ARAUJO FILHO, J.E. E MACAU, E.E.N. - "Thermal Vacuum System Controlled By Fuzzy Reasoning", Proc. 3rd World Multiconference On Systemics, Cybernetics And Informatics e 5th International Conference On Information Systems Analysis and Synthesis, v.7, pp. 1-7, Orlando, EUA, July, 1999.

Thermal Vacuum System Controlled by Fuzzy Reasoning

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ABSTRACT

Fuzzy control systems represent techniques to deal with qualitative information in a rigorous way by using linguistic variable as a set of rules. An attribute of fuzzy control is to model these rules by incorporating the "experience" of the human expertise. This work focuses on thermal vacuum control system. When a space system is been developed it undergoes a test qualification program in order to guarantee that it will operate efficiently. The environmental condition of vacuum with solar exposition is produced in a test chamber. The environmental variations must follow a sequence that is expected during the orbit for each subsystem inside the spatial system and after for the whole system. The task of modeling the chamber and the specimen each time that a test is been carrying out seems to be hard. One alternative approach to control complex dynamic systems is to employ fuzzy controllers that make use of linguistic terms to represent its variables and parameters instead of differential mathematical models. Linguistic rules, which describe the operator's control strategy, are built to form the knowledge base. A control algorithm is developed to supervise the behavior of the system during the test making the decision and control process easier.

Keywords: Fuzzy Reasoning, Thermal-Vacuum Chamber, Space Sector, Fuzzy Control, Supervising System and Expert Systems.

1. INTRODUCTION

Given a physical system, control theory usually makes use of mathematical equations, such as differential and relational equations, in order to adequately represent some aspects of the dynamic behavior of the system to be controlled. With such a mathematical model, and the tools of system and control theory, the system structure and modes of response can be investigated. However, there are plants or process which dynamic characteristics are extremely hard to be modeled by using this approach, mainly because of their intrinsic nonlinearity and complexity [1].

For situations like that, an alternative approach is to consider intelligent control systems (Artificial Intelligence). In this scenario, fuzzy controllers can be used to implement "intelligent" controllers [2] since it is able to carry out methodologies and techniques used by human experts. In this scenario, the knowledge or rules of control can be brought out of expertise and translated into an intuitive natural language. Although the variables and parameters in mathematical models are based in numerical values, by using fuzzy systems such parameters change to linguistic nature. That language is refereed as fuzzy linguistic term and it is featured with a membership function. That concept was firstly presented as fuzzy sets by L.A. Zadeh [3].

The fundamental design assumption of fuzzy control system lies on process characteristics and the goals established to build the control law. A fuzzy control system is that one that accesses fuzzy logic to determine the action being employed on controlled system. This way, it is possible to understand the fuzzy controllers by associating the fuzzy sets and the control logic [4].

The fundamental idea behind this approach was to incorporate the "experience" of a human operator in the design of the controller by using mainly logical models called knowledge-based or rules-based models. From a set of linguistic rules, which describe the operator's control strategy, a control algorithm is construct where the words are defined as fuzzy sets. Thus, the fuzzy logic control system is a kind of expert knowledge-based system that contains the control algorithm in a simple rule-base.

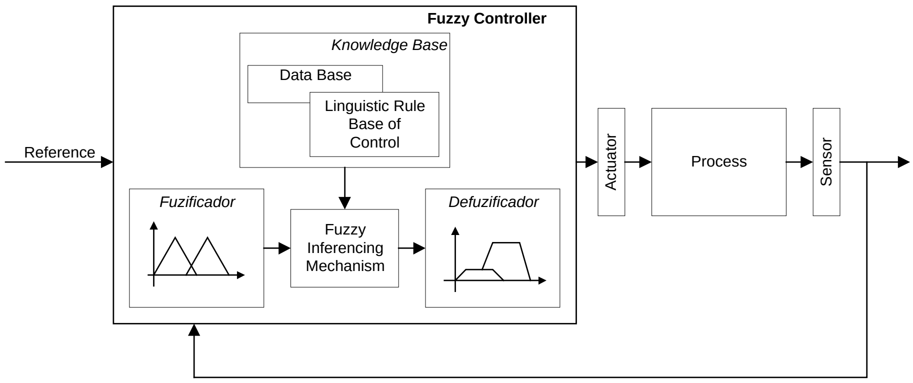

Figure 1 - Fuzzy Control System

The control law being used in this kind of controller is characterized with antecedent (set of conditions) and consequent (conclusion) parts that are respectively represented as IF ... THEN rules as vague predicate and an inferencing mechanism based on fuzzy logic [5]. The term inferencing is used for systems while reasoning is concerned with thoughts or reasons of human being. The set of this rules form the knowledge used in fuzzy controller. Thus, the more knowledge and detailed logical statements are considered to built the antecedent, consequent and inference mechanism, the more efficient is the control system. For this reason, more complicated control issues can be solved. Because its characteristics, fuzzy control system admit the possibility of implementing experience, intuition and heuristics. Another advantage of this approach is that a model of the process is not necessary [6].

Though this paradigm seems expert systems because both stem form the same origins, their differences can not be regardless [7]. The main contrast can be understood as the following: fuzzy systems can deal with uncertainty (in a great number of levels), while expert systems using classical logic can not (they are only two logical levels: true or false). The fuzzy system approach can model approximated (commonsense) reasoning by using inference mechanism of a possible imprecise conclusion (consequent) from a set of possible imprecise premises (antecedent) which is the fundamental principle of many heuristic rules [8].

2. PROBLEM

A satellite is composed of several sub-systems that interface with each other to form a whole system. In order to reach a fully operational status, the system and the sub-systems must be tested and operated in a manner that simulates as closely as possible their expected lunch and its working life. This qualification process will include different environmental tests that simulate all activities present at launch and post-launch operations. When the satellite is on its orbit, it is exposed to sunshine, Albedo, earth radiation and shadow. The vacuum can stretch the temperature range out boosting the positive temperature and decreasing the negative value, for instance, typically from -130°C to 80°C [9]. The environmental conditions of a vacuum with thermal loads are produced in a test chamber. That is pumped down to a vacuum and the thermal variations will follow an operational sequence complying with expected conditions during orbit as described. Figure 2 shows one of the thermal-vacuum chambers at the Laboratório de Integração e Testes (www.lit.inpe.br).

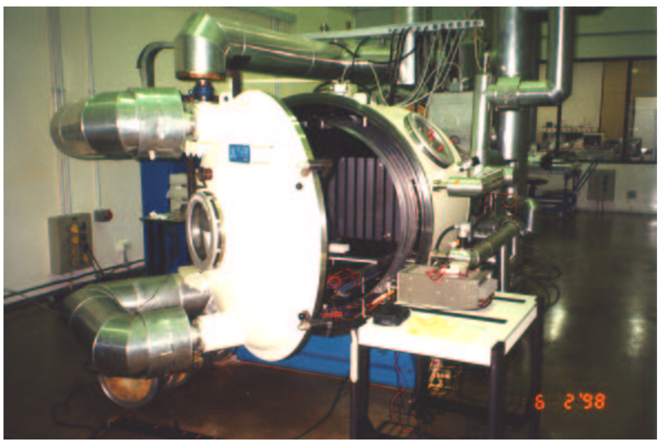

Figure 2 - Thermal-Vacuum Chamber

Control systems for the thermal-vacuum chamber was originally designed to control the temperature in shroud.

However, the norm that regulates the test proceeding for space sector establishes that the controlled variable of the process is the temperature at the specimen surface. As each specimen under test presents different thermal characteristics, for every testing to be performed a new mathematical model need to be achieved to describe the dynamic behavior of specimen and the chamber. Nevertheless, the endeavor of modeling both systems for each test not always reach an expected result. Nowadays, the control is done manually by an operator in a non-automatic manner because of the inherent difficulty of controlling the system.

3. SOLUTION

The use of fuzzy system and approximate reasoning applied to decision and control problem has been a research issue of great interest. This statement can be verified in many segments of the industrial sector ([10]-[14]), of the space sector ([15]-[17]) and in applications of temperature control systems ([18]-[20]).

The use of supervisory fuzzy control system in driving the decision making attempts to imitate human common sense reasoning. This supervisory approach solves the problem presented earlier and also avoids an upheaval - if some unexpected situation comes up - because the human expert can whenever select to use your own reasoning. Figure 3 depicts the block diagram for the supervisory fuzzy control system considering all elements involved.

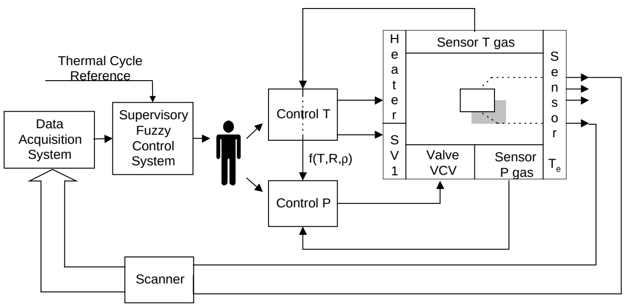

Figure 3 - Supervisory Fuzzy Control System

Figure 3 has its equivalent control block diagram in Figure 4. In this representation it is possible to visualize two feedback loops. The inner one represents a PID control system and the outer typify a fuzzy control.

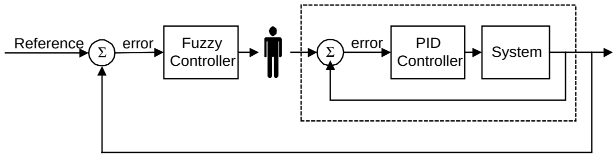

Figure 4 - Inner and Outter Control Action

While the first one is particularly useful for reducing steady-state error and for improving the transient response the second one is concerned to the suitable set point to guarantee an appropriated temperature on the specimen's surface in order to follow the requirements desired for the test.

The inference mechanism which deliver a suitable set point relies on a knowledge base concerned with the reasoning used by experts. The acquisition of knowledge base - extracted from a set of expert operators by extensive interviews - and other sources is codified to fuzzy logic on fuzzy association map.

The Mandani type [21] and the Takagi-Sugeno type [22] are the two basic structures for fuzzy control systems. Mandani Controller uses linguistic terms as the consequent by using fuzzy sets and then a defuzzification procedure determines the output value, like the following example:

Rule r: if x_1 is $A_1^{j_1}$ and ... and x_1 is $A_n^{j_n}$, then u is A^j, (1)

where $A_i^{j_i}$ is the jth term of linguistic variable i corresponding to the membership function $\mu_i^{j_i}(x_i)$ and A^j corresponds to the membership function $\mu^j(u)$ representing a term of the control action variable.

Although Takagi-Sugeno controller has its rule antecedent equivalent to the Mandani Controller, its rule consequent is determined by a function. This method uses crisp output values without using the defuzzification process.

Rule: if x_1 is $A_1^{j_1}$ and...and x_1 is $A_n^{j_n}$, then u is $f_r(x_{1,...}x_n)$ (2)

The consequent function depends on the input variables and that one is usually linear, although it can assume many other types.

The supervisory fuzzy control system used in this work employs crisp actions as membership function instead of fuzzy sets. Otherwise, input membership functions use traditional approaches.

Variables considered to build the input membership functions were error, *e* (Figure 5), and its changing, *i.e.* error variation, Δe (Figure 6). Each variable were fuzzified by using input fuzzy sets where the linguistic terms are arranged by using the letters N, P, S, M and L that represent “Negative”, “Positive”, “Small”, “Medium” and “Large” respectively.

At least one feature set the membership functions off from the traditional fuzzification process. While the traditional approach uses fixed values for fuzzy sets, in this work there are *adaptive fuzzy sets* along with the conventional one.

membership value, $\mu(\Delta u)$, and then a crisp incremental output value of the fuzzy controller, Δu, will be produced.

The Takagi-Sugeno-like rule antecedent in this work as shown in (2) employs two nonstandard ways. Different also from Mandani who utilize min operator, the input membership functions that have fixed range employs a min-max approach while those functions, which have variable boundary, apply a max-min approach. It can be represented as follows:

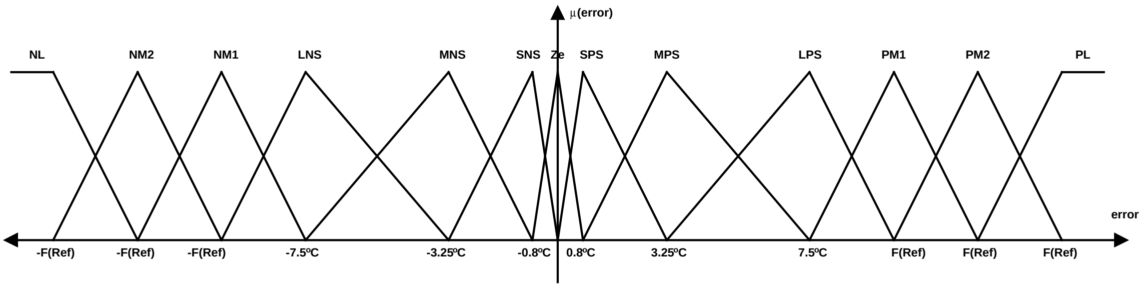

Figure 5 - Error Membership Function

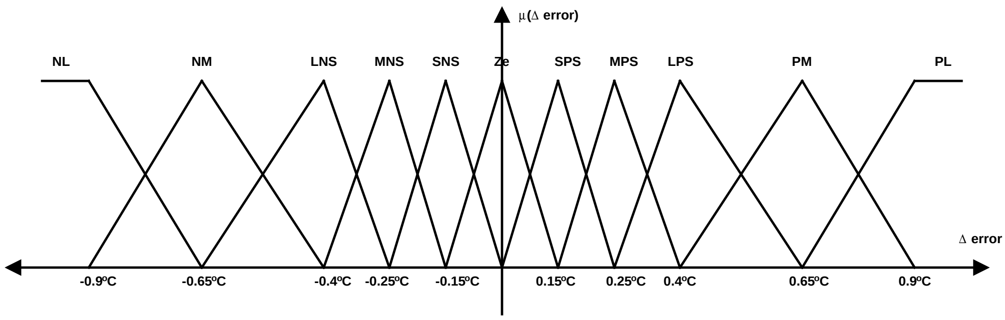

Figure 6 - Error Variation Membership Function

These adaptive sets change their initial and final limits considering the thermal cycle desired without change fixed fuzzy sets. These characteristics keep any floating as minimal as possible on steady state and adapt some sets to guarantee a good convergence during the transient period, specially because the range of the temperature is large. This adaptation in fuzzy sets behaves as *gain schedule fuzzy control systems.*

Established the rules antecedents it is now necessary to set up the consequent. The process of selecting one representative output lay on the expertise of operators and logic, such as AND and OR, to blend the $\mu_i(e)$ and $\mu_j(\Delta e)$ input membership functions. These membership values in the rule antecedent will generate the output

IF fixed lower limit < e < fixed upper limit THEN

First rule antecedent-consequent:

$R1_1$: IF x_1 is A_{11} AND...AND x_M is A_{M1} THEN A_{u1}
...
$R1_i$: IF x_1 is A_{1i} AND...AND x_M is A_{Mi} THEN A_{ui}
...
$R1_N$: IF x_1 is A_{1N} AND...AND x_M is A_{MN} THEN A_{uN}

Second rule antecedent-consequent:

$R2_1$: A_{u1} OR...OR A_{uN} THUS $A_{resultant}$

IF e ≤ fixed lower limit or e ≥ fixed upper limit THEN

First rule antecedent-consequent:

$R1_1$: IF x_1 is A_{11} OR...OR x_M is A_{M1} THEN A_{u1}
...
$R1_i$: IF x_1 is A_{1i} OR...OR x_M is A_{Mi} THEN A_{ui}
...
$R1_N$: IF x_1 is A_{1N} OR...OR x_M is A_{MN} THEN A_{uN}

Second rule antecedent-consequent:

$R2_1$: A_{u1} AND...AND A_{uN} THUS $A_{resultant}$

Finally, the crisp incremental output values of fuzzy control is:

IF $e \geq 0$ THEN $\Delta u = f(A_{resultant})$
IF $e < 0$ THEN $\Delta u = - f(A_{resultant})$,

where x_N is the controlled input variable - here error or difference between the real output and desired output and error variation -; operators AND and OR correspond respectively to min(x,y) and max(x,y); A_{MN} is the *M*th term of linguistic variable *N* corresponding to the membership function $\mu_N^M(x_i)$; A_{ui} corresponds to the membership function $\mu_N(u)$ representing a term of the control action variable; and $f(A_{resultant})$ is the linear function that will supply the output value of the fuzzy controller. In this work the equations 5 and correspond to the linear function when $e \geq 0$ *and* $e < 0$.

$$\Delta u = K_1 \mu(\Delta u)_{Final} + K_2 \qquad (3)$$

$$\Delta u = -K_1 \mu(\Delta u)_{Final} + K_2 \,, \qquad (4)$$

where the coefficients K_1 e K_2 are function of the whole Thermal-Vacuum System. These coefficients are determined through heuristic method based on the expertise of operators.

4. RESULTS

The Thermal-Vacuum Chamber shown in Figure 2 is used for the experiment. The Thermal system is comprised of a three zone thermal shroud to maintain the required thermal environment in the chamber. The operation of the thermal shroud is achieved by means of a recirculating, dense, and gaseous nitrogen (GN2) system. The GN2 system is a closed loop, forced convection, heating and cooling system. Resistance type heaters mounted inside the piping network provide heat as required while cooling the circulating gas stream is accomplished by spraying LN2 into the circuit. To maintain nearly constant heat transfer properties throughout the wide range of system operation, a constant density system is utilized by adjusting the pressure of the system in direct relationship to the temperature [23].

In this experiment K_1 and K_2 were determined to be 25 and 0, respectively. An operator set up the values of temperature and pressure indicated by the fuzzy supervisory control system.

The input signal for this experiment is a step reference value of 21°C. The graphical results Figure 7 express the output value related to the reference input.

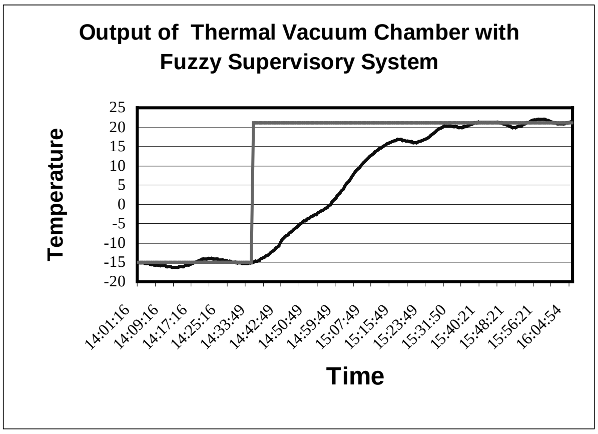

Figure 7 - Results

It is possible to identify oscillations when the temperature on the specimen to be tested seems to be reached the reference value. As the requirement for tests allows a tolerance between ± 1°C and ± 3°C than the oscillation found is acceptable.

Another characteristic that needs to be pointed out is the time of test. In these experiments the time of test is established to verify the convergence of the temperature and not to match the reference signal with the actual temperature on the specimen.

5. CONCLUSION

This work attends the initial goal of showing the employment of fuzzy systems in space qualification systems. The supervisory fuzzy control system described shows the use of approximate reasoning and the use of rule based decision associated with fuzzy theory applied to non-linear and complex system. The decision-make supervisory system is a non-linear process representing the qualitative knowledge of a human expert about system behavior and the desired control action. The task of tuning fuzzy sets representing the knowledge base was made by trial-and-error method instead of automatic tuning techniques. Although this approach is good enough to stabilize the system, it is difficult to know if it accomplish optimal performance. Furthermore, this work presents the use of fuzzy sets mixed with crisp action to control without any additional lost. Finally, the decision-make supervisory system achieves the goal of controlling the thermal vacuum chamber used to simulate the environment in-flight life of a satellite making advanced real time automation possible.

Future research efforts will focus on increasing the efficiency of the current approach by using this one at the operator's place. In addition, the task of tuning fuzzy sets can be implemented by using systematic synthesis and tuning methodologies, such as neural network or genetic algorithm, in order to reach an optimal result.

6. ACKNOWLEDGMENTS

J.E.A.F. would like to acknowledge the Conselho Nacional de Pesquisas (CNPq – Brazil – www.cnpq.br) which supported this work in part by grant no. 381212/97, the Instituto Nacional de Pesquisas Espaciais (INPE – The Brazilian Space Research Institute – www.inpe.br) and the staff of its laboratory, Laboratório de Integração e Testes (LIT – The Laboratory responsible for Assembly, Integration and Testing of satellites and qualification of industrial products which demand a high degree of reliability – www.lit.inpe.br).

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