Fuzzy Reference Gain Scheduling Control Systems

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Abstract

This article presents an innovative combination of fuzzy control with gain-scheduling control, in which the shape of the membership functions change according to different operational conditions. In this kind of adaptive controller, the membership function parameters are function of the reference, yielding an effective and flexible controller. This method can be implemented in processes which are nonlinear over a large range of values and whose parameters can vary in time. This approach has been applied in a highly non-linear termal-vacuum process that presents time-delay, for which conventional controllers are not appropriate.

1 Introduction

Given a dynamical system, controllers are designed to determine an appropriate action, in such a way as to allow the system to follow a set point and reject the influence of unwanted disturbance signals. However, due to time-variance and nonlinearities, the expected behavior of dynamical systems is subject to changes. If the changes in the system operation conditions are known in advance, parameters of the controller (*gains*) can be adjusted directly as a function of the operating conditions (*scheduling*) in a preprogrammed way. Such a control approach is called *gain scheduling* [1][2].

Fuzzy control systems (FC) use the concept of fuzzy logic proposed by Zadeh [3] and was first applied to control systems by Mamdani [4]. This method determines control actions through the use of rules that take into account the lack of accuracy and the uncertainties found in qualitative information yielded by human experts. It has been used in problems where practical mathematical models are not easily available, specially where nonlinearities are present. It has been often used as an alternative to conventional control approaches such as proportional-integral-derivative (PID) control and state-space and frequency-domain methods.

Used together, these approaches brought up the concept of *fuzzy gain scheduling* control systems (FGS). This idea has been described in many different manners such as rule-based schemes for gain scheduling of PID controllers [5], Takagi-Sugeno fuzzy models for the design of fuzzy gain scheduling controllers [6], fuzzy gain scheduling scheme for conventional PI and optimal load frequency controllers [7], hierarchical fuzzy gain scheduling controllers based on local controllers [8], fuzzy gain scheduling controllers based on sliding-mode analysis [9][10], and fuzzy gain schedulers based on the H_∞ technique [11].

However, in practice most of the fuzzy logic gain scheduling schemes are based on the selection of the most suitable local gain out of a set of gains that taken together act as a global nonlinear control law.

In this work, another manner to control a system is proposed by using a combination of gain scheduling and fuzzy logic. It is called here a fuzzy reference gain scheduling control system and was first informally considered in [12]. This control approach is based neither on linearizations about a set of equilibrium point nor on the dynamic linearization about a nominal trajectory. There is not a gain pool computed earlier as it is usual, yet this approach considers a specific set of membership functions whose parameters (e.g., support and core) change as function of the reference. A gain scheduling approach based on the change of reference values was proposed in [13], but it does not deal with fuzzy systems. In the literature it is also reported an approach in which parameters of the membership functions change dynamically in function of the state variables [14], whereas in the approach proposed here, the parameters change in function of the reference value.

2 Fuzzy Reference Gain Scheduling

A *fuzzy reference gain scheduling* control system (FRGS) follows the same basic idea of the traditional fuzzy control systems. The control law is modeled through the application of an inference mechanism on a set of rules of the kind IF *condition* THEN *conclusion*. The condition and conclusion in the rules address a set of so-called linguistic variables, to which of each only a limited number of terms (membership functions) can be assigned. However, whereas in the conventional approach the terms associated to the linguistic variables are always the same, in the approach proposed here these terms change as function of the reference signal (set point). These terms will be called here *adaptive fuzzy sets* (see Figure 1), whereas the ones used in the conventional approach will be called *constant fuzzy sets*.

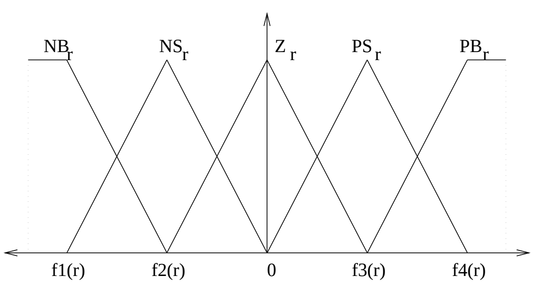

Figure 1: Adaptive fuzzy set.

The distinction between constant and adaptive terms can be made clear by means of a simple example. Let us suppose that in a given application x is a linguistic input variable taking values in a domain $X = [-1, 1]$, to which is associated a set of terms $T = \{N_r, Z_r, P_r\}$. Let $\mu_A : X \rightarrow [0, 1]$ be the membership function of a term $A \in T$, and $c(A) = \{x_0 \in X \mid \mu_A(x_0) = 1\}$ and $s(A) = \{x_0 \in X \mid \mu_A(x_0) > 0\}$ respectively denote the core and support of A. Let us suppose that each term $A \in T$ is shaped as a trapezoid and represented by a 4-tuple $< s_1, c_1, c_2, s_2 >$, with $s(A) = [s_1, s_2]$ and $c(A) = [c_1, c_2]$.

Consider now that r is a reference value inside a domain $R = [0, 100]$. Then a set of adaptive terms for T could be $N_r =< -1, -1, -f(r), 0 >$, $Z_r =< -f(r), 0, 0, f(r) >$ and $P_r =< 0, f(r), 1, 1 >$, where $f(r) = r/200$. In this particular example, distinct constant terms are derived for different values of r. For instance, for $r = 10$ the cores of the terms are close to 0, with $N_{10} =< -1, -1, -.05, 0 >$, $Z_{10} =< -.05, 0, 0, .05 >$ and $P_{10} =< 0, .05, 1, 1 >$, whereas for $r = 100$ the cores of the terms are more spread apart with $N_{100} =< -1, -1, -.5, 0 >$, $Z_{100} =< -.5, 0, 0, .5 >$ and $P_{100} =< 0, .5, 1, 1 >$. As a consequence, many of the values of x that are considered to be "close to 0" when r is low, can be considered to be "far from 0" when r is high. The use of these adaptive sets in a FRGS may thus generate different actions for the same input value, and thus create different control surfaces, depending on the reference value (see Figure 2).

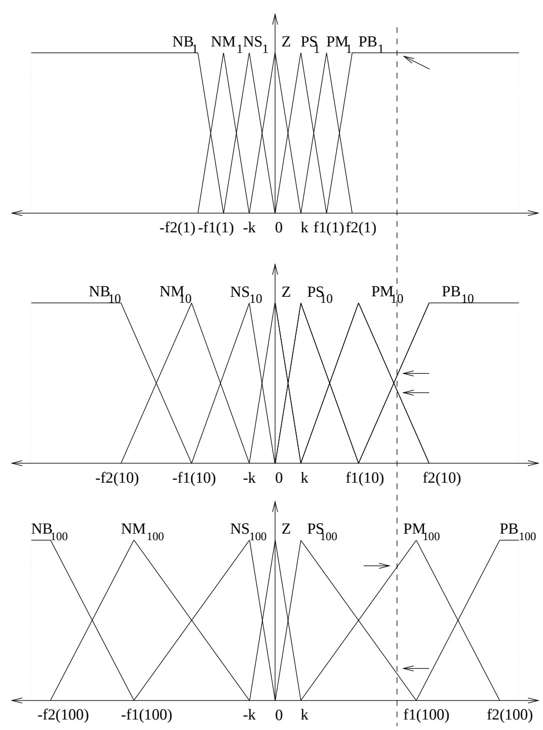

Figure 2: Comparison of membership functions.

It is worth mentioning that nothing prevents the mixing of constant and adaptive terms in a given application of the proposed methodology. This shows that this approach is more flexible than the simple adjustment of an abcissa considering the reference value.

In a FRGS the reference signal is thus the mechanism that modifies the parameters (terms) of the controller, since it limits the operational conditions concerned with the process. This approach can be implemented using adaptive fuzzy sets either in the premise or in the conclusion of the rules, and with different inference schemes (e.g. Mamdani, Sugeno, etc). Moreover, it is useful both in regulation problems, where there are levels of reference (steps) to be followed, or in servomechanism problems in which the reference modifies continuously at time.

3 Aplications

This new method can be interesting in control processes with different operating conditions established by the reference. For instance, they can be particularly interesting to control thermal-vacuum chambers used in environmental tests to qualify space products. The thermal-vacuum test consists of a chamber, a shroud (set of pipes) which transmits heat, and some devices and auxiliary equipment able to determine specific conditions for the test be performed. After mechanical and cryogenic pumps achieve the high vacuum, the temperature inside the chamber is modified to simulate space conditions. The operation of a thermal shroud is achieved by means of a re-circulating, dense, and gaseous nitrogen (GN2) system. Cooling the circulating gas stream is accomplished by spraying liquid nitrogen (LN2) into the circuit, while resistance type heaters provide heat as required.

The operation of this thermal-vacuum system follows different set points (levels of reference) at distinct moments of time. This feature forces the system to deal with several operational conditions. If the controller is not robust enough to reach the desirable response under these variations in the operational conditions, an alternative is to use an adaptive control approach. The controller for such a system should thus present different control surfaces, depending on the set points. The use of a conventional gain-scheduling controller would beforehand require specifying a pool of parameters for each set point value. The use of a FRGS controller provides a means of achieving the desired control by using a set of laws that allows control surfaces to adapt to the different operational conditions that the system is supposed to work. Additionaly, this approach allows the incorporation of the expertise of the thermal-vacuum chamber human operator.

A FRGS approach, in conjunction with a Tsukamoto-like inference mechanism, was applied in a thermal-vacuum system developed at the Integrating and Testing Laboratory (LIT) of the Brazilian National Space Research Institute (INPE). An detailed understanding of this approach can be seen in [12]. The following graphic presents the step response according to different references which define specific operational conditions.

Figure 3: Thermal-vacuum chamber response.

4 Conclusions

We have presented here a fuzzy reference gain scheduling control system, which combines gain scheduling and fuzzy controllers. Besides the traditional parameters of control incorporated by the experience of human operators, this approach can include knowledge about variation in the concepts underlying the membership functions, due to changes in operational conditions. This knowledge allows the control surfaces to adapt as required by operational conditions, mainly determined by the reference.

This control approach is more general than the ones based in scaling factors. Indeed, the approach presented here makes it possible for the parameters to change homogeneously, as a scaling factor, but it also allows the parameters to change independently or even to remain constant. This control approach is also not a modification of already existing "if-then" rule-based controllers. In fact, it can be employed along with any of the rule-based models existing in the literature.

The response obtained over a real system has shown the effectiveness and flexibility of this control approach. This experiment considered a termal-vacuum system, very non-linear in nature, whose behavior can change in the same way as the specimen that is undergoing to space environmental tests. These features show the effectiveness and robustness of this method and that it can deal with complex processes without the need of a mathematical model.

This approach is appropriate for higly non-linear or time-variant systems. In future works, we intend to investigate its use in regulation or servomotor problems.

Acknowledgements
J.E. Araujo Filho and Sandra Sandri acknowledge support from the Brazilian research funding agency CNPq with grants 38.1212/97 and 52.0176/96-0, respectively.

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