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AUTOMATION OF CLOSED ENVIRONMENTS IN SPACE FOR HUMAN COMFORT AND SAFETY

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Abstract

For prolonged missions into space and colonization outside the Earth's atmosphere, development of Environmental Control and Life Support Systems (ECLSS) are essential to provide astronauts with habitable environments. The Kansas State University Advanced Design Team have researched and designed a control system for an ECLSS like that on Space Station Freedom. The following milestones have been accomplished:

- Completed computer simulation of the CO_2 Removal Assembly.
- Created a set of rules for the expert control system of the CO_2 Removal Assembly.
- Created a classical controls system for the CO_2 Removal Assembly.
- Established a means of communication between the mathematical model and the two controls systems.
- Analyzed the dynamic response of the simulation and compared the two methods of control.

Introduction

Design Team Description

The Advanced Design Team at Kansas State University is composed of students from several academic disciplines. Currently participating disciplines include Computer Science, Mechanical engineering, and Chemical Engineering. The team's graduate Teaching Assistant is an electrical engineer. Faculty support comes from the Mechanical, Electrical, Chemical, and Computer Engineering Departments as well as the Computer Science Department.

Physical System

The Carbon Dioxide Removal Assembly, designed to remove carbon dioxide from the cabin air, involves removal of CO_2 by molecular sieves. The process is required to remove carbon dioxide generated by the respiratory processes of the astronauts and to maintain acceptable levels of carbon dioxide within the cabin.

Figure 1 is a block diagram representation of the CO_2 Removal Assembly. The system takes input air from the Temperature Humidity Control Subsystem (1), and valves (2,11) direct the air flow, allowing it to flow across one of the desiccant beds (3,10), which dehumidify the air using zeolite 13X and silica gel. The moisture must be removed to avoid poisoning the desiccant found in the adsorbing sorbent bed (8,14). Because the dry air is heated in the process, it is forced across a heat exchanger (6) by a blower (5), and the air is cooled before being sent through a sorbent bed. The sorbent beds remove the carbon dioxide by means of zeolite 5A, which acts as a molecular sieve adsorbing the carbon dioxide. The dry air returning from the molecular sieves through unidirectional control valves (13,9) is revitalized by the moist desiccant of the second desiccant bed (10). After the air is rehydrated it is then returned to the Temperature and Humidity Control Subsystem (12) and redistributed throughout the cabin.

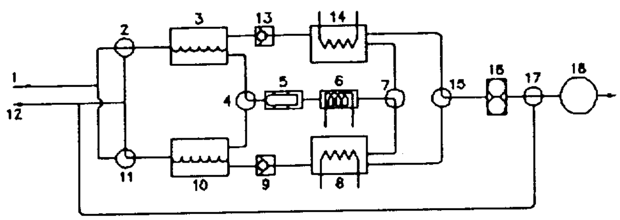

Fig. 1 CO_2 removal assembly

Concurrently, a second desorbing sorbent bed (14) is being heated, causing the separation of the carbon dioxide from the desiccant. The desorbed carbon dioxide is drawn from the bed by means of a pump (16) and is sent to an accumulator tank (18). After the adsorbing desiccants have become saturated, the desorbing beds are once again dry. The control valves (5,7,15) redirect air flow in the system. The previously adsorbing beds begin the desorbing process and the previously desorbing beds begin adsorbing. The system is presently configured to cycle every thirty minutes.

Mathematical models of the various components were created to allow analysis of the subassembly's performance. The role of the modeling is to duplicate the actual system's response to a given set of parameters. Knowing how an actual system should respond, it is possible to explore control systems for use in governing the subassembly. The control systems regulate the state variables throughout the subassembly.

Controls

Description

The CO_2 removal subassembly is responsible for maintaining the partial pressure of CO_2 within normal limits as the astronauts and other equipment and experiments produce it. NASA grades air quality by the partial pressure of CO_2, with normal CO_2 pressure being 0.0667 kPa. When the CO_2 partial pressure is above 0.4 kPa, the air is classified as "degraded;" above 1.015 kPa the condition is classified as "emergency." The CO_2 removal subassembly removes CO_2 from the cabin environment and stores it as a gas in a CO_2 accumulator tank until a Bosch reactor breaks it down to solid carbon and water.

The CO_2 removal subassembly uses a variable speed fan to force air through the system's beds, ducts, and heat-exchangers. The desiccant beds and the CO_2 sorbent beds operate on 30-minute cycles, where one bed adsorbs mass for 30 minutes while the companion bed is desorbing. After 30 minutes the beds reverse roles and the full adsorbing bed desorbs its mass, while the empty desorbing bed adsorbs mass.

Classical Controls

There are two inputs that control the operation of the CO_2 removal subassembly, the partial pressure of CO_2 in the cabin and the pressure of CO_2 in the CO_2 accumulator tank. The cabin CO_2 pressure input is used as input to a classical control to maintain the cabin CO_2 pressure. If the partial pressure of CO_2 in the cabin deviates from the desired 0.0667 kPa, the system would modify the air flow rate.

The input from the CO_2 accumulator tank was based on the gas pressure in the tank. The Bosch reactor is an important producer of fresh water and a shortage of CO_2 may mean a corresponding shortage of fresh water. The Bosch reactor shuts down if the pressure of the supply CO_2 (the CO_2 tank) dips below 101.125 kPa, so the system is turned on if the pressure in the CO_2 accumulator tank drops below 137 kPa. This safety buffer of 36 kPa assures that the tank pressure should not go below the lower limit of 101.125 kPa.

Internal to the CO_2 removal subassembly are controls that maintain the pressure of the CO_2

accumulator tank and a valve that is positioned before the CO_2 accumulator tank and after the CO_2 pump that controls the purity of the CO_2 entering the tank.

The cabin air is driven through the system by a variable speed, zero-inertia fan that is controlled to maintain cabin pressure of 0.0667 kPa. Classical control of the fan speed is accomplished by using a proportional-integral-differential (PID) compensator in a negative feedback loop. The PID compensator uses an error function δ, defined as the difference between the actual CO_2 cabin pressure and the desired cabin pressure. The magnitude of the change in the pump speed is given in the following equation.

$$\Delta_{fanspeed} = \delta + \frac{d\delta}{dt} + \int \delta dt \qquad (1)$$

The fan speed is then adjusted by this amount, increasing or decreasing the tank pressure.

Expert Systems Control

The expert system uses triangular functions to control the simulation. A triangular function consists of three values: low, medium, and high, as shown in Figure 2.

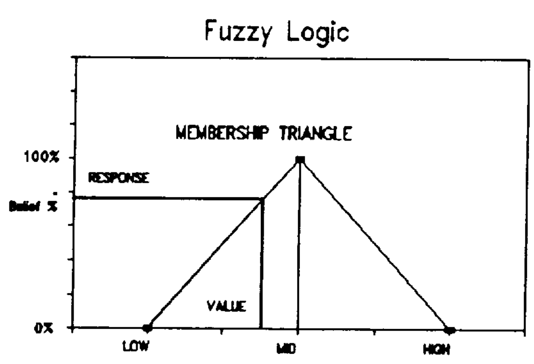

Fig. 2 Fuzzy logic membership triangle

A function is used to calculate a percentage belief when the value being considered is in the range low to high. When the value does not lie in the range low to high, the percentage belief is zero.

The percentage belief is used to determine directly the amount of change that must be made. This expert system uses two triangles to control the simulation. The left triangle represents the low pressure function. The right triangle represents the high pressure function. There is also overlap between the high and low triangles. This is not uncommon in fuzzy logic. The intersection point of the two triangles is chosen to correspond to the target control value and to a 50% belief in both triangles. This is done so that when the system variable deviates from the target value, the belief is immediately greater than 50% in one of the triangles, prompting the system to try to correct it. The slope of both triangles is adjusted to control the rate at which the expert system changes the simulation. Pump speed, pump duration, and pressure deviation are factors used in determining the adjustments to the triangular functions. The pressure can be controlled more accurately when the pump speed is changed more often. However, this can cause wear on a pump and must be taken into consideration.

Dynamic System Simulation

Introduction

The simulation with controls needed to be tested thoroughly. This would result in two benefits. First, it would be possible to determine if the physics of the CO_2 removal process were being correctly modelled. Second, it would allow an insight into the abilities of both the system and the controllers to handle various situations. The method used to evaluate the control systems was to determine which "weighting factor" provided the most desired response. The major characteristic sought in the solution was the ability of the controller to dampen out initial transients and settle upon a closely bound mass flow rate and, therefore, CO_2 rate. This resulted in the system being run at a nearly constant rate, which greatly reduces wear on the fan due to cycling.

Although many tests were run, the test condition used for the evaluation of the controllers was a simple twin step function with an initial offset. It was desired to maintain cabin CO_2 at 0.0667 kPa throughout the test. The initial value in the cabin was set at 0.07 kPa. The CO_2 production rate was initially given as $1.7*10^{-5}$ kg/sec, indicative of resting astronauts. At four hours into the simulation, this value was increased to $7.0*10^{-5}$ kg/sec, a number representing a double-sized crew performing hard work. Finally, at eight hours the level was decreased to $3.0*10^{-5}$ kg/sec a level appropriate for the standard four-man crew performing typical functions.

Classical Control Results

The classic, or PID, controller was designed around the corrective algorithm that follows.

$$\dot{m} = \dot{m} + \left(\frac{\delta}{k1} + \frac{\frac{d\delta}{dt}}{k2} + \frac{\int \delta dt}{k3} \right) \qquad (2)$$

where m refers to the mass flow rate through the blower. In its initial form the values of k1, k2, and k3 were all equal to unity. This resulted in two major effects. First, the controller was able to vary the flow rate quickly resulting in the controller's exhibiting a very high frequency. Second, the influence of the derivative term was very small. Figure 3 shows this controller's response to the test conditions detailed in the preceding paragraph. The partial pressure of CO_2 in the cabin corresponds to the top curve and, is scaled along the right-hand axis. The mass flow rate through the system is the bottom curve, and is scaled along the left-hand axis.

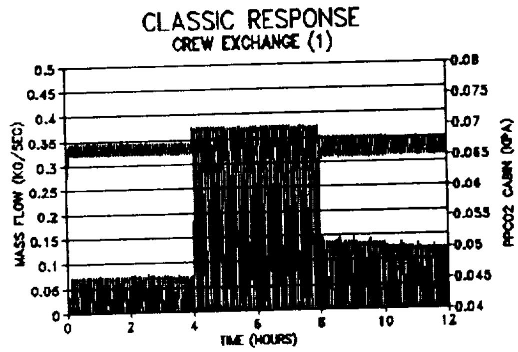

Fig. 3 System response with weighting (1,1,1)

This figure obviously has little if any dampening evident; therefore, this initial set of constants scored poorly on the scale of desirability. This led to the need to increase the impact of the derivative term and to lower the frequency of the controller as the original constants lead to value searching at unrealistic rates.

For a second try, the values of k1 and k3 were increased to 10. This would result in a slower frequency due to the controller changing the mass flow at a slower rate and a better dampened system as the relative impact of the derivative term would be increased. The results of this controller when subjected to a similar test are shown in Figure 4. This controller was able to achieve an appreciable amount of dampening during the four to eight hour interval corresponding to the highest CO_2 production rate. However, at other times it was unable to achieve dampening, and so this set of weighing factors did not represent a satisfactory solution.

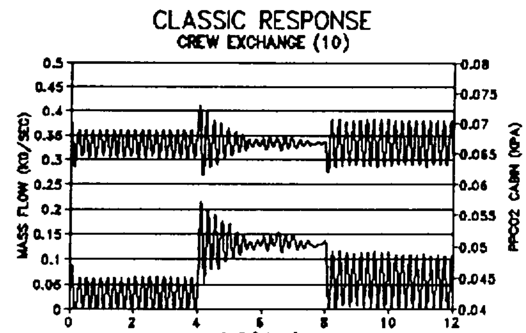

Fig. 4 System response with weighting (.1,1,.1)

There is no reason that the values of k1 and k3 had to be left equal to each other. Since the system was well-behaved and smooth, it was not necessary to incorporate a large integral term. This fact allows us to assign a very large value to k3 and, in essence, to reduce the PID controller to a nearly PD controller. By reducing the input from the integral term, it was possible to increase the contribution of one of the remaining terms and maintain a similar controller. Since the value of k2 was already fairly small, it was decided to decrease the value of k1 back to 25 to increase the effectiveness of the proportional term.

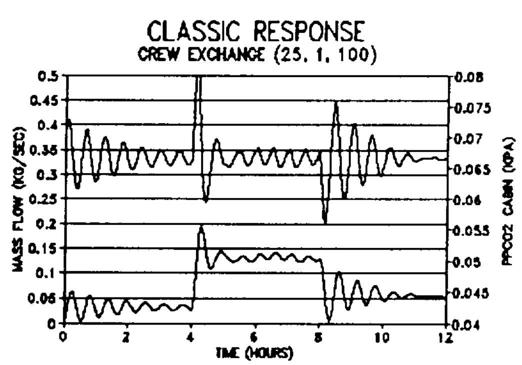

Fig. 5 System response with weighting (.04,1,.01)

The net result was a controller with the constants set at k1 = 25, k2 = 1, k3 = 100. These constants do not represent a calculated attempt at optimizing the controller, but rather a logical qualitative approach to examine the effect of the different error terms on the overall responses to the test. The data for its response to the test case is shown in Figure 5.

This controller exhibits several characteristics. First it suffers from a large spike in partial pressure corresponding to the onset of the step functions. The maximum value attained was 0.084 kPa of CO_2. The duration of the spike was for only a few minutes, and is not a problem to the crew. On the positive side, this controller was able to quickly reduce the magnitude of the oscillations and rapidly achieve a steady mass flow rate. In comparison to our previously listed criteria, this set of constants was elected as best for use in the classical PID controller.

The PID controller was very successful in regulating the system and maintaining desirable cabin conditions. The effect of the constants on the response of the system was as expected, lending an air of credibility to the model and the controller. Again, the controllers tested were chosen for their capable and satisfactory performance, rather than as the result of a formal optimization study.

Expert Control Results

The expert controller was subjected to testing using the same cabin conditions as described above. It was again necessary to attempt to modify the expert controller to provide some degree of dampening to lessen the wear on the fan and motor driving the air through the sorbent beds. The understood restraint on maximizing dampening is that the system must maintain the cabin CO_2 levels at approximately the 0.0667 kPa set point.

The expert system algorithm first generates a belief, a percentage basis of its need to execute a change. This belief is multiplied by a weighting factor to generate a new mass flow rate. The actual algorithm follows.

$$\dot{m} = \dot{m} \pm \left(k_1\left(2 \cdot \%_{Belief} - 1\right)\right) \quad (3)$$

The most obvious characteristic of this equation is that the controller's frequency is proportional to k1 or the weighting factor; that is, a large factor will generate a high frequency controller. The inverse of this is that a small weighting factor will result in a lower frequency controller.

The original controller was designed with k1 equal to 0.05. The result of this controller when tested with the crew exchange scenario is shown in Figure 6. The upper curve corresponds to the right-hand axis and displays the partial pressure of CO_2 in the cabin in kPa. The left-hand axis goes with the lower curve to show the mass flow rate in kg/sec.

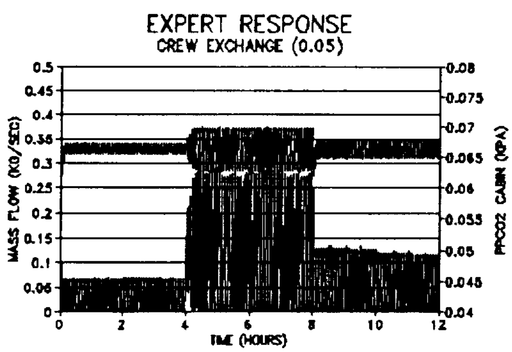

Fig. 6 Dynamic response with weighting (.05)

The controller exhibits no apparent dampening, and so does not appear very suitable for our application. The next course of action was to remember, as with our work on the PID controller, that a lower frequency controller provided smoother mass flow rates and an increase in dampening. Following that hunch, the value of K1 was lowered to 0.005 and the test was run again.

This served to slow the controller's time of response, and also to achieve a slight dampening effect. The results for this run are shown in Figure 7. The quickest dampening however was limited to the region when CO_2 was the highest. This trend was similarly observed in the PID controller when the frequency was slightly too high. This indicates that the weighting factor is close to the desired value and only needs fine tuning.

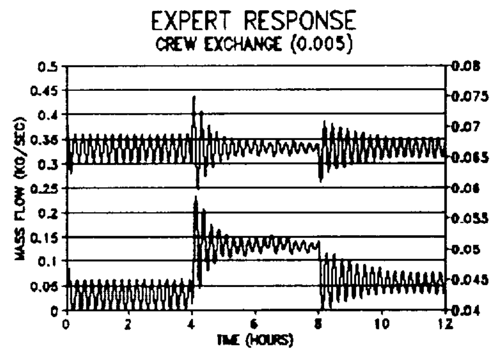

Fig. 7 Dynamic response with weighting (0.005)

The final variation on the expert system weighting factor was to set k2 = to 0.002. The graph in Figure 8 represents the results of that test. It can be seen that the increase in controller frequency enabled the controller to decrease the amplitude of the transient spikes. That reduction, coupled with the fact that the dampening was even more successful, made the weighting factor of 0.002 appear to be the most capable option for the expert controller.

Again, it is important to stress that the expert controller, like the classic controller, is not optimized. Although the apparent best choice from among several options was taken, the values are not presented as optimums. No mathematical solution was undertaken as an attempt to find the best weighting factor; rather, the selected controller is merely a functional and capable controller for the system.

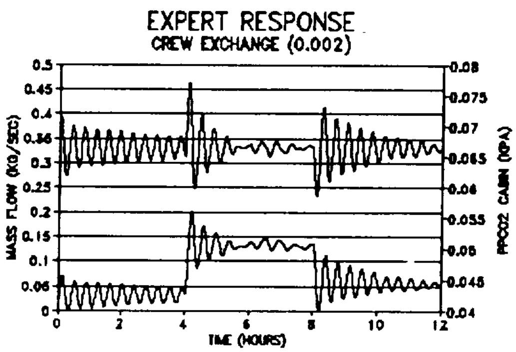

Fig. 8 Dynamic response with weighting (0.002)

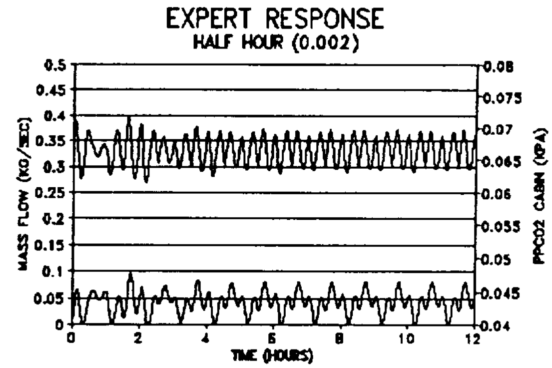

Fig. 10 Expert response to half hour loading

Dynamic Case Studies

In addition to the situation utilized in the examples above, the controllers and simulation were subjected to a series of other tests. First, the simulation was tested to determine its response to a sinusiodal CO_2 production rate that always created a heavier load on the same sorbent bed. This would provide insight into the system's response at being excited at a given frequency. The results for this test can be found in Figures 9 and 10. Here, as before, the upper curve is the partial pressure on the right axis, and the mass flow rate is the bottom curve scaled along the left-hand axis.

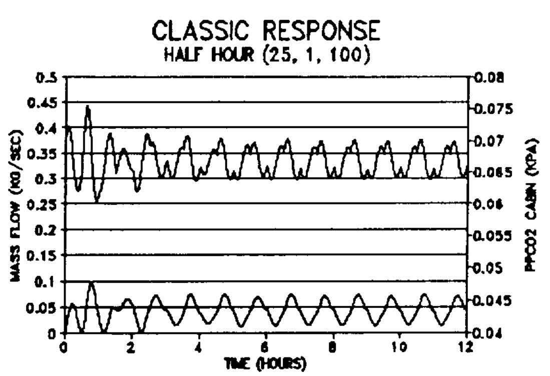

Fig. 9 Classical response to half hour cycle

The next case was conducted to determine the natural frequency of the controllers. By imparting a single impulse, in this case a short-term high CO_2 production spike, it is possible to observe the system's natural frequency. The results of this test can be seen in Figures 11 and 12. The expert controller has a higher frequency than the classical controller. That does not necessarily imply that the expert controller has the faster response capability, only that it cycles at a higher rate. Also in this scenario it is easy to observe the dampening abilities of the control systems as they reduce the oscillation's amplitudes. The final point of interest is the visibility of the half hour frequency imparted due to bed switching. It is responsible for the steady state oscillations visible in the graphs.

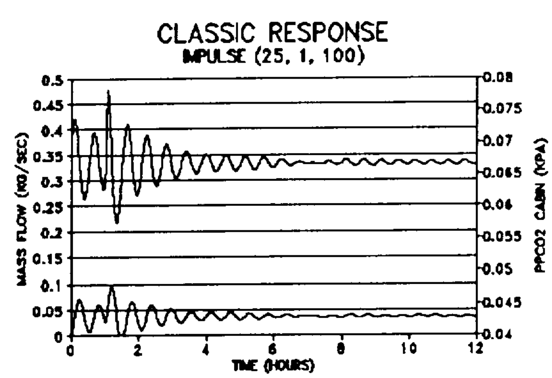

Fig. 11 Classical response to an impulse

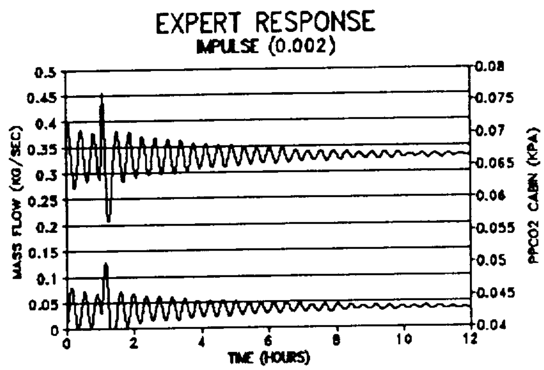

Fig. 12 Expert response to an impulse

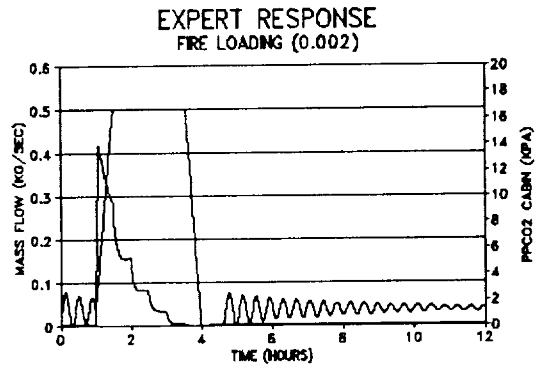

Fig. 14 Expert response to a fire

The final scenario examined was the controllers' abilty to handle a massive CO_2 production rate. This would simulate a fire in a Space Station module, or possibly a leak in the CO_2 accumulator tank. The results of this trial are given in Figures 13 and 14. The classical system was able to respond more quickly, as evidenced by its more rapid increase of the mass flow rate. The slower response of the expert system resulted in the CO_2 partial pressure reaching a value of 14 kPa as opposed to the PID's peak value of 12 kPa. The major consideration, however, is how long before the CO_2 level returns to acceptable limits. Here, both controllers show the situation under control by two hours later.

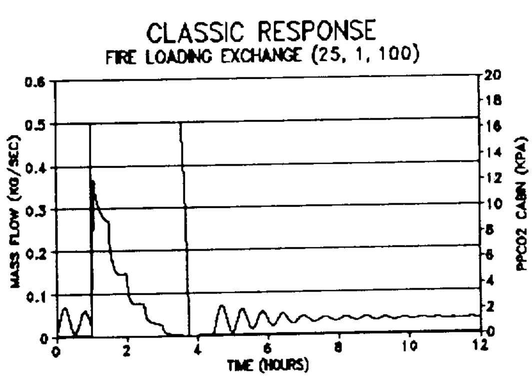

Fig. 13 Classical response to a fire

Conclusions

The first conclusion that can be gathered from this report is that the simulation presented is a success. The physical phenomena modeled are accurate and respond correctly to parameter changes. This implies that the simulation is capable of being used as a test bed for evaluating almost any parameter's influence on the system's behavior. It is possible to determine the effects of possible disasters (such as a fire), or merely to examine how the system operates under normal conditions.

Both controllers were found to be capable of handling the tasks assigned. There is currently no way to determine if one controller is superior to the other. Neither was formally optimized, and so the limits of their abilities is still not known.

Recommendations

It is recommended that a formal optimization of the controllers be done. Once optimization is completed, a rigid and weighted set of criteria should be drafted. After testing the controls with the simulation code, the control schemes could be scored against the criteria. Once this is completed, the better control system should be implemented as the control scheme of choice.

Note that a single type of control may not necessarily be the best choice. Rather, a control hierarchy where an expert system oversees a series of classical controls (or vice versa) might be the most effective choice.