A SURVEY OF STABILITY OF FUZZY LOGIC CONTROL WITH AEROSPACE APPLICATIONS

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Abstract: During recent years considerable efforts have been devoted to guarantee the stability of fuzzy logic control (FLC). Several stability analysis methods have been established, and stable control designs have been introduced. This is important to pave the way for the use of FLC in applications were no risks should be run. Aerospace is a clear example of a field where control must be sure. This paper is motivated by an ESA research project on stability of FLC concerning, in particular, aerospace potential applications. The paper present a review of the research on FLC stability, both in time and frequency domains, including also several alternatives of stable control design methods. In addition, there is a section about FLC applications in aerospace.

Keywords: Fuzzy control, aerospace control, stability analysis

1. INTRODUCTION

Fuzzy logic control (FLC) is an interesting candidate to be considered for aerospace use. This method of control has demonstrated several advantages, with many successful applications. But it seems there is some reluctance to use it, due to stability concerns.

Along last years an effort has been done to study the stability of FLC. Several analytical methods and tools have been developed, offering now the means for a good control design with fuzzy logic.

The paper presents a survey of FLC stability, with the main lines of research. In addition describes possible applications in spacecraft control, with a mention of published uses of FLC in aerospace. The paper is a summary of part of the results of an ESA research project.

2. BASIC ISSUES

In practical terms, the PID is considered as a safe control. The matter is if FLC is also safe.

When using a controller, for instance a PID, the study of stability refers to a complete system: the plant and the controller. The characteristics of the plant are important to have, or not, stability. This also happens when using FLC. Of course, it is important to know if the controller itself is stable.

There are several types of FLCs. In many cases, Mamdani (Mamdani, 1974) controllers are static nonlinear blocks. There are also PID-like versions based on the Mamdani concept. Takagi-Sugeno (TS) (Takagi and Sugeno, 1985) controllers are usually dynamic blocks. Only dynamic blocks can be stable or unstable.

Frequently, TS FLC is based on a previous modelling of the plant as a TS system.

From the theoretical point of view, it is not easy to define stability. There are many notions and definitions. In general two approaches can be distinguished. One is to consider the behaviour of transients. The other seeks for bounded outputs when inputs are bounded (BIBO stability). In linear systems the first type of stability implies the second type. In nonlinear systems things are different. Besides this, stability can be local or in the large (perhaps global). be related to equilibrium states or trajectories, etc. In general, the engineer should be aware of the type of stability that is pertinent for each particular case.

3. STABILITY OF FUZZY LOGIC CONTROL

Linear systems are a particular case of a more general category: nonlinear systems. Since fuzzy logic can approximate any function (Castro, 1995; Zeng, et al. 2000). the stability of FLC is usually studied under the perspective on nonlinear control theory.

There are two main contexts for the analysis of stability: time domain or frequency domain. Frequency domain methods are mainly used for Mamdani FLC. A representative research group using this kind of methods is connected with J. Aracil (Seville, Spain). Lyapunov (time domain) methods are mostly used for Takagi-Sugeno FLC. Here a representative research group is connected with K. Tanaka (Tokyo, Japan).

Relevant books with contents on FLC stability are (Passino and Yurkovich, 1999; Farinwata, et al., 2000; Palm, et al., 1997; Aracil and Gordillo, 2000).

In the following a selection of contributions about FLC stability will be presented, according to several analysis alternatives.

3.1 Time Domain.

There are two main methods. The Lyapunov ´s direct method is based on linearization. The Lyapunov´s indirect method use Lyapunov functions.

Lyapunov's Direct Method.

(Wu and Lin, 2000) model the nonlinear plant as a TS system; then they develop a TS FLC based on classical linear quadratic optimal control, giving a sequence of local controllers; by linearization they ensure the stability of each controller, so the complete control is uniformly asymptotically stable with infinite gain margin. (Ying, 1994a) studies an equilibrium state of a closed-loop system including a TS controller; a necessary and sufficient condition for local asymptotic stability is given; from this condition a design method is described, with examples.

Lyapunov's Indirect Method.

The initial contributions were from (Kiszka, et al., 1985). with an energetistic approach, and from (Birdwell and Wang, 1994) on the stability of the Fuzzy-PID controller. In 1992 (Tanaka and Sugeno, 1992) achieve an important contribution: a sufficient stability condition in terms of Lyapunov function; a common matrix P, with certain properties, must be found for all the subsystems of the TS controller; the nonlinear plant is modeled as a TS system. The group of Tokyo continued with the use of LMIs to get the P matrix (Tanaka, 1995; Wang and Tanaka, 1996; Tanaka, et al., 1996a, b, 1997, 1998a, b, c; Tanaka and Wang, 2000) including robustness and optimality aspects. Besides, (Wang, et al., 1995, 1996) propose the Parallel Distributed Compensation (PDC) design method for stable control.

Related with the contributions from Tokio, (Kawamoto, et al., 1992) is one of the firsts to apply the method suggested in 1992 by Tanaka and Sugeno. (Wong, et al., 1997, 1998) get an easy way to find a common L-function. (Joh, et al., 1998) consider the stability problem as related to switching systems: they give an interactive algorithm for the choice of the common matrix P. (Johansson, et al., 1998, 1999) use quadratic piecewise L- functions, so the gain-scheduling nature of TS FLCs is exploited to get more easily the common L-function. (Joh and Langari, 2000) develop a stable control design method based on PDC and LMIs: global asymptotic stability is guaranteed.

The passivity approach has demonstrated versatility and insight capability. (Calcev, 1998) uses this way to study the absolute stability of Mamdani FLC; this FLC can stabilize a general nonlinear passive plant, including Lagrangian systems. (Calcev, et al., 1998) apply passivity for PID-like FLC and derive conditions for asymptotic stability for linear and nonlinear plants. (Gorez and Calcev, 2000) present a synthesis of their work, considering several types of FLCs, including TS FLC. In the case of linear plants, these authors derive a frequency domain criterion on a Nyquist plot.

3.2 Frequency Domain.

In general circle's criterion is more conservative than Popov's, and Popov's criterion more conservative than Describing Function.

Describing Function.

This is one of the first approaches for FLC stability study. (Kickert and Mamdani, 1978) began with an equivalence of Mamdani FLCs and multidimensional multilevel relay systems. In a series of papers (Ying, 1993, 1994b, 2000) this equivalence is further analysed. (Abdelnour, et al., 1993) use the equivalence to study the transient response of a PID-like FLC + 2nd. order linear plant.

(Wang, et al., 1990) decompose the PID-like FLC into a PID plus a nonlinear term; the D.F. is applied to this term: the conclusion is that if the PID+plant is stable, then the complete FLC+plant is also stable. (Atherton, 1993) shows how to use the D.F. to study the stability of a PID-like FLC controlling a nonlinear plant. (Kim, et al., 2000) describe the structure of FLC with fuzzy basis functions: the D.F. is found both for static and PD-like FLCs.

(Leephakpreeda, 1999; Leephakpreeda and Batur, 1994) study the stability robustness of FLC; the higher harmonics discarded by the D.F. are considered as model uncertainty, and H_∞ is applied.

The group of Seville has a series of contributions, starting with the application of D.F. to Mamdani FLC and linear plant (Gordillo, et al., 1997). (Gordillo, et al., 1998) extend the stability analysis to the MIMO case. (Cuesta, et al., 1999) further extend the method for TS FLC with asymmetrical nonlinearities and MIMO systems. (Ollero, et al., 2000) present a short overview of the frequency domain stability analysis, with mention to multiple equilibrium states, D.F. for MIMO systems, and robust analysis of limit cycles. Other contributions of the group are (Aracil, et al., 1989, 1993, 1997) and (Ollero, et al., 1998).

Popov's Method.

(Melin, 1995) shows how to apply the Popov's criterion (with a Nyquist plot) to PID-like FLC, according to sufficient conditions for global asymptotic stability. (Wang, 1998) notes that using Popov's conditions for stability the requirements on the FLC (Mamdani) are not very strong: so there is an opportunity to specify the FLC by optimization. (Choi, et al., 2000) use a signed-distance to simplify the set of rules; absolute stability is proved.

Circle's Criterion.

The first works started with the equivalence with multilevel relays: (Ray and Majumder, 1998) studied the Mamdani FLC as a static nonlinearity inside a sector; then they show how to use the circle's criterion for linear SISO and MIMO plants. (Ray, et al., 1984) extends the method to PID-like FLCs.

Conicity refers to multivariable circle's criterion. (Espada and Barreiro, 1999) employ conicity and small-gain to develop a method for re-design of FLCs, to robustify them. Previous work was (Espada and Barreiro, 1994; Barreiro, 1997). A related research is (Xu, et al.,1996).

(Tanaka and Ikeda, 1998) consider the case of Fuzzy Phase-Lead Compensation (FPLC); the problem is transformed to a TS FLC; following the line of (Kitamura and Kurozumi, 1991) and (Katoh, 1993). they determine conditions for the stability of the FPLC + SISO linear plant; the paper also applies H_∞ for FPLC + MIMO linear plants.

(Kang, et al., 1998) develop a design method for Fuzzy Feedback Linearization; the nonlinear SISO plant is modeled as TS system; the work includes a robust stability analysis based on conicity.

3.3 Other Studies.

To complete this section, it is worth to mention some other studies. For instance, related to nonlinear control theory, the chapter of (Layne and Passino, 2000) on stability analysis; the contribution of (Lim, 1992) on absolute stability for a class of nonlinear plants; the paper of (Piegat, 1997) on hyperstability. Robust stability has been studied by (Farinwata, 2000; Farinwata and Chu, 2000), and by (Fuh and Tung, 1997; Kang and Kwon, 1997).

Several contributions of (Cao, et al., 1996a, b, 1997a, b) deals with observer + state feedback structures. (Tanaka and Sano, 1993a, b, c) study stable design in the frequency domain. (Kim, et al., 1995) treat stability and stabilization. (Kosko, 1998) study generalized additive fuzzy systems; this paper includes an interesting review.

4. STABLE FLC ALTERNATIVES

For FLC synthesis, a way to ensure stability is to employ stable control design methods. Several alternatives have been proposed for FLC. In the following a brief list of contributions is given.

PID-like FLC.

(Malki, et al., 1994): stable fuzzy PD; (Chen and Ying, 1997): the BIBO stability of nonlinear PI; (Sio and Lee, 1998): stability of fuzzy PID.

Mamdani FLC.

(Kania, et al., 1980; Langari and Tomizuka, 1990, 1993): FLC with internal dynamics. (Chen, et al., 1995) use a fuzzy relation matrix.

Takagi-Sugeno.

(Sugeno, 1999) presents an extensive survey on stable TS FLC designs.

Classic methods.

(Smith and Comer, 1992): cell state space. (Qin and Borders, 1994): multiregion. (Wang, 1994b): supervisory. (Hajjaji and Rachid, 1994): explicit formulas for FLC. (Galichet and Foulloy, 1995): synthesis and equivalences of FLC.

Adaptive.

(Wang, 1993, 1994a; Tsay, et al., 1999): stable adaptive fuzzy control. (Myung, et al., 2000): stabilization of adaptive FLC. (Lee and Vucovich, 2000): adaptive fuzzy control of nonlinear systems.

Gain-scheduling.

(Zhao, et al., 1993): fuzzy gain-scheduling of PID controllers. (Filev, 2000): gain-scheduling and TS FLC. (Rugh and Shamma, 2000) present a survey of the general topic (not only fuzzy) of gain-scheduling.

Model-based.

(Johansen, 1994; Feng, et al., 1997; Kiriakidis, 1998).

Parallel Distributed Compensation.

(Ma and Sun, 2000; Akar and Ozguner, 2000).

Sliding-mode.

One of the first contributions is (Hwang and Lin, 1992). (Suyitno, et al., 1993) show that sliding-mode FLC is superior to a sliding-mode controller + PID. (Palm, 1994) says most FLCs are similar to sliding-mode controllers, and that is the reason of their robustness. (Palm and Driankov, 1997) present a sliding-mode based stability analysis of fuzzy gain-schedulers. (Wang and Lin, 1998, 1999) use sliding-mode for tracking. (Tong, et al., 2000) propose an adaptive version, for MIMO nonlinear plants.

Feedback alternatives.

(Ma, et al., 1998): controller and observer. (Ying, 1999): feedback linearization, good discussion. (Cao, et al., 1999): fuzzy-state feedback. (Han, et al., 2000): dynamic output feedback.

Predictive systems.

(Batur and Kasparian, 1991): predictive fuzzy expert controller. (Setnes and Babuska, 2000): fuzzy modelling for predictive control.

(Skrjank and Matko, 1994, 2000; Valente de Oliveira and Lemos, 2000; Huang, et al., 2000)

Robust FLC.

(Zhao, et al. 1995): model-based TS FLC. (Jadbabaie, et al., 2000): observer-based, LMIs. (Mudi and Pal, 1999): self-tuning PID-like. (Kang, et al. 1998): TS model and feedback linearization. (Linder and Shafai, 1999) apply a TS FLC to the ACC Benchmark with good results. (Lam, et al., 2000): TS model of the nonlinear plant, FLC design based on LMIs; this paper presents an interesting review.

(Lo and Chen, 1999) use Kharitonov regions to design robust FLC. (Tanaka, et al., 1996a; Chen, et al., 1996, 1999) use $H\infty$ for TS FLC and nonlinear plant. (Chang, 2000) use $H\infty$ tracking theory and sliding-mode control for robust tracking of nonlinear MIMO systems.

Uncertain plants.

(Ying, 1994a): stable FLC for unknown model of the plant. (Teixeira and Zak, 1999): stable FLC for uncertain nonlinear plant.

Other.

(Langari, 1992, 1993; Lewis and Liu, 1994): nonlinear strategies. (Wang, 1999): automatic design of FLC.

5. MIXING OF FLC WITH GENETIC ALGORITHMS AND/OR NEURAL NETWORKS

Some additional background is needed for the next section. Let us include a succinct review of the hybridising of fuzzy logic, genetic algorithms (GA) and/or neural networks (NN).

The preferred optimization method for fuzzy logic control and modelling is the use of GA. Actually, GA can make easy the design of FLC (it can be used for automatized design). There is a lot of research on Genetic-Fuzzy combinations. (Cordon, et al., 1997) published a list of 345 research papers related to this. First contributions were made, with Mamdani FLC, by (Thrift, 1991; Karr, 1991a, b, c). One of the examples was the FLC optimization for a satellite rendezvous problem.

Fuzzy modelling of plants can be also subject to optimization. The book (Babuska, 1998) is useful to study this aspect.

An important research topic today is multiobjective optimization. Search-based methods are an usual way to attack this kind of problems (Ng, 1993). (Fonseca and Fleming, 1995, 1998a, b) present a review of evolutionary algorithms in multiobjective optimization, and develop a Pareto-based method. (Ziztler and Thiele, 1999) compare several evolutionary methods and propose a new Pareto-based method. (Obayashi, et al., 2000; Obayashi, et al., 2000) use parallel multiobjective GA for supersonic wing shape optimisation and the design of cascade airfoils. (Sefrioui and Periaux, 2000) develop a multiobjective GA based on Nash games; an example is given: the optimal design of a nozzle.

The application of multiobjective GA to FLC is studied by several papers. (Gacogne, 1997) about the Mamdani FLC. (Blumel, et al., 2000) use a multimodel approach and Mamdani FLC to design a missile autopilot.

Fuzzy systems can be made with neural networks. Neural networks are trainable, but cannot directly encode structured knowledge. Fuzzy systems do have structured knowledge. The idea is to build neuro-fuzzy systems combining both advantages: training and structure. Some important neuro-fuzzy controllers are FALCON (Fuzzy Adaptive Learning Control

Network) (see the book (Lin and Lee, 1996)). FBFN (Fuzzy Basis Function Network) (Wang and Mendel, 1992). and GARIC (Generalized Approximate Reasoning-based Intelligent Controller) (Berenji and Khedkar, 1992, 1993).

Some interesting contributions about neuro-fuzzy control are (Tanaka and Sano, 1995b) on frequency shaping of FLC using NN, (Kim, et al., 1995) on fuzzy net controllers design using GA, (French and Rogers, 1998) on I/O stability of neuro-fuzzy control, (Lin and Chung, 1999) on soft-switch of low level controllers, and (Neidhoefer and Krishnakumar, 2001) with 3 levels: NN for inverse model, GA and adaptive critics (they propose a near-autonomous aircraft).

Pertinent reference literature on these topics are the books: (Man, et al., 1999) on GA with applications, (Sanchez, et al., 1997) on GA+FLC applications, (Sutton and Barto, 1998) on reinforcement learning. In addition there are several survey papers: (Kaynak, et al., 2001) on sliding-mode control and artificial intelligence, (Kaelbling, et al., 1996) on reinforcement learning.

Concerning aerospace, the book (Dracopoulos, 1997) offer interesting pages on GA and NN applied to satellite attitude control, NN modelling of the Euler equations, inverse control reinforcement, satellite detumbling, and adaptive attitude control considering sensor noise. Likewise, (Fortuna, et al., 2001) propose a satellite attitude control with NN.

6. AEROSPACE APPLICATIONS OF FUZZY CONTROL

There are different types of control problems in aerospace. Most of them are related with regulation, path-planning and tracking. Some of the possible applications of control have been considered by FLC, others still remain open for FLC. This review will focus on three main problems: attitude control, rendezvous and re-entry.
In general, space systems and missions are complex: risks must be minimized in each part and level. Conventional bullet-proof control solutions are the favourite choice. Given a problem, advanced control techniques can be considered if they clearly offer advantages and/or conventional solutions cannot solve the problem.

The interesting facets of FLC are the following:

- Rules: good for supervisory control, gain-scheduling, sliding-mode, smooth switching, learning.
- Nonlinear action: optimization of energy/time, better transients, inverse control of nonlinear systems.
- Function approximation: modelling, adaptation, observer-based control.

6.1 Attitude Control.

There are several constituents in the problem of attitude control. There are many types of satellites, with different designs and missions. Let us take the case of a telescope: good regulation is required, but also fast attitude manoeuvres to change targets quickly. Other satellites obey to different requirements, for monitoring, communications, tracking, space exploration, etc. Attitude control is the same name for a variety of control problems.

Efforts of automatic control research, about attitude control, concentrate on energy/time optimization, gain-scheduling and adaptation for large-angle manoeuvres, linearized feedback, predictive control, sliding-mode control, robust control, nonlinear control, high-precision regulation, singularity avoidance, underactuated systems. It is interesting to note that it has been shown (Piper and Kwanty, 1992) that attitude can exhibit complicated behaviour.

The field of attitude control offer good opportunities for FLC, at least following and improving the alternatives considered by the previous research. In particular, FLC can apply optimal nonlinear control, and the hybridising with GA and NN can be useful for adaptation/learning.

Actually, the literature on FLC and aerospace offer two types of contributions on attitude control: pure FLC, and neuro-fuzzy. Examples of pure FLC are (Steyn, 1994) that designs a stable FLC for the nonlinear plant with constraints, the result is compared with an adaptive LQR, and the FLC is better; (Satyadas and Krishnakumar, 1997) that present a GA-optimized attitude FLC; (Nam and Zhang, 1997) that present a fuzzy MIMO control of a flexible spacecraft; (Chen, et al., 2000) that design a mixed H_2/H_∞ adaptive FLC, using a dynamic game approach, and study an application example.

Interesting contributions with neuro-fuzzy control are (Berenji, et al., 1994). applying GARIC to the Space Shuttle, (Schram, et al., 1994) on robust control with Fuzzy CMAC, and (van Buijtenen, et al., 1998) on adaptive TS FLC with reinforcement learning (the final limit cycle of the attitude is reduced).

6.2 Rendezvous.

The rendezvous of satellites follows a sequence of phases: homing, closing, final approach, docking and structural latching. Guidance, attitude, manoeuvres, precision are the main points of the control problems involved. In practice manual control is, at least in some moments, applied. The desire is to get a complete autonomous operation.

Research on this field began with optimization purposes. Several control and guidance strategies have been studied, such sliding-mode, range-rate nonlinear algorithm, and feedback subject to constraints.

Simple FLC solutions have been proposed by (Lea, 1988) for the proximity operations, (Krishnakumar, et al., 1995) doing a FLC synthesis via pilot modelling, and (Brown, 1997) with an improved pilot model. This is in consonance with the specific capabilities of fuzzy logic to easily capture expert knowledge.

Genetic Algorithms have been applied to optimize the FLC control of satellite rendezvous. This is one of the examples taken by the first contributions on GA and FLC (Karr, et al., 1989, 1990, 1997). Likewise, (Gopalan, et al., 1995) apply GA and FLC for autonomous rendezvous and docking; (Ortega and Giron-Sierra, 1998) consider this problem including smooth operation.

6.3 Re-entry.

Of course, re-entry refers to coming back to the Earth surface. This is the case of Space Shuttle and other vehicles. The atmosphere put important difficulties to be overcome by a careful trajectory optimization and control design (good tracking, heat and acceleration limits). Other related problem is the entry in other atmospheres (if any) when exploring planets.

The research literature on the topic covers many control alternatives. Optimization for tracking; feedback linearization; scheduling; nonlinear control with inverse dynamics. Other kinds of control approaches: adaptive, sliding-mode, predictive, robust. Some of the studies are devoted to specific cases, such the entry of X-33, or the flight of the X-38. It is worth to mention the work of (Shin, et al., 2001) with a worst-case analysis.

FLC contributions in this are the following. About atmospheric re-entry: (Bikdash, et al., 1999, 1997) propose a fuzzy guidance of the Space Shuttle using a TS FLC with an on-line optimizer. About flight control: (Fujimori, et al., 1999, 1998) design a fuzzy gain-scheduling, which is better than LQ; (Nho and Agarwal, 2000) design a FLC for aircraft landing.

Apart from the FLC applications mentioned above, there are others related to intelligent sensors, fault-diagnosis, training of operators and pilots, specific control loops, etc.

7. CONCLUSIONS:

A reason that prevents engineers to use FLC is that it is supposed stability cannot be guaranteed. Part of this paper is devoted to show that now there are methods for stability analysis and design of FLC.

It is expected more aerospace applications of FLC in the future. Mainly because the general trend to autonomous systems. The recent advent of university satellite research, may be also an opportunity to consider and apply advanced control strategies.

ACKNOWLEDGMENTS

The authors wish to thanks the support of the European Space Agency: Research Project ESTEC/Contract no. 14099/99/NL/MV.

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