AN INITIAL SURVEY OF FUZZY LOGIC MONITORING AND CONTROL UTILISATION IN MEDICINE

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ABSTRACT: Intelligent systems have appeared in many technical areas, such as consumer electronics, robotics and industrial control systems. Many of these intelligent systems are based on fuzzy control strategies which describe complex systems mathematical model in terms of linguistic rules. Since the 1980s new techniques have appeared from which fuzzy logic been applied extensively in medical systems. This paper surveys the utilisation of fuzzy logic control and monitoring in medical sciences.

KEYWORDS: Fuzzy logic, fuzzy control, therapy, treatment, medicine, healthcare, survey.

INTRODUCTION

The last couple of decades have witnessed a significant developments in control systems theory. In the meantime, developments in electronics and computers have resulted in many application areas of control theory. Although medicine is a science which is not related to control engineering, it is being affected to such an extent that it is now possible to use available control techniques for on-line devices, especially during surgical operations and in intensive care units. The current applications area of control engineering in medicine constitute a wide spectrum ranging from simple dosage prescription schemes to highly sophisticated adaptive controllers.

In medicine, the principle of “measuring everything measurable and trying to make measurable that which has not been measurable so far” (Galileo) is still practised, nevertheless, some fundamental limitations have already being recognised. Real world knowledge is characterised by incompleteness, inaccuracy, and inconsistency. Fuzzy set theory, which was developed by Zadeh (1965), makes it possible to define inexact medical entities as fuzzy sets. It provides an excellent approach for approximating medical text. Furthermore, fuzzy logic provides reasoning methods for approximate inference.

This paper presents an initial survey of the utilisation of fuzzy logic control and monitoring in medicine based on National Library of Medicine (UAS) and INSPEC. The word “fuzzy” was used with “control or treatment or therapy or planning” The survey uses longitudinal rubric (time scale) as well as transversal rubric (intellectual connectivity of medical disciplines).

FUZZY CONTROL AND MONITORING IN MEDICAL FIELDS

Imprecisely defined classes play an important role in human thinking. Fuzzy set theory derives from the fact that most natural classes and concepts are fuzzy rather than crisp nature. On the other hand, people can approximate well enough to perform many desired tasks. The fact is that they summarise from massive information inputs and still function effectively. For complex systems, fuzzy logic is quite suitable because of its tolerance to some imprecision. In the following sections a brief description is given of the key contribution which fuzzy control, estimation, and measurements technology have made in each of the topics which have been identified in a medical literature search.

CONSERVATIVE DISCIPLINES

Conservative medicine can be classified into the following disciplines: internal medicine, cardiology, invasive care, paediatry, endocrinology, oncology gerontology, and general practice. The literature search only found limited application of fuzzy control mostly in general practice and cardiology. Fuzzy logic is utilised for improved monitoring in pre-term infants (Wolf et al, 1996).

INVASIVE MEDICINE

The invasive medicine field involve surgery, orthopaedics, anaesthesia, and artificial organs. The field of surgery is very wide as many factors contribute to it such as diagnostics, image processing, pathophysiological reasoning, and anaesthesia control. In anaesthesia, many applications have been reported in the use of fuzzy logic to control drug infusion for maintaining adequate levels of anaesthesia, muscle relaxation, and patient monitoring and alarm. In the field of orthopaedics, there has been no reported application of fuzzy control.

The field of anaesthesia is where most of the applications of fuzzy control have been reported. It involves monitoring the patient vital parameters and controlling the drug infusion to maintain the anaesthetic level constant. It includes depth of anaesthesia (Abbod and Linkens, 1998), muscle relaxation (Linkens and Mahfouf, 1988; Westenskow, 1997), hypertension during anaesthesia (Oshita, 1993), arterial pressure control (Zbinden et al, 1995) and mechanical ventilation during anaesthesia (Schaublin et al, 1996), and post-operative control of blood pressure (Ying and Sheppard, 1994).

Different methods have been used which utilise fuzzy logic, the first being a real-time expert system for advice and control (RESAC) based on fuzzy logic reasoning (Greenhow et al, 1992). Later examples involve a basic fuzzy logic controller (Linkens and Mahfouf, 1988), self-organising fuzzy logic controller (Linkens and Hasnain, 1991), and hierarchical systems (Shieh et al, 1999),.

Most of the fuzzy logic control applications in the field of artificial organs are concerned with artificial hearts. A fuzzy controller has been implemented for adaptation of the heart pump rate to body perfusion demand by pump chamber filling detection (Kaufmann et al, 1995). Another more advanced system based on neural and fuzzy controller for artificial heart was developed by Lee et al (1996). Future prospects for cardiac assist patients involving fuzzy logic was described by Mussivand (1998).

REGIONALLY DEFINED MEDICAL DISCIPLINES

There are different fields which belong to regionally defined medical disciplines: gynaecology, dermatology, dental, ophthalmology, otology, rhinology, laryngology and urology. Although there are many application fields, the literature search has only resulted in a single application of fuzzy inference to dental medicine. Although the application is not directly related to control, it utilises fuzzy inference for personal identification / sex determination from teeth (Takeuchi, 1993).

NEUROMEDICINE

Neurology, psychology, and psychiatry are the sub-subjects of the neuromedicine field. The neurology sector did not score literature on fuzzy control. In psychology, there has been modelling of the functional status of a human operator based on fuzzy logic which is used to predict and evaluate the operators behaviour (Astanin, 1989). Also, fuzzy logic was used to analyse the effect of face expression on speech perception in direct communication (Massaro and Cohen, 1996). The prediction of patient response to new pharmacotherapies for alcohol dependence has been measured using fuzzy logic since it has been not successful using standard statistical techniques (Naranjo et al, 1997).

In the field of psychiatry, a complex psychiatric computer expert system, including functions that help the physicians and the hospital staff in the administrative, diagnostic, therapeutic, statistical, and scientific work has been developed (Kovacs and Juranovics, 1995).

IMAGE AND SIGNAL PROCESSING

Image and signal processing are mainly concerned with signal processing, radiation medicine, and radiology. The application of fuzzy control is divided into two sections, control and monitoring. Most of the applications have been concerned with signal processing. The first application is a combined fuzzy monitoring and control of the electrical and chemical responses of nerve fibres (al-Holou and Joo, 1997). Another application is the automation of matrix-assisted laser desorption/ionization mass spectrometry using fuzzy logic feedback control (Jensen et al, 1997). Fuzzy feedback control was implemented for artificial ventilation of lungs (Vasi'leva et al, 1989). On the monitoring side, fuzzy signal processing has been implemented in many applications such as sleep monitoring (Gath et al, 1983), monitoring of preterm infant (Wolf et al, 1996), clinical monitoring of disease progression (Steimann, 1996), and analysis of eyes movements (Allum et al, 1998).

Radiation medicine is mainly concerned with tumour monitoring and quantification. Fuzzy clustering is used to analyse magnetic images of tumour response to therapy (Vaidyanathan et al, 1997; Velthuizen et al, 1995). In another application, high energy radiotherapic images with poor quality, have used a fuzzy image enhancing process (Krell et al, 1998). Lastly, a two dimensional image restoration technique using fuzzy logic was developed for diagnostic and treatment planning for radiation therapy (Butt et al, 1998).

LABORATORY

The only direct application of fuzzy control strategies was the application of pH-state to fed-batch cultivation of genetically engineered Escherichia coli. The control of the substrate concentration at an appropriate level was sought in order to avoid the accumulation of acetate, thereby elevating the expression level of plasmid-encoded protein (Jin et al, 1994).

Analysis and interpretation of laboratory data sets was the other indirect application of fuzzy logic. Two typical applications are: interpretation of pathophysiology by laboratory data (Shimizu et al, 1990), and analysis of the variations of clinical test data on fasting therapy using a fuzzy similarity dendrogram (Arimo et al, 1993).

BASIC SCIENCE

Basic science consists of different categories: medical information, anatomy, pathology, forensic medicine, genetics, physiology, pharmacology, and education. The use of fuzzy logic in medical informatics began in the early 1970s. Recent work on fuzzy controllers is more concerned with stability, self-organising, and synergies with other computing techniques such as neural network and genetic algorithms. Management and retrieval of information using fuzzy logic is one of the possible application discussed by Chiodo et al (1994).

In the fields of anatomy, pathology, forensic medicine and genetics, there are many application of fuzzy logic mostly based on image analysis and fuzzy clustering. In pathology, an expert system was used based on fuzzy logic for reasoning with uncertainties in selecting treatment strategy suitability (van Ginneken and Smeulders, 1991). In forensic medicine, fuzzy logic was used to personal identification (sex determination) from teeth (Takeuchi, 1993). In genetics, fuzzy logic has been used to develop control strategies for the application of pH-state to fed-batch cultivation of genetically engineered escherichia coli (Jin et al, 1994).

In pharmacology and biochemistry, fuzzy logic prediction was used for the rodnet carcinogenicity of organic compounds using a fuzzy adaptive least squares method (Moriguchi et al, 1996). In education, the use of fuzzy logic has different facets. Fuzzy mathematics was utilised for evaluating the teaching of students in a clinical setting (Chen, 1996). Evaluation of the self-taught ability of nursing administrators with fuzzy medicine was also reported (Wang and Sun, 1996).

HEALTHCARE

There has been a growing interest in healthcare among many people. Some topics related to healthcare are: drinking water quality, driving fatigue, health risks in work environment (Genaidy et al, 1998), and healthcare organisations.

During the management process in health organisations, certain situations can arise when data necessary for decision-making is in fuzzy form. As an example, the problem of resource allocation among consulting rooms in the outpatient division of one hospital in Tbilisi was chosen. The aim is to minimise patients' queues as well as physicians' idle time (Kachukhashvili et al, 1995).

FUZZY CONTROL TECHNIQUES

Various therapeutic situations are related to control problems. Although the early medical systems appeared at the same time as the article by Zadeh (1965), there has been little communication between the research fields, but recently this has changed due to the developments in computer systems, and rapid development of the literature searching methods motivated by the internet and the World Wide Web. Many systems are being developed which utilise fuzzy logic and fuzzy set theory.

FUZZY CONTROL SYSTEMS

Rule-Based Open-Loop Systems

Deterministic open-loop fuzzy control approaches have been proposed in many applications. Generally, in open-loop configuration, it is assumed that the pharmacokinetics relationships can be modelled exactly by a linear system with known parameters. Open-loop fuzzy control is based on a different approach. Rather than assuming the patient model is known, the physiological behaviour is modelled using control rules and actions. Most of the controllers are advisory systems. In healthcare, the "heaviness" is defined by mean of fuzzy sets for advising workers how heavy their load is (Genaidy et al, 1998). Also, fuzzy control was used to develop a computer-based system for control of oxygen delivery to ventilated infants (Sun et al, 1994). An open-loop system for treatment of diabetic out-patients was developed for calculating the insulin dose (Stadelmann et al, 1990; Kokutei et al, 1993). Advisory expert systems can also be considered as an open-loop controller for advising on drug administration in general anaesthesia (Greenhow et al, 1992).

Rule-Based Closed-Loop Systems

Closed-loop control in medicine emerged as a serious contender for many forms of control in late 1970s. It was pioneered by Sheppard et al (1997) and Asbury et al (1980) when they demonstrated through clinical experiments that this form of control is safe, effective and in many cases better than manual control. Closed-loop control methods can be divided into two groups: adaptive and non-adaptive. In a following section, more details are given of the different types of closed-loop controllers.

FUZZY TECHNIQUES FOR BIOMEDICAL DATA ANALYSIS

Fuzzy Clustering

Clustering algorithms are mainly concerned with partitioning the data into a number of subsets. Within each subset, the elements are similar to each other. On the other hand, elements from different sets are as different as possible. There are different fuzzy clustering techniques based on unsupervised learning such as relation criterion functions, object criterion functions, c-means clustering, etc. Most of the clustering techniques are being applied to diagnosis. C-means clustering was applied for brain injury using magnetic resonance images (Thatcher et al, 1997), and tumour measurement in response to treatment (Velthuizen et al, 1995, Viadyanathan et al, 1995).

Fuzzy Classification

Classification differs from clustering by the labelling method, the former giving a label to each data set, while in the latter method a label is given to each data set. Supervised learning is usually used for classification. Most of the fuzzy classification applications occur in the psychology field (Massaro and Cohen 1996; Massaro et al, 1996). There are also forensic application (Takeuchi, 1993), and classification of pathophysiology laboratory data (Shimizu et al, 1990).

Fuzzy Modelling and Identification

Fuzzy logic models can be developed from expert knowledge or from process (patient) input-output data. In the first case, fuzzy models can be extracted from the expert knowledge of the process. The expert knowledge can be expressed in terms of linguistics, which is sometimes faulty and requires the model to be tuned. Therefore, identifying the process is a more attractive way using the help of expert knowledge. This process requires defining the model input variables and the determination of the fuzzy model type. There are two ways to develop a fuzzy model, the first beings based on defining the initial parameters of the model (membership functions) and selecting the rules construction method (if-then). Neurofuzzy algorithms are often used for the tuning of parameters (Bleckert et al, 1998, Ashford et al, 1995). The second method is used if there is no knowledge about the process, when the rules and membership functions can be extracted directly from the data by clustering the input / output space (Velthuizen et al, 1995).

FUZZY METHODOLOGIES

Basic Controllers

Fuzzy rule-based systems include many aspects of fuzzified values, such as the rules antecedents and consequence. The rules structure are usually of the form *if .. then*. In its basic form this type of control is equivalent linguistically to a PI controller, and depending on the output, whether it is incremental or absolute, the controller is known as PI or PD respectively. An example of such a rule is *if the blood pressure is above the target and decreasing slowly, then reduce the drug infusion.* A more sophisticated structure is a PID, where the input, its derivative, and integral are considered as three inputs. The rules are composed either from the expert (anaesthetists) or crafted by hand depending on the experience of the programmer. This includes tuning the membership functions in terms of the shape, width and position. This type of controller is widely used and is the most applicable control type in anaesthesia (Derrick et al, 1998).

Self-learning Systems

Self-learning systems are concerned with the control of systems with unknown or time varying structure or parameters. The self-organising fuzzy logic controller has the ability to realise adaption by building its fuzzy rules on-line as it controls the process, altering and adding as many rules as it judges necessary from off-line criteria. This approach has many successful applications in the control of muscle relaxation (Linkens and Hasnain, 1991), and simultaneous control of blood pressure and muscle relaxation (Linkens, 1994).

Model Based and Adaptive Systems

Model-based and adaptive systems are most successful when a physician plays a part in the closed-loop. The adaptive scheme play an important role in adapting the controller to changes in the process (patient) and its disturbances. Fuzzy modelling and control are often based on qualitative assessment of the patient condition using fuzzy inductive reasoning (Nebot et al, 1998, Nebot et al, 1996). A self-adaptive fuzzy controller with reinforcement learning is yet another technique applied to simulation of a paraplegic standing up (Davoodi and Andrews, 1998). Even for patient monitoring, adaptive controllers are being utilised for intelligent monitoring of diabetic patients (Bellazzi,et al, 1995).

Hybrid Systems (Neural, Genetic and Wavelets)

Reasoning with fuzzy logic is possible without the need for much data because the backbone of the logic is expressed as *if-then* rules. However, the rules cannot be expressed unless the logic is defined, when there are unknown logical relationships. Thus attempts are being made to combine different techniques such as neural networks and genetic algorithms, with fuzzy logic organising the mapping relationship by learning. Neurofuzzy networks were developed by fusing the ideas that originated in the fields of neural and fuzzy systems (Brown and Harris, 1995). A neurofuzzy network attempts to combine the transparent, linguistic, symbolic representation associated with fuzzy logic with the architecture and learning rules commonly used in neural networks. These hybrid structures have both a qualitative and a quantitative interpretation and can overcome some of the difficulties associated with solely neural algorithms which can usually be regarded as black box mappings, and with fuzzy systems where few modelling and learning theories exist. Many applications are being reported using fuzzy-neural control (Lee et al, 1996) and modelling (Linkens and Abbod, 1999).

Although writing fuzzy rules is easy, specific forms of membership functions are much harder to derive. In this case a genetic algorithm (GA) is used to adjust the membership function towards convergence. GA are exploratory search and optimisation methods that were devised on the principles of natural evolution and population genetics. Modelling clinical data can be achieved using genetic-fuzzy logic technique (Linkens et al, 1999).

Cascading two techniques is another approach to hybrid fuzzy control, for example by using the discrete wavelet transform analysis to extract features from the clinical data, then feeding the features to a fuzzy logic systems (clustering or neurofuzzy) to extract the final output (Linkens et al, 1997). This methodology was also applied for forecasting generalised epileptic seizures from the EEG signal by wavelet analysis and dynamic unsupervised fuzzy clustering (Geva and Kerem, 1998).

Hierarchical and Supervisory Systems

A totally fuzzy-logic-based hierarchical architecture for manipulating procedures on a complex process (i.e. the patient) has been developed (Shieh et al, 1999). The novel hierarchical architecture for fuzzy logic monitoring and control of intravenous anaesthesia has two main objectives: the primary task is to utilise auditory evoked response signals for augmenting cardiovascular and body function signs into a multi-sensor fuzzy model-based strategy for anaesthesia monitoring and control,. The secondary task is to extend an existing fuzzy patient model for use as a training simulator.

As for supervisory control, a multiple drug haemodynamic control system by means of a fuzzy rule-based adaptive control system has been developed for controlling the mean arterial pressure and the cardiac output. Supervisory capabilities are added to ensure adequate drug delivery (Held and Roy, 1995).

DISCUSSION

This survey was conducted in order to establish a roadmap that is able to forecast the future developments of fuzzy control and monitoring technology in medicine and healthcare. The medical activities have been divided into fields, each of which is further divided into special applications that belong to each field. A total of 34 sectors were defined. These sectors are organised in a hierarchical scheme according to the medical procedures. This means that significant methodologies relationships and demands can be correlated. This scheme substantiates the hypothesis that a successful application in one sector should lead to a successful application in the neighbouring sector.

The information gathered in this study are arranged according to its time of publication with respect to the medical sectors as shown in Table 1. This will substantiate the actual state-of-the-art, and also the dynamic process of the information in each sector can be determined. Table 2 considers the type of fuzzy technology used in medicine and healthcare arranged according to its time of publication. This shows the type of fuzzy technology developments in the field of medicine during the last decade. Merging Tables 1 and 2 will give an overview of the type of fuzzy technology applied in each medical field. Table 3 shows this correlation.

CONCLUSIONS

Based on this study, future developments of fuzzy control and monitoring technologies in medicine and healthcare can be forecast. The sectors of medical activities can be brought together in a hierarchical scheme according to the mode of the medical procedure. This means that significant methodologies, relationships and demands are correlated. This scheme substantiates the hypothesis that a successful application in one sector should lead to a successful application in neighbouring sectors.

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Table 1: Number of fuzzy technology publications applied in each medical sectors based on time scale.

Publication year	<89	90	91	92	93	94	95	96	97	98
Conservative disciplines										
internal medicine	-	-	-	-	1	-	-	-	1	-
cardiology	-	-	-	-	-	2	2	-	2	3
invasive care	1	-	-	-	-	1	-	-	-	1
paediatry	-	-	-	-	-	-	-	-	-	-
endocrinology	-	-	-	-	-	-	-	-	-	-
oncology	-	-	-	-	-	1	2	-	2	1
gerontology	-	-	-	-	1	-	-	2	2	2
general practice	1	1	-	-	1	1	1	2	4	2
Invasive medicine										
surgery	-	-	-	-	2	1	-	2	3	1
orthopaedics	-	-	-	-		1	-	1	-	-
anaesthesia	4	1	1	4	4	4	2	5	7	2
artificial organs	-	-	-	-	-	-	2	2	5	3
Regionally defined medical disciplines										
gynaecology	-	-	-	-	-	-	-	-	-	-
dermatology	-	-	-	-	-	-	-	-	-	-
dental medicine	-	-	-	-	-	1	-	-	-	-
ophthalmology	-	-	-	-	-	-	-	-	-	-
otology, rhinology etc	-	-	-	-	-	-	-	-	-	-
urology	-	-	-	-	-	-	-	-	-	-
Neuromedicine--										
neurology	-	-	-	-	-	-	-	-	-	-
psychology	-	-	-	-	1	-	1	2	1	2
psychiatry	-	-	-	-	-	-	1		-	-
Image and signal processing										
Signal processing	1	-	-	-	-	1	1	2	2	2
radiation medicine	-	-	-	-	-	-	-	-	-	-
radiology	-	-	-	-	-	-	-	1	1	-
Laboratory										
biochemical & tests	3	1	-	-	1	1	-	-	-	-
Basic science										
medical information	2	-	2	1	2	4	1	1	1	-
anatomy, pathology etc	-	1	-	-	2	1	2	-	1	2
physiology	1	-	-	-	-	-	-	-	1	-
pharmacology	1	-	-	-	1	-	-	-	1	-
education	1	-	-	-	1	1	-	-	1	1
Nursing	-	-	-	-	-	-	1	-	-	-
Healthcare	1	-	-	-	-	-	2	-	1	1

Table 2: Type of fuzzy technology application in medicine and healthcare over time.

Publication year	<89	90	91	92	93	94	95	96	97	98
closed loop control	4	1	-	1	3	5	3	6	9	3
open loop control	-	1	-	1	1	3	-	-	-	2
PI, PID	-	-	-	1	-	-	-	-	1	1
Identification	-	-	-	-	1	-	1	-	1	1
Model based	3	1	-	-	3	1	5	4	8	6
Adaptive	2	-	1	-	-	2	4	-	-	1
Monitoring	-	-	-	-	-	-	3	2	1	-
Classification	1	1	-	-	1	3	1	3	8	-
Self-Learning	-	-	-	-	-	-	-	-	1	2

Hybrid	-	-	-	2	-	2	3	1	4	3

Table 3: Type of fuzzy technology application within each medical field.

	C-L	O-L	PID	Iden	M-B	Adp	Mnt	Class	S-L	Hyb
Conservative disciplines										
internal medicine	-	-	-	-	-	-	-	2	-	-
cardiology	-	-	-	-	1	2	2	2	-	2
invasive care	1	-		-	2	-	-	-	-	-
paediatry	-	-	-	-	-	-	-	-	-	-
endocrinology	-	-	-	-	-	-	-	-	-	-
oncology	1	-	-	-	-	-	2	1	-	2
gerontology	-	-	-	2	1	-	1	2	-	1
general practice	3	-	-	1	3	1	-	3	-	2
Invasive medicine										
surgery	3	-	-	-	2	-	2	-	-	2
orthopaedics	-	1	-	-	-	-	-	-	-	1
anaesthesia	18	2	3	-	1	4	-	-	3	3
artificial organs	7	-	-	-	-	1	-	2	-	2
Regionally defined medical disciplines										
gynaecology	-	-	-	-	-	-	-	-	-	-
dermatology	-	-	-	-	-	-	-	-	-	-
dental medicine	-	-	-	-	-	-	-	1	-	-
ophthalmology	-	-	-	-	-	-	-	-	-	-
otology, rhinology etc	-	-	-	-	-	-	-	-	-	-
urology	-	-	-	-	-	-	-	-	-	-
Neuromedicine										
neurology	-	-	-	-	-	-	-	-	-	-
psychology	-	-	-	-	1	-	2	3	-	1
psychiatry	-	-	-	-	1	-	-	-	-	-
Image and signal processing										
Signal processing	-	-	-	-	2	-	2	3	-	2
radiation medicine	-	-	-	-	-	-	-	-	-	-
radiology	-	-	-	-	-	-	-	2	-	-
Laboratory										
biochemical & tests	-	-	-	-	-	-	-	4	-	2
Basic science										
medical information	-	2	-	-	4	2	3	2	-	2
anatomy, pathology etc	-	3	-	3	1	-	-	2	-	-
physiology	-	-	-	-	2	-	-	-	-	-
pharmacology	3	-	-	-	-	-	2	-	-	-
education	-	2	-	-	2	-	1	-	-	-
Nursing	-	-	-	-	-	-	-	1	-	-
Healthcare	-	1	-	-	2	-	1	1	-	-

Notation: C-L: closed-loop, O-L: open-loop, PID: proportional-integral-derivative, Iden: identification, M-B: model based, Adp: adaptive control, Mnt: monitoring, Class: classification, S-L: self-learning, Hyb: hybrid controllers.