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AUTOMATION OF CLOSED ENVIRONMENTS IN SPACE FOR HUMAN COMFORT AND SAFETY

KANSAS STATE UNIVERSITY

INTRODUCTION

Project Description

The development of Environmental Control and Life Support Systems (ECLSS) for Space Station *Freedom*, future colonization of the Moon, and Mars missions presents new challenges for present technologies. ECLSS that operate during long-duration missions must be semi-autonomous to allow crew members environmental control without constant supervision. A control system for the ECLSS must address these issues as well as being reliable. The Kansas State University Advanced Design Team is in the process of researching and designing controls for the automation of the ECLSS for Space Station *Freedom* and beyond.

The ECLSS for *Freedom* is composed of six subsystems. The temperature and humidity control (THC) subsystem maintains the cabin temperature and humidity at a comfortable level. The atmosphere control and supply (ACS) subsystem insures proper cabin pressure and partial pressures of oxygen and nitrogen. To protect the space station from fire damage, the fire detection and suppression (FDS) subsystem provides fire-sensing alarms and extinguishers. The waste management (WM) subsystem compacts solid wastes for return to Earth, and collects urine for water recovery. The atmosphere revitalization (AR) subsystem removes CO_2 and other dangerous contaminants from the air. The water recovery and management (WRM) subsystem collects and filters condensate from the cabin to replenish potable water supplies, and processes urine and other waste waters to replenish hygiene water supplies.

These subsystems are not fully automated at this time. Furthermore, the control of these subsystems is not presently integrated; they are largely independent of one another. A fully integrated and automated ECLSS would increase astronauts' productivity and contribute to their safety and comfort.

Three-Phase Design Plan

A three-phase approach was implemented by the Kansas State University Advanced Design Team to design controls for the ECLSS. The first phase, completed within one year, researched the ECLSS as a whole system and then focused on the automation of the atmosphere revilatization (AR) subsystem.

During the second phase, the system control process was applied to the AR subsystem. To aid in the development of automatic controls for each subsystem and the overall ECLSS, mathematical models have been developed for system simulation on a computer. Expert system control as well as conventional control methods are being tested on the models. Using the AR subsystem control system as a "proof of concept," the other ECLSS subsystems will be automated.

Finally, during phase three, the control system of the six subsystems will be combined to form a control system for ECLSS. The expert system developed for the AR will be expanded to control the ECLSS, as well as provide fault diagnosis and isolation to the astronauts.

The Kansas State University Design Team has completed phases one and two. Mathematical models for the CO_2 removal assembly, CO_2 reduction assembly and oxygen generation assembly, as well as an expert system, have been developed for the AR. The mathematical models are written in the C-Language. At this time, the models function independently at the assembly level. The expert system, using an expert system shell called CLIPS, monitors and controls the AR subsystem assemblies in a hierarchical manner.

Design Team Description

The Kansas State University Advanced Design Team is composed of engineering students from several disciplines, a student from general science and education, two graduate student assistants, and engineering faculty members. Architectural, chemical, computer, electrical, and mechanical engineering disciplines are represented by both students and faculty.

Document Organization

This document presents a portion of the work done by the design team during the 1990-91 academic year. First, part of the CO_2 removal assembly model is presented. Then a portion of the removal assembly's expert system is discussed. Complete details for the three models and the experts system can be found in the final report.

MATHEMATICAL MODELING

CO_2 Removal Assembly Model

Description. The CO_2 removal assembly is part of the (AR) Subsystem. Its purpose is to remove CO_2 from the cabin atmosphere, deliver CO_2 to the CO_2 reduction assembly and return humidified air to the cabin. This is done using a four-bed molecular sieve consisting of two desiccant beds to remove water vapor from incoming air, two CO_2 adsorption beds, a

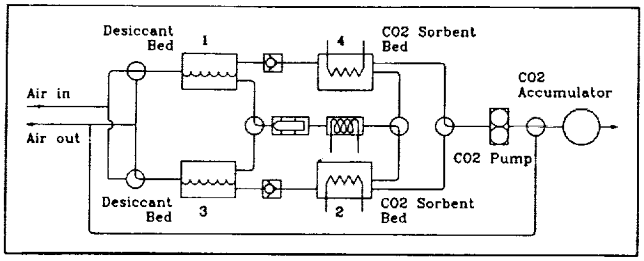

Fig. 1. CO_2 Removal Assembly.

blower to force air through the system, a CO_2 pump, a CO_2 accumulator, a precooler and five multiple-flow selector valves. Figure 1 illustrates these major components.

Math Model. This physical system is modeled using the following simplifications: (1) all beds are modeled as lumped systems; (2) adsorbing/desorbing processes along the bed are averaged; (3) thermal equilibrium is assumed (which negates the dependence on bed length); and (4) the CO_2 desorbent bed is in thermal equilibrium.

All four beds have been modeled as lumped systems. For simplicity, we have neglected the fact that the adsorbing/desorbing processes vary as a function of distance through the bed. In our model, we have assumed instantaneous thermal equilibrium, which, in effect, negates the dependence on bed length. We intend to improve the model by subdividing each bed into many smaller beds. To implement this scheme, the overall bed volume and sorbent mass will be divided by the number of "plugs." The simulation will be modified using 2-D arrays.

The following are the equations that model the CO_2 desorbent bed, incorporating the assumptions listed above.

$$P_b = K_1\left(\frac{m_d}{m_b}\right)(T_b\text{-}T_{ref}), \tag{1}$$

$$T_b = T_g, \tag{2}$$

$$P_g = \frac{m_g R T_b}{V_g}, \tag{3}$$

$$\frac{dm_d}{dt} = (P_b\text{-}P_g)k_2, \tag{4}$$

$$\frac{dm_g}{dt} = (P_b\text{-}P_g)k_2\text{-}m_o, \tag{5}$$

$$\frac{dT_b}{dt} = \frac{\left(\frac{dm_d}{dt} S_c + \text{Power}\right)}{m_b C_{vb}}, \tag{6}$$

The required definitions are given by

P_b = CO_2 equilibrium pressure of bed (kPa)
k_1 = constant (picked to be $0 \leq K_1 \leq 1$)
m_d = mass of CO_2 in sorbent material (kg)
m_b = mass of sorbent in bed (kg)
T_b = temperature of the bed (K)
T_{ref} = reference temperature (K)
T_g = temperature of CO_2 gas (K) (substitute T_b)
P_g = pressure of CO_2 gas in bed void space (Kpa)
m_g = mass of CO_2 gas in void space (kg)
R = CO_2 gas constant (kPa.m^3/kg.K)
V_g = void space of bed, also volume of CO_2 (m^3)
k_2 = transfer coefficient ($0 \leq K_2 \leq 1$)
m_o = CO_2 gas mass flow rate, determined by pump (kg/s)
S_c = heat of sorption of CO_2 (J/kg CO_2)
Power = power applied to bed (J/s)
C_{vb} = heat capacity of sorbent material (J/kg.K)
dm_d/dt = rate of CO_2 desorbed (kg CO_2/s)
dm_g/dt = change in mass of CO_2 in void space (kg CO_2/s)
dT_b/dt = change in temperature of bed (K/s).

Sample Output. Several simulation runs were conducted, altering a single parameter each time. The model seems most sensitive to pump speed (w) and reference temperature (T_{ref}). Figure 2 shows the temperature of the desiccant bed for the model running with the following conditions:

Mass flow rate of air into model	= 0.2 kg/s
H_2O concentration into model	= 0.01 kg H_2O/kg air
CO_2 concentration into model	= 0.001 kg CO_2/kg air
Temperature of air into model	= 300 K
Angular velocity of CO_2 pump	= 200 rad/s
Reference temperature of model	= 250 K

CO_2 Removal Assembly Expert System

Conventional control systems like those required by an ECLSS can quickly become unmanageable and even unstable; expert systems allow more freedom to design the control system using

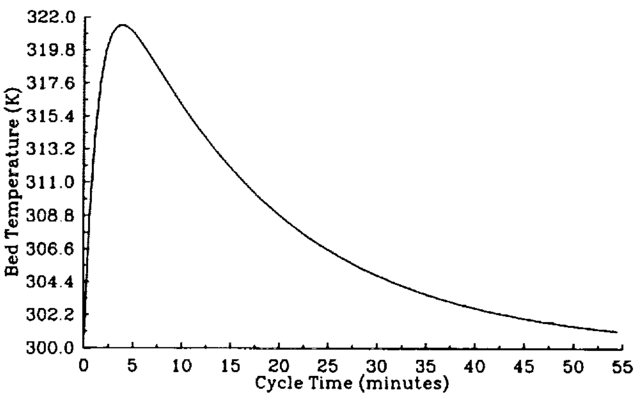

Fig. 2. Temperature of Desiccant Bed.

and implementing rules of thumb and heuristic reasoning. Therefore, an expert system allows development of control without complete characterization of the component. In this manner, the mathematics of expert systems allows inexact reasoning or fuzzy logic. In other words, expert systems allows implementation of expertise or rules directly, much like the human thought process. For these reasons, an expert system was developed to control the atmosphere revitalization assembly.

The atmosphere revitalization expert system (ARES) was created using the CLIPS expert system shell. ARES consists of mathematical models of the AR and a control system, Savant.3. Savant.3 contains a knowledge base for each of the three assemblies in the AR. These knowledge bases contain expert knowledge for each assembly in the form of rules, and represents this in English conditional statements. Savant.3 also converts sensor values into English statements, makes inferences using the knowledge base, generates commands based on the inferences, and provides an explanation of conclusions. Each time ARES is activated it provides one command for each assembly.

Knowledge Base

The knowledge base of ARES consists of three smaller knowledge bases. The assembly knowledge bases together contain rules used to identify current operation conditions and diagnose problems in the AR.

The knowledge base incorporates fuzzy membership functions for the sensor data used. In this way, decisions are made by assignment of weights between zero and one that correspond to the assurance of how "true" a decision provided by the inference engine. This allows the expert system to arrive at two or more conclusions that may conflict due to the inexact mathematics of expert systems. The response that has the greatest weight or has the higher confidence rating is selected to be executed by the inference engine. The following section discusses, in part, the rules and expertise of the CO_2 removal assembly knowledge base.

CO_2 Removal Assembly

The main function of the expert system is to monitor the components of the CO_2 removal assembly. Different sensor values are read and compared to certain parameters, and the expert system makes a decision based on those sensor values. The focus of the rules was to detect component failures. Currently, the rules do not include any valves or the four beds.

Rule #1. The expert system monitors the temperature sensor at the output of the precooler. If the value is not within acceptable parameters, the expert system decides if failure has occurred. If a failure decision is reached, the expert system instructs the removal assembly to shut down.

Rule #2. The expert system monitors the two pressure sensors located on either side of the blower and checks the differential pressure. If the pressure differential is unacceptable, the removal assembly is instructed to shut down.

Rule #3. The expert system monitors the power sensor on the CO_2 pump. If the value is unsuitable, then the removal assembly is instructed to shut down.

Rule #4. The expert system monitors the pressure sensor located on the CO_2 pump. If the value is not within the established parameters, the removal assembly is instructed to shut down.

Rule #5. The expert system monitors the gas flow at the CO_2 accumulator through two gas flow sensors located on either side of the accumulator. If a failure decision is reached, both the CO_2 removal and the CO_2 reduction assemblies are instructed to shut down.

Savant.3 (Decision Mechanism)

This section is a summary of the program sections of Savant.3. Savant.3 is the decision mechanism of ARES. It consists of five sections of which the knowledge base has been discussed. The other four sections are the inference engine, the operations resolver, the response selector and implementator, and the explanation facility.

The inference engine of Savant.3 is a shell above CLIPS. First, the inference engine interprets the rules of the knowledge base. Next, it evaluates the fuzzy membership functions by assigning a weight (confidence value) to the sensor values given by the mathematical models of ARES. Finally, it selects the best response for each assembly.

The second section titled Resolve Operations, is used to locate and resolve linguistic statements using functions such as "and," "or," and "is not". This is necessary since the knowledge base was written in standard English statements, allowing ease in interpretation. At this point in the program, all rules that are true with any confidence factor are placed on a "fired" rule list inside CLIPS.

The next step is to select the proper response from the list of "fired" rules. The Response Selection and Implementation section of Savant.3 is responsible for selection. This section selects the response with the strongest confidence factor from among the conflicting responses on the "fired" rule list, and this response is then constructed into a command for each assembly.

The final section of Savant.3 is the Explanation Facility. This section is not necessary for operation of ARES, but is very important. ARES is only as accurate as the experts of each assembly. It is no smarter than its programmers and therefore is susceptible to incorrect conclusions. The Explanation Facility allows the user to see the steps taken by ARES in making decisions for each assembly. It does this by retracing the paths used to determine the selected responses, and generates a dialogue explaining the responses arrived at, allowing the user to revoke the decision.

Verification and Testing of Expert System

A simple expert system was designed to help monitor and control the ECLSS for a space station. Currently, the system has control over only portions of the air revitalization system. After rules that govern the system's behavior are written and placed into the knowledge base, the expert system was tested to discover programming errors. The final stage of the expert system's development is verification—applying a series of inputs and insuring the resulting decisions are correct. Even though the current system contains only four components that may be varied, verification is a difficult task. To verify all possible conditions, combinations would require around 300 individual tests. The complete expert system to govern the entire ECLSS will be nearly impossible to verify completely. A number of different sets of conditions were tested and checked. These condition sets fall into nine cases, six of that are described below. For each case, the conditions are stated first, then a brief description of the system response is given. The four conditions which can be varied are

1. Cabin-O_2—Used to determine amount of breathable air currently available to the astronauts. Helps control oxygen generation assembly (OGA).
2. Inlet-CO_2—Indicates amount of CO_2 present in the cabin atmosphere. Helps control CO_2 removal assembly.
3. CO_2-Accumulator—Indicates level of CO_2 storage tank located between CO_2 removal and CO_2 reduction assemblies. Helps control these same two assemblies.
4. H_2O-Accumulator—Indicates level of water in storage tank located between CO_2 reduction and OGA assemblies. Helps control these same two assemblies.

CASE 1:

Condition: All values in normal operating range.

Response:

OGA—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Reduction—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Removal—Commanded to move to an efficiency mode. Since no supplies are low and cabin CO_2 is normal, CO_2 removal assembly can reduce power requirements by decreasing production slightly.

CASE 2:

Condition: Both accumulators are empty, all other values in normal operating range.

Response:

OGA—Commanded to turn on (if currently off) or to continue in normal operating mode. This system will not, however, be able to operate if no water is available. This system should turn off until water is available.

CO_2 Reduction—Commanded to turn on (if currently off) or to continue in normal operating mode. This is to refill the empty H_2O accumulator.

CO_2 Removal—Commanded into high removal mode. This will help to replenish the CO_2 accumulator and provide resources needed by the CO_2 Reduction assembly to refill H_2O accumulator.

CASE 3:

Condition: Both accumulators at a low level, all other values in normal operating range.

Response:

OGA—Commanded to turn on (if currently off) or to continue in normal operating mode. This system will not, however, be able to operate if no water is available. This system should perhaps turn off for a while until water is available. This is the correct response as programmed although not really the correct way to handle the given situation.

CO_2 Reduction—Commanded to turn on (if currently off) or to continue in normal operating mode. This is to refill the empty H_2O accumulator.

CO_2 Removal—Commanded to move to high production mode. This will help to replenish the CO_2 accumulator and provide resources needed by the CO_2 reduction assembly to refill H_2O accumulator.

CASE 4:

Condition: Both accumulators at a high level, all other values in normal operating range.

Response:

OGA—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Reduction—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Removal—Commanded to move to an efficiency mode. Since no supplies are low and cabin CO_2 is normal, CO_2 removal assembly can reduce power requirements by decreasing production slightly.

CASE 5:

Condition: Inlet CO_2 at a high level, all other values in normal operating range.

Response:

OGA—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Reduction—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Removal—Commanded to move to a high removal mode. This is an attempt to remove the excess CO_2 from the cabin and restore a proper CO_2-O_2 balance for the astronauts.

CASE 6:

Condition: Inlet CO_2 at a low level, all other values in normal operating range.

Response:

OGA—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Reduction—Commanded to turn on (if currently off) or to continue in normal operating mode.

CO_2 Removal—Commanded to turn off. This is done to avoid overfilling the CO_2 accumulator before the need to remove CO_2 becomes important. This also conserves power at times when the system is not needed.

Limitations

The biggest limitation at present is the number of rules on which the system can operate. With only four pieces of data with which to make decisions, those decisions will be limited in scope and accuracy. Next, the system produces confidence factors because of the narrow scope of the current expert system. Finally, the expert system does not always produce the best decision. As noted in cases 2 and 3 above, the OGA is commanded to turn on even though adequate resources for operation may not be available. It is evident that further options need to be considered and tested before a final decision is made as to the operation of the system.

CONCLUSIONS

Because of the complex nature of the conditions that may affect operation of the ECLSS, standard control schemes do not provide an adequate means for system maintenance. The expert system, on the other hand, is more tolerant of inexact data and does not need constant supervision. For these reasons, an expert system makes a better choice for ECLSS control.

The expert system designed this semester used the CLIPS expert system shell. This shell program proved to be cumbersome and difficult to implement, and should be avoided in future design if possible.

The rules defined in the previous sections obviously do not represent a set that will completely control the assembly. Rather, these rules are a beginning set that defines the overall or general operation of the assembly's main components. Many other, more detailed rules will be needed to complete the knowledge bases for the expert system and to provide an adequate control system for the ECLSS. Further information about the operation and interaction of the various subassemblies will be required before such rules can be defined.

The Savant.3 decision mechanism is the most complete portion of the current expert system design. The inference engine, which interprets knowledge base data, and the response selector, which chooses an action based on the number of conclusions and their associated confidence factors, will not be affected by the addition of new rules. In fact, these sections could be used with no alteration in an expert system for control of the entire ECLSS. The only section of Savant.3 that will need to be altered will be the operation section. Because this section depends on the rules in the system, it will not be able to be completed until all rules have been entered into the system.

Currently, the system testing shows correct operation based on the available rules. However, because of the small number of rules available to test at this time and because of the general nature of those rules, the decisions reached are not necessarily the best or even the correct ones. It should be restated, however, that the responses gained at this time are the correct ones for the system programmed.