Tools and Methods for Spacecraft Control Systems: A Geno-Fuzzy Approach

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ABSTRACT

The goal of the paper is to analyze which computational methods and modeling tools based on Fuzzy Logic helped by Genetic Algorithms are available right now. The emphasis is put on the analyses and design of spacecraft control systems due to its complexity.

A spacecraft control system measures the position and attitude of the craft and produces guidance and rotation commands to place it in a specific orbit and with a specific orientation. Spacecraft control units are complex systems difficult to handle during the analysis and design phases of the engineering life cycle.

The article describes who-is-who in the development arena of the support tools and methods, which commercial products are available, and which of them are freely obtainable.

The state of the art is presented, and the advantages and disadvantages of each system are carefully examined from a critical point of view.

1. FUZZY LOGIC AND GENETIC ALGORITHMS FOR SPACECRAFT CONTROL

For a relatively small servicing spacecraft, the control requirements demand a high degree of uncertainty in critical vehicle parameters like total mass, feed-forward thrust impulses, moments of inertia, center of mass, etc. These requirements are translated into huge complexity during the design phase: the navigation block is based on complicated filtering schemes, the guidance block is made of parameter tables of considerable size, with contingency recovery situations, and the control block must be designed using multiple input-output techniques for a six-degree-of-freedom vehicle. Much of this complexity in the design of the control system comes from the way in which the variables of the system are represented and manipulated.

In the search for an easy, efficient, cost-effective control design and development technique, fuzzy logic (FL) seems to provide a method of reducing system complexity while increasing control performance. Fuzzy set theory was originally introduced by Prof. Zadeh in 1965 [12][13]. Since then, many researchers have introduced fuzzy logic techniques to solve different types of control problems [3][4]. The ability to model problems in a simple and human-oriented way [9][26], and the ability to produce smooth control actions around the set points makes fuzzy logic an especially suitable candidate for use in space applications [17][20][21][23].

While the fuzzy controller deals with the uncertainty of the model of the vehicle, the genetic algorithm tries to optimize the controller for a particular constraint. The controller will try to cope with the nonlinear equations of motion of the spacecraft dynamics and kinematics, and the imperfections in sensors and actuators.

Fuzzy systems have two parameters, which can be optimized: a rule database and the fuzzy sets. Two approaches can be taken to obtain an optimum solution: either using the heuristic method, in which the control engineer obtains the best system to satisfy the criteria, or by finding an analytical solution to the problem. On most occasions, the design of the optimum system requires the knowledge of an expert operator.

Many recent publications have demonstrated the possibility of optimize those parameters automatically (analytically) by means of genetic algorithms (GAs) [1][7][14]. Genetic algorithms were introduced 30 years ago, but only recently have they been recognized as a promising technique to optimize these types of functions. GAs are optimization methods based on natural evolution. They are easy to apply, and they perform fast in comparison with the CPU computer consumption of other alternatives [16][18][22][27].

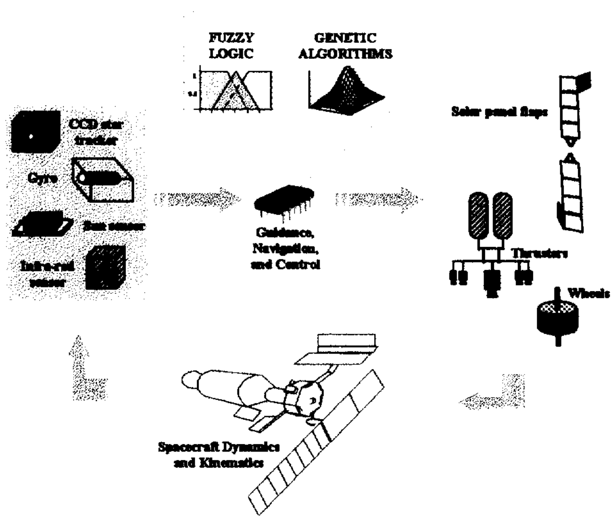

Figure 1

2. METHODS, TOOLS, AND STANDARDS

Geno-fuzzy computational methods and modeling tools to help in the design and development of spacecraft control units are of primary importance to both, the control engineer and the spacecraft project manager. Methods and tools will allow the spacecraft engineer to speed up the design and development cycle. They will also allow the project manager to cut down in development time and manpower cost. Standards and conventions allow interchange of ideas, methods, and tools among working teams.

Figure 2 represents the cycle followed by the control engineer to design a spacecraft control system. This design is the so-called classical one. This type of design cycle is used with the control methods like robust eigenvalue assignment, Linear

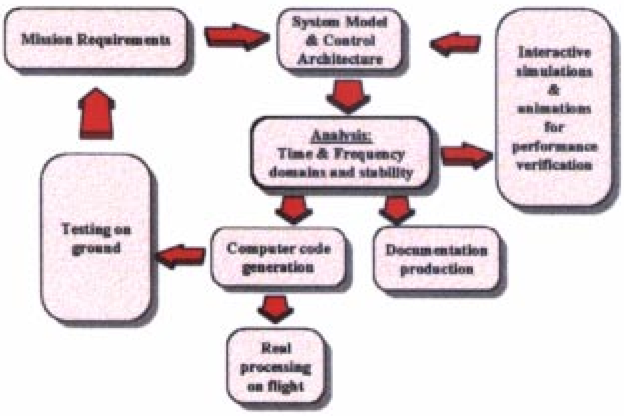

Figure 2

Quadratic (LQ) method, etc. [5][6].

Figure 3 represents the cycle followed by the control engineer when using fuzzy logic [25]. Comparing figure 2 with figure 3 is possible to see the matches between both techniques.

The mission requirement part can be compared to the study of the physics of the problem. In both cases the control engineer has to study the problem.

Next, the engineer has to come up with a model of the plant and the corresponding control architecture. The analysis of the stability of the controller is an important step in the robust control techniques scheme [8][11][15]. The simulations are a well-proven tool for the design and soft testing of controllers: this step can be applied to both, classical robust control techniques and FL based techniques. The testing on ground is the ultimate integration, validation, and verification tool for control design. Again, this step can be applied to both, classical robust control techniques and FL based techniques [10][19].

Nowadays, the computer code generation and the production of the associated documentation are steps, which required the help of a computer. Most robust control design techniques are helped by Computer Assisted design Tools (CSDT). Section 4 of this article will deal with the introduction on the market of CSDT tools using fuzzy logic and optimization methods.

Methods. By methodology is understood a collection of methods and procedures to design, construct, verify, and test a spacecraft control system.

Tools. By tools is understood a set of computer routines to aid and help in each of the tasks mentioned in the previous point.

Standards and conventions. This is defined as a group of rules and regulations to apply when designing, building, and testing the controller. The standardization helps when different engineering groups must share a common framework [2].

Figure 4 shows the key cornerstones of methods, tools, and standards in the FL-GAs control design and development technique.

A methodology to design and build FL-GAs controllers should include among others, the following elements:

- Guides to requirement management, analysis, design, and verification of FL-GAs based systems.
- Guides to apply software engineering standards to the coding phase (easy if automatic code generation is possible).
- Guides for quality assurance and test procedures.

A good tool for FL-GAs controller development would include the following elements:

- Creation and modification of universe of discourse, fuzzy sets and membership functions graphically.
- Automatic generation of rules databases based on state variables.
- Available library for most partial common control problems; the user can pick up some building blocks and construct a bigger controller from them.
- Automatic optimization of membership functions and rule databases based on parametric probabilistic problem characteristics; the user can select the probabilities of crossover, mutation, and reproduction, and change them if necessary.
- Automatic generation of a fitness function to match a particular problem.
- The automatic generation of code in C, FORTAN, Ada, etc.
- The generation of documentation, and the control of the revisions of the documents.

The goal of standards and convention is to facilitate trade, exchange and technology transfer among engineering teams across the world. The standardization and the establishment

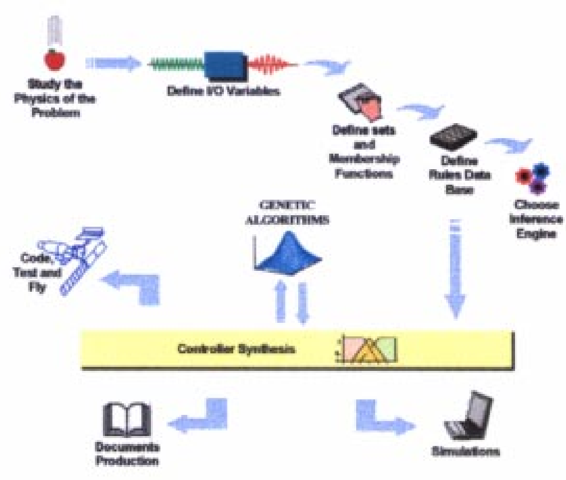

Figure 3

of conventions would allow, among others: the unique labeling of designations, units, and symbols used, and the production of glossaries and thesaurus of FL and GAs terms.

FL-GAs systems will be chosen as alternative control design technique if they can prove that are less expensive, while maintaining the controller within the prescribed requirements.

A design control technique is less expensive than others when it keeps the development team size small and the development and validation time short. By opposition, a design control technique become expensive when there are few or none existing tools available to help in its implementation, when the technique is difficult to understand, and the learning curve is pronounced, or when the output of the design does not meet the specifications, and multiple iterations are needed.

3. WHO IS WHO

To be able to write this article, it was conducted a market research of fuzzy logic design and development tools. This research included questions like the nature and purpose of the tool, output, availability, price, suitability for space applications, etc.

Late in this section, the topic discussed in section 2 is explored, trying to match the tools mentioned here with suitability to methods, standards, and conventions.

The number of tools analyzed here are numerous (see table 1). Most of them are commercial, and few of them are freely available. This relative high number of applications has been interpreted as an on-going maturity process in the marketplace. In comparison, few years ago, the number of available tools was much reduced and most of them were freely obtainable. This means that now commercial companies are seen fuzzy logic as a potential good market. This can further be interpreted as a starting success of fuzzy logic as common, easy, control problems solver.

Table 1, represents a snapshot of the available tools in the market. Mainly, companies from USA, Germany, and UK are now developing this kind of applications. The range of platform varies, but mainly the target is focussed in the PC market.

The available columns in table 1 detail the product name, the company which supplies the product or the name of the developer (if the product is for free). The table also shows, the output, the optimization help (Opt.) if any, the suitability for space control applications (Spac.), the operating system used (OS), and the price.

Nearly all products are development environments. That is, they allow the user to design, develop, and test a system controlled by fuzzy logic sets and rule databases. The input is the block design of the system to control. The output varies, but most of them are able to generate C-code automatically or MATLAB® m-files, for further processing [24]. The Educational Fuzzy Control Package is a software suitable for educational purposes which will be welcome for new comers wanting to know the principles of FL over the computer.

Few products are targeted to generate assembler code automatically (FLASH, FIDE). This is particularly useful when the code will be inserted into the EPROM of a micro-controller.

Table 1 shows also the suitability of the products when applying to spacecraft control systems.

Not mentioned in table 1 are other products like the fuzzy logic toolbox from Boeing for their Easy-5 tool, or the fuzzy logic toolbox from Mathematica (Wolfrang Research). These are also excellent products, and available for a wide range of platforms.

Nearly all development environments allow the creation of universes of discourse, fuzzy sets, and membership functions for a particular problem (CubiCalc, A-B FLEX, Fuzzy Control Manager, MATLAB ToolBox, FUZZLE, etc.). However, none of them contain a repository of already solved problem as example, or blocks ready to use to construct more complex problems. This can be due to the raising use of FL in the market in this moment.

From the point of view of the optimization, only one tool (the FL ToolBox of MATLAB®) is able to perform optimization. However, the method is not based on genetic algorithms but ANFIS. None of the systems presented here uses genetic algorithms as optimization tool. The combination FL-GAs is still far from being standard. However, a genetic algorithms toolbox is freely available for MATLAB®.

Most of the products have targeted the output as C-code (CibuCalc, FUZZLE, fuzzyTECH, FuzzyCLIPS, FIDE, AB-FLEX, etc.). This means that the code generated can be integrated in an already C-coded system with little difficulties. However, none of the packages described here are able to generate Ada code. Ada code is well appreciated in a good number of spacecraft control problems (civil and military).

Product	Company	Output	Opt.	Spac.	OS	Price
CubiCalc	Hyperlogic (USA)	C code	No	No	Win 3.1	$2000
DataEngine	Management Intelligenter Technologien GmbH (Germany)	Visual Plots	No	No	Win95, WinNT	DM5990
Fuzzy Control Package	Bytronic International Ltd. (UK)	Educational package	No	No	Win95	Upon request
LPA Fuzzy Logic	Logic Programming Associates Ltd.	Visual plots	No	No	Win, Mac, Unix	Upon request
FUZZLE	MODiCo, Inc. (USA)	C or FORTRAN code	No	No	Win95	Upon request
fuzzyTECH	INFORM GmbH (Germany)	MATLAB m-files, C code, Embedded control for specific marteted controllers.	No	No	Win95 and WIN NT	Upon request
Matlab Fuzzy Logic ToolBox	The MathWorks, Inc. (USA)	C code	Yes	Yes	Win, Mac, Unix	Upon request
FuzzyCLIPS	Togai InfraLogic, Inc (USA)	C code	No	No	Windows, MAC, UNIX	Upon request
Fuzzy Control Manager	TANSFERTECH (Germany)	C code, plots	No	No	Win 95	DM 3100
Fide	Aptronix, Inc. (USA)	Java, C code, MATLAB m-files, and assembly code	No	No	Windows 3.0	Upon request
A-B FLEX	Global Technical Services (USA)	MATLAB m-files, C code	No	No	Win95	Upon request
FLDE	Syndesis, Ltd (USA)	MATLAB m-files, C code	No	No	Win95	Upon request
FlexTool	Flexible Intelligence Group, LLC. (USA)	Visual plots	No	No	Win95	$1.000
FLASH	Rigel Corporation (USA)	Assembler code	No	No	Unknown	$100
FISMAT	Prof. Zadeh (USA)	Plots	No	No	Win, Mac, Unix	free
Xfuzzy	IMSE-CNM (E)	Plots			Unix	Free

Table 1

Some products have targeted the output of their environments as MATLAB® m-files. This makes sense with the user has already this software or he/she is targeting to perform simulation under this system.

Special mention has to be made to the free products listed here. Those can be a very good alternative to commercial systems, and certainly will be very helpful for a starting point in the development of FL control systems: FISMAT, and

Xfuzzy. FISMAT is a MATLAB® ToolBox developed by Prof. Zadeh. It was developed to foster the development of FL as alternative in control problems. Quite successfully, it can be freely used and it is suitable for an enormous kind of problems. Xfuzzy is a recent initiative from the University world. It is able to handle medium size problems with a quick response. It does run in all known UNIX systems. The source code is available.

4. THE FUTURE OF GENO-FUZZY TECHNIQUES

The future of the applicability of geno-fuzzy tools and techniques in the aerospace industry is still unclear. It is true every day there are more and more tools on the market. Fuzzy logic is arising as a cheap-fast-better alternative to common control problems. The extrapolation of this scenario to the spacecraft control problem is not immediate.

Spacecraft control engineers and project managers are rather conservative in exploring new methods or alternatives. In addition, fuzzy logic based spacecraft control systems have to be very well proven on-ground before committing to the flight.

The market place is still quite young: diversity of tools with different scopes, enormous range of prices, lack of highly desirable features.

Spacecraft program managers will not employ FL-GAs techniques in their projects unless they are proven to be cheap, safe, and able to satisfy the agreed control specifications. Spacecraft control engineering teams will not employ FL-GAs techniques unless they are proven to be efficient, easy to use,

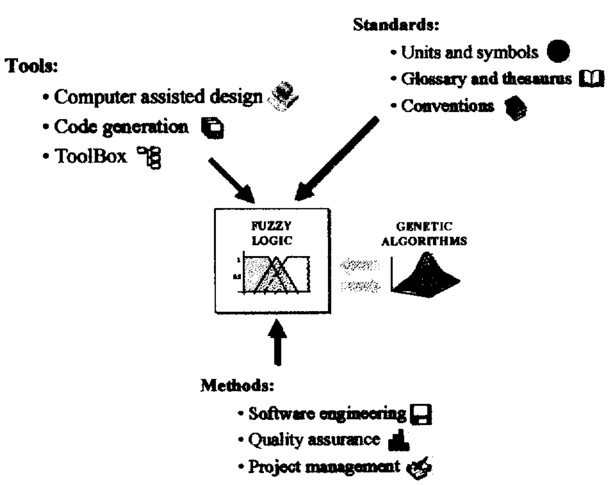

Figure 2

and secure.

One of the directions in which the market place could mature is the establishment of the mentioned methods, standards, and conventions. Once methods and conventions are agreed by the FL community, tools developers will have a clear direction for the investment on the development effort. The initiative to establish these methods and conventions must come from a well-recognized authority and must be endorsed by good reputation institutions.

5. CONCLUSIONS

In the search for an easy, efficient, cost effective, control design and development technique, fuzzy logic seems to provide a method for reducing system complexity while keeping control performance.

Since the publications of professor Zadeh [7][8], many researchers have introduced fuzzy logic techniques to solve different types of control problems. The ability to model problems in a simple and human oriented way and the ability to produce smooth control actions around the set points makes fuzzy logic an especially suitable candidate for space applications.

The article aimed at presenting a snapshot of the current tools and development environments for control problems solving using fuzzy logic. The introduction of genetic algorithms as tool for optimizations is also considered.

The market place is still young and immature. Methods, standards, and conventions need to be established to allow the tool developer to reach a good level of usefulness, performance, and reliability.

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