-Plex = Bioregenerative Planetary Life Support Systems Test Complex
CELSS = Controlled Ecological Life Support System
ECLSS = Environmental Control and Life Support System
FDIR = Fault Detection, Isolation, and Recovery
FPGA = Field Programmable Gate Array
ISS = International Space Station
PID = Proportional Integral Derivative
SEI = Space Exploration Initiative
SSF = Space Station Freedom

I. Introduction

An integrated, automated life support system has long an ultimate goal for NASA life support programs. It is assumed that life support for the next long duration missions will use physical/chemical recycling systems that substantially close the oxygen and water circulation loops. This closed, tightly coupled life support system would require an overall supervisory control system and automatic fault detection to optimize performance and minimize crew intervention. After Space Station Freedom (SSF) was reduced in scope in 1991, the International Space Station (ISS) Environmental Control and Life Support System (ECLSS) design was based on SSF subsystems. The ISS ECLSS first was expected to include supervisory control and automation. When this proved to be inadvisable, it was expected that ISS upgrades or a future system would achieve autonomy.

After the design of the ISS ECLSS in the early 1990's, extensive research investigated upgrading ISS for supervisory control and automation. With the deployment of the ISS ECLSS in the 2000's, NASA changed life

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support focus from system level improvements to refining the existing ISS ECLSS subsystems. Recently new work has considered providing supervisory control for a system similar to the ISS ECLSS.

The purpose of this paper is to review past efforts on the advanced control and automation of closed, integrated, physical/chemical life support systems with architecture and technology similar to the ISS ECLSS and its precursors dating back to the 1960's. The broad field of Artificial Intelligence (AI) has experienced boom and bust, but has recently produced world changing advances. Meanwhile the attempted application of AI to space life support has included a variety of efforts with different attractive approaches, but life support control has not been significantly improved. Even though life support has been an interesting potential application of AI, its use of AI will probably be based on the general progress of AI rather than NASA life support research. The ISS ECLSS has been only a single working system, in space with difficult access, while other potential AI platforms such as automobiles have been developed for advanced controls and AI over many generations of models and tens of millions of units. However, understanding the earlier investigations of AI in life support should be helpful in its future implementation.

II. Controls and automation background

Control systems have long been used and are very familiar. They vary from extremely simple, such as a home heater thermostat, to highly complex, such as an industrial plant process control system. Automation has become amazingly effective and widespread in recent years.

A. Mechanical controllers

The simplest controllers implement a predetermined sequence of steps, such as the mechanical clock timer in a clothes washer. A home heater thermostat may use a mechanical temperature sensor, such as two temperature sensitive metal strips with an adjustable distance, and use it to turn the heater on at a set temperature. The sensor and switch combine to form a simple on/off feedback control loop. Simple sequences and feedback loops are now usually implemented in programmable logic controllers or programmed in computers as part of an overall system controller.

B. Classical analog electronic controllers

The classical Proportional Integral Derivative (PID) feedback controller is widely used for continuous process control. It measures the difference between a sensor value and its set point and computes a corrective signal based on three terms, one proportional to the difference, one proportional to the integral of the difference over time, and one proportional to the current derivative or rate of change of the difference. The process of setting the relative weights of the three terms is called tuning and it determines the transient response and stability of the controller. A typical feedback controller use would be in automobile cruise control. Discrete component analog controllers have been replaced by digital controllers using Field Programmable Gate Arrays (FPGA's) or by minicomputers.

The individual regenerative life support systems typically require sequence, on-off, and continuous process control implemented by a dedicated controller or minicomputer. This level of control is necessary and taken for granted, but much more sophisticated control is possible and has been suggested.

C. System wide monitoring

It would be useful to be able to continuously monitor the performance of all the life support systems from a central location, on the ground or in a space habitat. This requires a network to link all the systems to a central computer and data display. The life support system variables would have to be brought to an external interface and connected to the network. Monitoring the usual control variables would be useful, but additional variables can be provided to monitor system health and provide problem indicators. The crew would use the data to observe and manually operate the system and to guide trouble shooting.

D. Supervisory control

In supervisory control the central computer can change the set points in the individual system controllers to satisfy some constraints or optimize some overall measure of performance. The central computer may acquire individual system control functions that replace the lower level system controllers. Supervisory control is suitable for small rapid process adjustments, but the crew would be required to plan and implement major long term actions and configuration changes. Supervisory control systems can form the foundation for implementing automation.

E. Automation and artificial intelligence

Automation extends computer control to overall system management intended to reduce or even eliminate human operation. To have computers replace operators has been the objective of research in artificial intelligence.

Artificial intelligence (AI) was founded as an academic discipline in the 1950's, and has gone through periods of boom and optimism in the 1960's and 1980's followed by periods of disillusionment and loss of funding, called AI winters, in the late 1970's and 1990's. (Wikipedia, artificial intelligence)

> "In the twenty-first century, AI techniques have experienced a resurgence following concurrent advances in computer power, large amounts of data, and theoretical understanding; and AI techniques have become an essential part of the technology industry, helping to solve many challenging problems in computer science, software engineering and operations research." (Wikipedia, artificial intelligence)

The history of AI research includes many separate fields of application with little connection, such as language understanding and robotics. Different AI techniques have been used, such as neural networks and genetic algorithms. And particular institutions and research groups often apply one specific approach to one particular objective. The AI techniques that have been suggested for automation or intelligent control include adaptive control, Bayesian probability, case-based reasoning, connectionism, decision theory, evolutionary computation, expert systems, fuzzy logic, genetic algorithms, hierarchical control, intelligent agents, knowledge-based systems, machine learning, model based control, neural networks, planning and scheduling, reinforcement learning, robust control, rule-based systems, rule-based reasoning, supervised learning, and simulated annealing. Each has its applications and limitations. This AI history and research agenda is reflected in the different past attempts to automate life support.

Automation is largely concerned with normal operation in nominal conditions, but it can be extended to diagnose and even in some cases repair faults.

F. Fault detection, isolation, and recovery (FDIR)

Serious systems operation faults are readily observed by nearby persons. Remotely monitored basic sensors for power, temperature, pressure, output flow, etc. also can indicate faults. Specific sensors, instrumentation, or computation may be provided to detect incipient or less obvious faults. Sensor data trends can be identified. Rotating machinery noise or chemical process byproducts can be monitored. More capability is needed in modern aerospace systems in the form of automatic fault detection, isolation, and recovery (FDIR).

FDIR is often model-based and using AI techniques. Essentially either a mathematical or knowledge based model of the system is created and its predicted values are compared to the system operational data. Differences are monitored to detect faults, and fault diagnosis can be done by classifiers trained by supervised learning or by training neural networks. (Wikipedia, fault detection and isolation) Model based FDIR has made great academic advances and is now widely applied to aerospace systems, space applications, and even ISS, as indicated by the following titles. "Advanced model-based FDIR techniques for aerospace systems." (Zolghadri, 2012) "Integrated FDIR Analysis Tool for Space Applications." (Piras et al., 2013) "Applying Model-Based Reasoning to the FDIR of the Command and Data Handling Subsystem of the International Space Station." (Robinson et al., 2003)

III. Life support interest in advanced controls and automation

Overviews of space life support typically do not mention the need for advanced controls and automation, but management and engineering plans have often express a strong need for them.

A. Little controls and automation in life support overviews.

General overviews of space life support do not usually mention advanced controls or automation. They are not discussed by Humphries, Seshan, and Evanich (1994), by Eckart (1996), or by Doll and Eckart (2000).

Wieland's major compendium on life support has less than a half page on automation. "One approach to automate control and diagnosis of the ECLSS for S.S. Freedom relies on "model-based reasoning" in which sensor data are compared with predictions from a computer model of the ECLSS to identify where performance does not match the specifications and to alert the crew as to the location of a problem or a potential problem." (Wieland, 1994) This is a reference to (Boeing, 1990).

B. Management and engineering indications of interest

Space life support management and engineering plans have often suggested the use of advanced controls and automation, and FDIR, but not always.

A regenerative system with architecture and subsystem technologies was tested with humans in a closed chamber in 1966. It was noted soon after that future missions "will require the development of regenerative systems more advanced than those presently available. This equipment must be maintainable, highly reliable, and possess automatic features to enhance mission success." (Hall, 1969) These goals still remain to be achieved. An early test plan had the objective to "Investigate and evaluate concepts and techniques of systems automation in the areas of monitor and alarm, fault isolation, automatic checkout, and parametric feedback control." (LaRC, 1971)

Initial space station planning anticipated automation, "Fault detection, isolation, and post repair verification is an integral part of maintenance and is a major technology development area. The complexity and large quantity of interactive functions within a regenerative life support system make automation a necessity." (Shuey, 1982)

A project to advance life support beyond the ISS ECLSS planned to investigate autonomous control, heuristic software, and adaptive, algorithm-based, and hybrid control techniques. (Pathfinder, 1989)

Life support development for the Space Exploration Initiative (SEI) envisioned a highly integrated regenerative physical-chemical life support system that would "eventually lead to a control system utilizing artificial intelligence (AI)." (Evanich et al., 1990) The SEI supporting projects planned to first develop sensors, instrumentation, and monitoring systems, then research "novel robust and adaptive control schemes," and "to develop state of the art automation schemes which incorporate Artificial Intelligence (AI) techniques (expert systems, rule-based reasoning, neural networks, etc.)," finally leading to "fully autonomous integrated (life support system) LSS operation." (Bilardo, 1990)

Advanced life support maintained the objective of "Integrated Autonomous Control of Life Support Systems." (Berdich et al., 2004) The original 2004 detailed specification for the ISS water recovery system required FDIR, but this requirement was deleted in 2006 because of the difficulty of implementation. (MSFC-SPEC-2841F, 2006) Soviet researchers remained convinced the need for adaptive control, AI, and FDIR. (Zaretskiy et al., 2009) However, the NASA 2010 technology roadmaps did not include life support automation and FDIR, although robotics and autonomous systems was an important separate area. (NASA, 2012) The NASA 2015 life support technology roadmap again did not mention advanced controls or automation for life support, but the robotics and autonomous systems roadmap mentioned life support as an example of a potentially autonomous system. (NASA, 2015)

Very recent planning for future life support emphasized "an Integrated ECLSS Hierarchical Control Architecture, and the development of an Intelligent System intended to aide in isolating the cause of any fault." "The control system uses a hierarchical, modular, integrated, digital architecture similar to the Internet. The artificial intelligence system is based on Bayesian networks and will enable preventive maintenance and quick fault isolation." (Stapleton et al., 2018)

IV. Review of NASA research in control and automation of life support

NASA's past efforts in life support controls and automation will be reviewed in chronological order. Many different and independent approaches have been taken, but they fall into two groups, advanced controls and AI based automation.

A. Early investigations, 1966-1979

1. *General Dynamics, 1966.*

The General Dynamics life support system study planned automatic control for pressure, temperature, oxygen, carbon dioxide, and humidity, with manual overrides. "The LSS shall have an automatic control system." "Although the equipment is inherently stable or automatically controlled, man is integrated into the system for start-up and shutdown, monitoring and manual override when necessary, and maintenance." Standard industrial control is assumed. (General Dynamics, 1966)

2. *AILSS, 1970.*

In the proposed Hamilton Standard design, the sensors are interfaced to provide a common output level for continuous monitoring. The displays are installed for major parameters to inform and warn the crew. Automatic fault detection is provided, but the fault isolation routine is completely manual, requiring manual measurements from operational fault isolation instrumentation. (Hamilton Standard, 1970.)

3. *LaRC, 1971.*

LaRC planned to investigate life support systems automation for monitor and alarm, fault isolation, automatic checkout, and parametric feedback control. (LaRC, 1971)

4. *Yang et al., 1979.*

Life Systems investigated fault diagnosis and repair and suggested built-in analysis and fault correction using redundant components. (Yang et al., 1979)

B. Space station plans and Space Station Freedom, 1985-1995

1. Block, Heppner et al., 1985-1986.

A life support control system was proposed for space station. It would use a hierarchy of distributed subsystem controllers connected by a bus. The subsystem controllers would be microprocessors, some with lower level basic controllers. (Block et al., 1985)

A proposal was made for a generic set of hardware and software to implement the Space Station ECLSS subsystem controllers. Standard microcomputers, sensor conditioning, and structured software were proposed. (Heppner et al., 1986)

2. Malin and Lance, 1986.

A prototype knowledge-based expert system was developed for automated fault management in a regenerative life support subsystem. A commercial knowledge engineering software toolkit was applied to a carbon dioxide removal system. This was done to advance automation and robotics in the space program, at the suggestion of a NASA advisory committee for space station. Artificial intelligence was expected to aid planning, fault management, and reporting. (Malin and Lance, 1986)

3. Block, 1987.

Automatic control and monitoring of three Space Station ECLSS processors was implemented using microprocessors and a high speed network. This work demonstrated a generic approach to automation and control of life support based on a hierarchical system structure with a distributed control architecture at the lower system levels. Control authority was allocated between the crew, an upper level system controller, and lower level process controllers. This hierarchical controls technology can support embedded artificial intelligence and expert systems for automation. (Block, 1987a) (Block, 1987b)

4. Dewberry et al., 1989-1991.

An Advanced Automation Project conducted by the Marshall Space Flight Center, the University of Alabama in Huntsville, and Boeing in Huntsville investigated the application of expert systems to ECLSS using "divergent thinking." The project advocated a hierarchical control system architecture with four tiers, the system level controller, the ECLSS manager, the subsystem controller, and the rack-level controller. (Lukefahr et al., 1989) Software was developed to demonstrate how rule based programming can be used for simulation and diagnostics of ECLSS. (Dewberry et al., 1989) The research recommended the development of autonomous fault detection and isolation for ECLSS. (Dewberry et al., 1990)

The ultimate goal of the Boeing project was evolution to a fully autonomous ECLSS for Space Station Freedom and future manned missions that would be built on an upgraded system and would minimize the crew and ground manpower needed for operations. An ECLSS supervisor contained distributed control for subsystem functions spread throughout the space station, such as fire detection monitoring, inter-subsystem flow control for carbon dioxide, water, and other transfers, and off-line subsystem FDlR. Component performance and trend analysis of ECLSS pumps, valves, heaters, and filters would be a ground based sustaining engineering function. Real-time process control included control algorithms, and real-time fault detection, which were built into each subsystem. A model based approach would allow fewer sensors for subsystem FDlR and help overcome bad or missing sensor data. The automation project planned coordination among subsystems, inter-subsystem flow control, both real-time and off-line ECLSS subsystem FDlR, and component performance and trend analysis. Knowledge based real-time monitoring and diagnosis systems were used in advanced automation development The planned autonomous ECLSS subsystem real time and off-line FDlR processes used an internal causal model of the subsystem under test. Automated knowledge acquisition and knowledge engineering tools were used to capture ECLSS development knowledge for model development. (Dewberry and Carnes, 1990)

The Boeing 1990 annual report described the use of both expert systems associational and model-based approaches to fault diagnosis. The project's objectives were to demonstrate control and trend analysis at the ECLSS system level and FDIR for the water recovery and carbon dioxide removal systems. (Boeing, 1990) FDIR and health maintenance (failure prediction and prevention) are desirable capabilities, but ECLSS evolution to complete automation may not be feasible due to the adjustments required in fundamental processes and control strategies. (Dewberry, 1990) The planned Space Station Freedom ECLSS controls were embedded firmware with some flight software supervision, but still basically open loop and heavily monitored with scheduled control. (Dewberry, 1991) “The regenerative nature of the Space Station Freedom ECLSS will contribute closed loop complexities never before encountered in life support systems.” (Dewberry and Carnes, 1991)

5. Kansas State University, 1989-1992.

The Space Station Freedom ECLSS subsystems are not fully automated and the control of these subsystems is not presently integrated, so that they operate independently. ECLSS integration, automation, and control is urgently needed. (Kansas State University, 1990) (Kansas State University, 1991) The proposed classical control approach uses traditional methods to control the mechanical equipment. The proposed expert control system uses fuzzy logic and artificial intelligence to control the system. The two control systems were integrated with a computer simulation and compared. (Kansas State University, 1992)

6. *Voecks and Seshan, 1991.*

Smart sensors for life support will require hierarchical integration of in situ sensors and control elements involving distributed databases, prediction models, and rule-based reasoning modules for hypothesis generation and verification. (Voecks and Seshan, 1991)

7. *Cleveland, 1992.*

A robust, flexible architecture of distributed, independent control agents can achieve the coordination of a hierarchical command structure by basing command decisions on system state variables. (Cleveland, 1992)

8. *Evanich et al., 1992.*

Life support control methods can vary from the simple, decentralized, equation-based architectures such as proportional-integral-derivative (PID) and single-input, single-output control to the centralized rule-based and model-based approaches. (Evanich et al., 1992.)

9. *Williams, 1992.*

As in Dewberry et al., 1989-1991, above, Williams reports on the ECLSS Advanced Automation Project, and advocates model-based reasoning for fault diagnosis. Needs were identified for real-time and off-line FDIR and component and trend analysis. These processes were first to reside in ground support and later to migrate on-board Space Station Freedom.

Knowledge-based approaches are either model-based or associative, using heuristics obtained from experts to create expert systems. Model based reasoning is more capable and innovative. A knowledge-based system is used to model interfaces, structure, functions, commands, and behavior. The model-based approach to diagnosis is favored because it reflects engineering problem solving and because diagnosis based on failure data and predictions can't discover failures due to design or environmental changes. (Williams, 1992)

10. *Gardner, 1993*

Several automated functions were developed for the Atmosphere Revitalization subsystem for Space Station Freedom, including built in test, "smart" process transitioning algorithms, and a number of override commands. (Gardner, 1993)

11. *Finn, 1993.*

Automatic control systems will be required for future regenerative life support systems, including an advanced system-level controller to oversee the conventional controllers in the individual processors. Autonomous life support systems will require advanced sensors and supervisory controllers to provide automation and control of life support at all levels in the system hierarchy. These controllers are likely to incorporate both expert systems and modern control techniques such as adaptive control, robust control, neural networks, etc. Automatic FDIR and health maintenance systems are needed to provide failure prediction and prevention. (Finn, 1993)

12. *Hartung and Moore, 1995.*

Real-time software control functions are planned for the space station on-orbit life support functions. (Hartung and Moore, 1995)

C. Research and testbeds, 1996-2015

1. *Little and Drysdale, 1996.*

The CELSS (Controlled Ecological Life Support System) Breadboard Project data acquisition and controller design uses a microcomputer and distributed commercial controller boards. (Little and Drysdale, 1996)

2. *Bonasso, Schreckenghost, et al., 1998-2005*

Intelligent control systems have been developed to support life support system testbeds at JSC. They used the 3T autonomous control architecture originally developed for robotics. 3T integrates the continuous real-time control algorithms in the bottom layer with advanced AI algorithms in the top layer of automated planners and schedulers, by using a middle sequencing layer. The middle layer translates the goal states computed by the planning and scheduling layer into continuous activities carried out by the skills manager that does real-time control. (Bonasso et al., 2003)

One 3T based system was an inter-chamber atmosphere monitoring and control system that was used to manage gas transfer and storage during a 90-day closed chamber human test for the Lunar/Mars Life Support Test Program. Before it was developed, manually intensive traditional process control software had been used. (Schreckenghost et al., 1998)

Another 3T based system controlled the Integrated Water-Recovery System. The 3T intelligent control architecture led to software that operated autonomously, 24 hours a day, 7 days a week, for 16 months. (Bonasso et al., 2003) (Schreckenghost et al., 2005)

3. *Kortenkamp et al., 2001.*

Machine learning can create an adaptive life support control system. Reinforcement learning and genetic algorithms can help optimize resource utilization. An innovative multistep genetic algorithm generates control strategies that perform much better than traditional reinforcement learning or traditional genetic algorithms. (Kortenkamp et al., 2001)

4. *Pawlowski et al., 2001.*

A novel agent-based control strategy derived from economic models of markets is compared to two standard control strategies, proportional feedback and optimal control. Simulations are used to compare the dynamic behavior of the life support system after it is perturbed away from its nominal operating point under the three different control strategies. (Pawlowski et al., 2001)

5. *Boulanger et al., 2001.*

In the late 1990's, open fieldbus and middleware standards changed process control. Fieldbus pushed control closer to the process itself, and middleware can provide real-time process data to higher level control. Designing control for the Bioregenerative Planetary Life Support Systems Test Complex, or BIO-Plex, was considered and fieldbus was integrated with an existing life support subsystem. (Boulanger et al., 2001)

6. *Boulanger and Jones, 2003.*

Life support systems can be adequately controlled using simple, reliable, low-level methodologies, algorithms, and scheduling methodologies. Advanced control technologies are not necessary. They increase control system complexity without clearly demonstrating an increase in reliability. Reliable control system operation requires the fewest components and minimal complexity. (Boulanger and Jones, 2003)

7. *Overland, 2003.*

A control system was developed for the BIO-Plex, an advanced life support system testbed. Preliminary designs used controller input/output blocks with microcomputers in each system and an ethernet interface. The local computers provide an interface to the sensors and to the subsystems on each systems rack and the host local control software. Each local computer would connect to a hub which would connect to the backbone network. A workstation in each chamber would provide a human interface. (Overland, 2003)

8. *Wu and Garibay, 2004.*

The problem of controlling advanced life support was investigated using two machine learning algorithms, a genetic algorithm and a stochastic hill-climber. Five strategies were compared in different proportions. A proportional representation can effectively boost the performance of genetic algorithms but not necessarily of stochastic hill-climbers. For both algorithms, problem representation determines the shape of the landscape which determines the solutions that are reachable from any particular starting point. (Wu and Garibay, 2004)

9. *Biswas et al., 2004.*

A model-based diagnosis method was developed to detect, isolate, and identify faults in life support subsystems. The method was tested on a model of the Reverse Osmosis subsystem in the ISS Water Recovery System. (Biswas et al., 2004)

10. *Klein et al., 2004.*

A life support controller using reinforcement learning actively explores the space of possible control strategies, guided by a user specified long term objective function. The reinforcement learning algorithm exploited nonlinearities in the simulation dynamics, discovered unobvious strategies for maximizing mission length, and outperformed a controller designed by an expert. (Klein et al., 2004)

11. *Quasny and Pyeatt, 2004.*

Reinforcement learning was used to control the water recovery system of a simulated life support system. The agent learned an effective control strategy that extended the mission length until lack of water no longer caused mission termination. (Quasny and Pyeatt, 2004)

12. *Abdelwahed et al., 2004.*

A hierarchical online fault-adaptive control approach was developed for life support systems. Diagnosis and fault-adaptive control is done by lower level units. An upper level control structure uses predefined set-point specifications to optimize the lower level controllers. When a fault occurs and is identified, the controllers use the updated system model to derive new upper level set points and reoptimize the lower level controllers. (Abdelwahed et al., 2004)

13. *Muscettola et al., 2005.*

Closed loop life support control requires augmenting basic control algorithms with general models and their associated high-level control strategies. The suggested approach uses fast simple responses at the lowest level and more complex responses based on model-based planning and scheduling at the higher level. (Muscettola et al., 2005)

14. Zhang et al., 2005.

In the usual systems engineering schedule, the software requirements specification is developed after the hardware design review. However, closed loop life support is a combination of processes that requires that the control software and system hardware be designed together. The most important difference from the standard approach is that the hardware must be designed for controllability, which forces the control software design to impose hardware requirements. (Zhang et al., 2005)

15. Bonasso and Martin, 2005.

An intelligent control software architecture for life support has been designed to be dynamically reconfigurable. This will allow rapid reconfiguration of the control system after a component failure. (Bonasso and Martin, 2005)

16. Abdelwahed et al., 2005.

A three-tier autonomous, distributed, hierarchical controller for life support uses a global coordinator to ensure resource requirements for the duration of the mission are not violated. The midlevel control handles the interactions between subsystem and system-level controllers. The hierarchical controller can respond to dynamic changes in resource constraints and operational requirements. (Abdelwahed et al., 2005)

17. Biswas et al., 2005.

Life support control experiments used two different layered control architectures, a model-based approach and a procedural approach. Both had strengths and weaknesses and a design was developed to combine the best of both.

18. Bonasso et al., 2007.

The 3T intelligent control architecture, which was used since 1995 in several long-duration life-support systems ground tests, was completely redesigned. 3T is a three layer, hierarchical, message passing architecture. The new approach is a distributed system with embedded hardware controllers. Redundant controllers allow the reconfiguration of the system in case of failure, decreasing downtime and increasing safety and efficiency. The new small, modular, embedded controllers replaced large racks used in the control of a water recovery cascade distillation system. (Bonasso et al., 2007)

19. Miyajima, Ishikawa, Nakane et al., 2007-2015.

A three layered control software was developed for closed ecology habitation experiments. An efficient planning and scheduling algorithm was used for operations scheduling. (Miyajima et al., 2007) Schedules developed by Lagrangian decomposition and coordination differed from those developed by a skilled operator. Integrating empirical knowledge into the Lagrangian method generated a schedule similar to an operator's while reducing complexity. (Miyajima et al., 2008)

Two methods developed for automatically creating schedules in advanced life support were Lagrangian decomposition and coordination and multi-agent reinforcement learning. They had complementary advantages and weaknesses and they were combined to compensate. (Nakane et al., 2010) The life support control system that combines Lagrangian automatic scheduling and multi-agent reinforcement learning was developed based on a hierarchical control method. In a computer simulation, automatic scheduling created an overall plan for operation while the subsystems were controlled by multi-agent reinforcement learning in a decentralized autonomous system. Multi-agent reinforcement requires preliminary learning, particularly for emergency events, but otherwise, all learning can be done on-line. (Nakane et al., 2011) The combined system can provide a flexible response to system modifications, which was difficult using only decentralized autonomous control. (Nakane et al., 2014) The combined system can respond to a subsystem malfunction, but with a time lag in the lower level multi-agent control. (Nakane et al., 2015)

D. Future systems, 2018

1. Stapleton et al., 2018.

NASA has outlined plans to transition from Low Earth Orbit toward Earth independent exploration, evolving the habitat capacity to support a trip to Mars and return home three years later. The Environmental Control and Life Support Systems (ECLSS) are being developed to enable this vision. UTC Aerospace Systems (UTAS) completed the first phase of this advancement, or NextSTEP, in September 2016, and is currently working on the second phase designing a universal ELCSS Module to support the different habitats currently being developed. With focus on the final exploration configuration, the team is developing elements that can be used to support future ECLS hardware. The areas of development included transition from the cislunar design to an exploratory ECLS, the development of a Universal ECLSS Pallet design that enhances in-flight maintenance, an Integrated ECLSS Hierarchical Control Architecture, and the development of an Intelligent System intended to aide in isolating the cause of any fault. The overarching design activities included in this effort define a time dependent strategy enabling deep space exploration.

This study on developing an ECLSS similar to ISS for deep space considered an integrated hierarchical control architecture and an artificial intelligence system for fault isolation. The control system uses a hierarchical, modular, integrated, digital architecture similar to the Internet. The artificial intelligence system is based on Bayesian networks and will enable preventive maintenance and quick fault isolation.

The proposed ECLSS control architecture uses state-of-the-art networks, computers, and software methods to provide high awareness and resilience. This approach is based on Integrated Modular Avionics (IMA) architectural principles instead of the more usual flat federated architecture. The control functions are hierarchical, reflecting the hardware organization. The hierarchical control system has four levels, which are:

1. Habitat level: Provides habitat- and mission-level information.
2. Centralized ECLSS level: Provides common functions, such as interaction with the crew, habitat, and ground, system-level coordination and optimization, and data recording.
3. ECLSS subsystem level: Controls subsystem-level behavior, detects failures, and communicates with the centralized controller.
4. Sensor and actuator level: gathers and formats sensor data, directs actuator commands, monitors power use, may provide a local response to failure detection.

The control system will be able to generate standard reports and respond to crew and ground queries. The system also collects and stores information used by the machine-learning processes in the artificial intelligence system. A COTS-based prototype is being designed using modular standard components.

Artificial intelligence is being added in the form of sensors, processors, memory, algorithms, and network communication to provide information about the components and subsystems for fault detection and isolation. The artificial intelligence system is intended to increase crew and ground support awareness of ECLSS behavior, increase ECLSS predictability, and minimize the time to detect and isolate failures. After seven intelligent system technology candidates were examined, it was determined that Bayesian networks (probabilistic graphical models) seem best considering fault detection and isolation, robustness, usability, prognostics, and other performance and cost parameters. Faults will be displayed on a touch screen graphical user interface.

V. Discussion

The history of life support planning and research in controls and automation for life support is interesting in itself and raises interesting questions. What were we trying to do? Did we do it? Why or why not? Was it worth it? What are the implications for future life support?

A. What were we trying to do?

From the Apollo era until now, life support has had the objective of adding an integrated hierarchical control architecture and an artificial intelligence system for fault isolation to a regenerative ECLSS. Extensive research was conducted, which reflected the general advances in and periodic disillusionment with automation and AI.

B. Did we do it?

Clearly not. The first prototype regenerative ECLSS that was tested in a closed chamber with humans in 1966 had partially closed oxygen and water loops, but the processes were not closely coupled in hardware and not controlled in an integrated manner. The chamber acted as a large buffer for oxygen, carbon dioxide, and humidity, reducing the need for close dynamic control. The ISS ECLSS still has similar low level conventional controllers for the individual processors, without advanced control or automation.

C. Why not?

A 1966 Mustang had no controllers or computers, but current automobiles are highly controlled and automated and are connected to local and global information systems. Standard automobiles have dozens of networked computers interfacing lower level sensors and controllers and providing data and warnings to the driver and externally for electronic testing and fault diagnosis. Many have top level supervisory control for automatic braking and lane keeping. The most advanced automobiles are self-driving, using global positioning and an array of sensors. In Silicon Valley, smart traffic lights respond to waiting and approaching automobiles.

Advanced controls and automation are available, but there is an obvious reason they have not yet been applied in space ECLSS. There has been only one operational ECLSS, in ISS, while there are about a billion automobiles on the road. Automobiles have gone through decades of competitive redesign, improving reliability and adding functionality. Tremendous funding and engineering effort have been applied to automating automobiles, with much more planned.

ECLSS has not had enough units or funding for design and redesign to provide a good opportunity to develop specific advanced controls and automation. Failure rates are high, maintenance is difficult, and normal operation requires considerable human effort. The basic processes are not fully integrated or individually controlled using advanced technology.

D. Was it worth it?

This is unclear. Although advanced control is now standard in industry, automation and AI remain major areas of research. In general, research is necessary because, even though most projects do not pay off, a few very successful ones create technical advances that more than pay for all the research being done. It seems that too little research is being done because its benefits are hard for the researchers to capture and because research results are often disruptive to the research organization.

ECLSS contributed support and an interesting challenge for automation and AI that produced original research. ECLSS testbeds benefited from automated planning and scheduling, saving operator time. And ultimately ECLSS can expect to benefit from general advances in automation and AI. However, research funding priorities can always be disputed, and currently closure and reliability seem much more important for ECLSS than advanced control, automation, and AI.

E. What are the implications for future life support?

In the fifty years since ECLSS automation was first proposed, the technology has become well developed and widely available. Life support will be able to use state-of-the-art technology without a need to fund targeted life support automation research. Higher degrees of closure and integration, and the reduction of storage buffer mass, would require more capable process control and automation. Missions using simple storage and resupply could use automation and planning to manage tanks and schedule shipments. An overall life support manager could combine initial storage, scheduled resupply, and on-demand recycling to optimize performance and minimize risk.

References

Abdelwahed, S., Wu, J., Biswas, G., and J.-Manders, E., "Hierarchical Online Control Design for Autonomous Resource Management in Advanced Life Support Systems," SAE Technical Paper 2005-01-2965, 2005.

Abdelwahed, S., Wu, J., Biswas, G., Ramirez, J. et al., "Online Hierarchical Fault-Adaptive Control for Advanced Life Support Systems," SAE Technical Paper 2004-01-2441, 2004.

Berdich, D. P., Campbell, P. D., and Jernigan, J. M., “Developing Advanced Human Support Technologies for Planetary Exploration Missions,” AIAA 2004-5839, Space 2004 Conference and Exhibit, 28 - 30 September 2004, San Diego, California.

Bilardo, V. J., “The Physical/Chemical Closed-Loop Life Support Research Project,” AIAA-90-3729, AIAA Space Programs and Technologies Conference, Huntsville, AL, 1990.

Biswas, G., Bonasso, P., Abdelwahed, S., Manders, E. et al., "Requirements for an Autonomous Control Architecture for Advanced Life Support Systems," SAE Technical Paper 2005-01-3010, 2005.

Biswas, G., Manders, E-J., Ramirez, J., Mahadevan, N., and Abdelwahed, S., “Online model-based diagnosis to support autonomous operation of advanced life support system,” Habitat.: Int. J. Human Support Res., vol. 10, no. 1, pp. 21–38, 2004.

Block, R. F., (1987a) “Prototype space station automation system delivered and demonstrated at NASA,” 1987.

Block, R. F., (1987b) “Automated Subsystem Control for Life Support System (ASCLSS) Final Report,” Honeywell 1987.

Block, R. F., Heppner, D. B., Samonski, F. H., Jr.;, and Lance, N., Jr., “Automated subsystems control development. [for life support systems of space station]”, SAE paper 851379, 1985.

Boeing, *Environmental Control and Life Support System Advanced Automation Project 1990 Annual Report*, 1990.

Bonasso, P. and Martin, C., "A Dynamically Reconfigurable Software Control Architecture for Advanced Life Support," SAE Technical Paper 2005-01-2964, International Conference on Environmental Systems, 2005.

Bonasso, P., Kortenkamp, D., and Thronesbery, C., “Intelligent Control of a Water-Recovery System: Three Years in the Trenches,” AI Magazine Volume 24 Number 1,2003.

Bonasso, R., Kortenkamp, D., and Kowing, J., "Distributed, Embedded Control for Life Support Development," SAE Technical Paper 2007-01-3024, International Conference on Environmental Systems, 2007.

Boulanger, R., and Jones, H., “Minimum Control Requirements for Advanced Life Support Systems,” 33nd International Conference on Environmental Systems, 7-10 July 2003, Vancouver, British Columbia, Canada.

Boulanger, R., Overland, D., and Jones, H., “Evaluation of Fieldbus and Software Component Technologies for Use with Advanced Life Support,” SAE Technical Paper 2001-01-2299, 2001.

Cleveland, G. A., “Distributed environmental control,” https://ntrs.nasa.gov/search.jsp?R=19930002736 2018-08-31T22:00:33+00:00Z 1992.

Dewberry B. S. and Carnes J. R. “Automation of the Environmental Control and Life Support System,” Space Station Evolution Symposium 1990.

Dewberry, B. S., “Space Station Freedom ECLSS---A Step Toward Autonomous Regenerative Life Support Systems,” N90-2729, Proceedings of 5th Annual Conference on Intelligence for Space Applications, May 1990, p. 193.

Dewberry, B. S., “The environmental control and life support system advanced automation project,” 1991.

Dewberry, B. S., Lukefahr B. D., Rochowiak D. M., Benson B. L., Rogers J. S. ,and McKee, J. W., UAH Research Report Number 824 A Diagnostic Prototype of the Potable Water Subsystem of the Space Station Freedom ECLSS, 1989.

Dewberry, B., and Carnes, J. R., "Intelligent Monitoring and Diagnosis Systems for Space Station Freedom ECLSS," 1991.

Dewberry, B., Carnes, J. R., Lukefahr, B. D., Rogers, J., Rochowiak, D. M., Mckee, J., "The ECLSS advanced automation project evolution and technology assessment," Technology for Space Station Evolution Workshop, January 17, 1990.

Doll, S., and Eckart, P., "Environmental Control and Life Support Systems (ECLSS)," in W. K. Larson, and L. K. Pranke, Eds., Human Spaceflight: Mission Analysis and Design, McGraw-Hill, New York, 2000.

Eckart, P., *Spaceflight Life Support and Biospherics*, Kluwer Academic, Dordrecht, 1996.

Evanich, P. L., Crabb, T. M., and Gartrell, C. F., NASA Life Support Systems Analysis workshop, 1992.

Evanich, P. L., Voecks, G.E., and Seshan, P. K., "Advanced Life Support Technology Development for the Space Exploration Initiative," AIAA-90-3726, AIAA Space Programs and Technologies Conference, Huntsville, AL, 1990.

Finn C. K., *A Survey of Life Support System Automation and Control*, NASA Technical Memorandum 103977, Ames Research Center Moffett Field, California, January 1993.

Gardner, D., "Controls Design for the Space Station Freedom Atmosphere Revitalization Subsystem," SAE Technical Paper 932043, 1993.

General Dynamics Corp., Life support system for space flights of extended time periods, 1966.

Hall, J., "Advanced Integrated Life Support Systems – A Status Report," SAE Technical Paper 690637, 1969.

Hamilton Standard, United Aircraft, *Trade-Off Study and Conceptual Designs of Regenerative Advanced Integrated Life Support Systems, (AILSS)*, NASA Contractor Report CR-1458, January 1970.

Hartung, R. and Moore, K., "A Review of Space Station ECLSS/ITCS Automation," SAE Technical Paper 951587, International Conference on Environmental Systems, 1995.

Heppner, D., Khoury, J., and Powell, J., "Control/Monitor Instrumentation for Environmental Control and Life Support Systems Aboard the Space Station," SAE Technical Paper 861007, 1986.

Humphries, W. R., Seshan, P. K., and Evanich, P.L., "Physical-Chemical Life Support Systems," in Sulzman, F. M., and Genin, A. M., eds., *Space Biology and Medicine, vol, II, Life Support and Habitability*, American Institute of Aeronautics and Astronautics, Washington, DC, 1994.

Kansas State University, Automation of closed environments in space for human comfort and safety, 1990.

Kansas State University, Automation of closed environments in space for human comfort and safety, 1991.

Kansas State University, Automation of closed environments in space for human comfort and safety, 1992.

Klein, T., Subramanian, D., Kortenkamp, D., and Bell, S., "Using Reinforcement Learning to Control Life Support Systems," SAE Technical Paper 2004-01-2439, 2004.

Kortenkamp, D., Bonasso, P., and Subramanian, D., "Distributed, Autonomous Control of Space Habitats," Proceedings of the IEEE Aerospace Conference. Washington, D.C.: IEEE Computer Society, 2001.

Langley Research Center (LaRC), Definition study for an extended manned test of a regenerative life support system, preliminary test plan, NASA CR-111999, 1971.

Little, W. and Drysdale, A., "The Automated Control and Monitoring of Advanced Life Support Systems," SAE Technical Paper 961512, 1996.

Lukefahr B. D., Rochowiak D. M., Benson B. L., Rogers J. S. ,and McKee, J. W., "ECLSS Advanced Automation Preliminary Requirements-- Final Report," University of Alabama Research Report Number 823, 1989.

Malin, J. T., and Lance, N., "An Expert Systems Approach to Automated Fault Management in a Regenerative Life Support Subsystem," AIAA-86-0321, AIAA 24th Aerospace Sciences Meeting, 1986, Reno, Nevada.

Miyajima, H., Abe, K., Hirosaki, T., and Ishikawa, Y., "Development of Advanced Life Support Systems Control Software Considering Computational Effort and Mathematical Validity," SAE Technical Paper 2007-01-3025, 2007.

Miyajima, H., Abe, K., Hirosaki, T., and Ishikawa, Y., "Development of Advanced Life Support Systems Control Software Integrating Operators' Empirical Knowledge," SAE Technical Paper 2008-01-1973, 2008.

MSFC-SPEC-2841F, Water Recovery System (WRS) Specification, Marshall Space Flight Center, December 13, 2004, revised January 24, 2006.

Muscettola, N., Kortenkamp, D., Fry, C., and Bell, S., "Planner-Based Control of Advanced Life Support Systems," SAE Technical Paper 2005-01-2961, 2005.

Nakane, M., Ishikawa, Y., and Miyajima, H., "Dynamic Transition to Fallback Operation of Material Circulation Control in Advanced Life Support System using Hierarchical Autonomous Control Method," 45th International Conference on Environmental Systems ICES-2015-16, 12-16 July 2015, Bellevue, Washington.

Nakane, M., Ishikawa, Y., and Miyajima, H., "Material Circulation Control with Modules Addition in Advanced Life Support System using Hierarchical Autonomous Control Method," 44th International Conference on Environmental Systems ICES-2014-023, 13-17 July 2014, Tucson, Arizona.

Nakane, M., Riaki, O., Ishikawa, Y., and Miyajima, H., "Applying Autonomous Control method for Material Circulation to Advanced Life Support System," AIAA 2011-5235, 41st International Conference on Environmental Systems, 17 - 21 July 2011, Portland, Oregon.

Nakane, M., Yamazaki, N., Ishikawa, Y., and Miyajima, H., "Autonomous Control Method for Material Circulation in Advanced Life Support System,", AIAA 2010-6227, 40th International Conference on Environmental System, 2010.

NASA, 2012, *Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,* National Research Council, National Academy Press, Washington, D.C. 2012.

NASA, 2015, *Technology Roadmaps*, National Research Council, National Academy Press, Washington, D.C. 2012, http://www.nasa.gov/offices/oct/home/roadmaps/index.html, accessed November 13, 2018.

Overland, D., “Advanced Control System Architecture for BIO-Plex,” SAE Technical Paper 2003-01-2576, 2003.

Pawlowski, C., Bell, A., Crawford, S., Sethares, W. et al., “Advanced Control Techniques For Efficient And Robust Operation Of Advanced Life Support Systems,” SAE Technical Paper 2001-01-2298, 2001.

Piras, A., Malucchi, G., Di Tommaso, U., “Integrated FDIR Analysis Tool for Space Applications,” Proc. DASIA 2013, Porto, Portugal, 14-16 May 2013. (ESA SP-720, August 2013)

Project Pathfinder: Physical/Chemical Closed-Loop Life Support (P/C CLSS) Project Plan, NASA Ames Research Center, 1989.

Quasny, T. and Pyeatt, L., “Reinforcement Learning in the Control of a Simulated Life Support System,” SAE Technical Paper 2004-01-2440, 2004.

Robinson, P., Shirley, M., Fletcher, D., Alena., R., Duncavage, D., and Lee, L., “Applying Model-Based Reasoning to the FDIR of the Command and Data Handling Subsystem of the International Space Station,” ntrs.nasa.gov/search.jsp?R=20030054509 2018-11-09T22:29:05+00:00Z, 2003, downloaded November 8, 2018.

Schreckenghost, D., Bonasso, P., Hudson, M., Milam, T. et al., “Aiding Supervision of Automated Life Support Systems,” SAE Technical Paper 2005-01-2967, 2005.

Schreckenghost, D., Ryan, D., Thronesbery, C., Bonasso, P., Poirot, D., “Intelligent Control of Life Support Systems for Space Habitats,” IAAI-98 Proceedings, American Association for Artificial Intelligence AAAI, 1998.

Shuey , M. A., and Hamilton Standard, “Life Support System Considerations for Space Station,” April 1, 1982, the Space Congress Proceedings.

Stapleton, T., Heldmann, M., Torres, M., Bowers, J., and Corallo, R., “Environmental Control and Life Support for Deep Space Travel,” ICES-2018-343, 48th International Conference on Environmental Systems, July 2018, Albuquerque, New Mexico.

Voecks, G., and Seshan, P., “Real-time In situ Sensors and Control Integration for Life Support Systems,” SAE Technical Paper 911356, 1991.

Wieland, P. O., Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems, NASA Reference Publication RP-1324, 1994.

Wikipedia, artificial intelligence, https://en.wikipedia.org/wiki/Artificial_intelligence, accessed November 8, 2018.

Wikipedia, fault detection and isolation, https://en.wikipedia.org/wiki/Fault_detection_and_isolation, accessed November 8, 2018.

Williams, G. P. W., “Model-Based Diagnosis of SSF ECLSS, International Conference on Life Support and Biospherics,” University of Alabama in Huntsville, 1992.

Wu, A. S., and Garibay, I. I., “Intelligent Automated Control of Life Support Systems Using Proportional Representations,” IEEE Transactions on Systems, Man, and Cybernetics – Part B: June 2004.

Yang, P. Y., You, K.C., Wynveen, R. A., and Powell., J. D., Jr., Fault diagnostic instrumentation design for environmental control and life support systems, Life Systems, 1979.

Zaretskiy, B., Gavrilov, L., and Kurmazenko, E., “Crew Life Support System for Interplanetary Vehicles,” SAE Technical Paper 2009-01-2464, 2009.

Zhang, X., Hoo, K., and Overland, D., “Modeling and Control Studies of an Integrated Biological Wastewater Treatment System,” SAE Technical Paper 2005-01-2963, 2005.

Zolghadri, A, “Advanced model-based FDIR techniques for aerospace systems: Today challenges and opportunities, Progress in Aerospace Sciences 53 (2012) 18–29.