JOÃO DALLAMUTA
HENRIQUE AJUZ HOLZMANN
(ORGANIZADORES)

Collection:
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Ano 2022

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APRESENTAÇÃO

A engenharia elétrica tornou-se uma profissão há cerca de 130 anos, com o início da distribuição de eletricidade em caráter comercial e com a difusão acelerada do telégrafo em escala global no final do século XIX.

Na primeira metade do século XX a difusão da telefonia e da radiodifusão além do crescimento vigoroso dos sistemas elétricos de produção, transmissão e distribuição de eletricidade, deu os contornos definitivos para a carreira de engenheiro eletricista que na segunda metade do século, com a difusão dos semicondutores e da computação gerou variações de ênfase de formação como engenheiros eletrônicos, de telecomunicações, de controle e automação ou de computação.

Produzir conhecimento em engenharia elétrica é portando pesquisar em uma gama enorme de áreas, subáreas e abordagens de uma engenharia que é onipresente em praticamente todos os campos da ciência e tecnologia.

Neste livro temos uma diversidade de temas, níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espirito de parceria.

João Dallamuta

Henrique Ajuz Holzmann

SUMÁRIO

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MAPAS COGNITIVOS FUZZY DINÂMICOS ADAPTATIVOS APLICADOS EM PROCESSO INDUSTRIAL

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RESUMO: Neste trabalho, será apresentada uma versão de um controlador Baseado em Mapas Cognitos Fuzzy, do Inglês Fuzzy Cognitive Maps. (FCM) Entretanto, o então Dynamic Fuzzy Cognitive Maps nesse trabalho foi adaptativo, ou seja, os pesos das suas relações causam e efeitos são refinados conforme erro de saída. Uma breve introdução sobre controle adaptativo, teoria de FCM e uma descrição do processo serão fundamentadas para melhor compressão da proposta. Os resultados são comparados com uma versão Fuzzy Mandani, já validada na literatura para clarificar as ações de controle do controlador proposto. Ressalta a baixa complexidade do FCM comparada a versão clássica do Fuzzy Mandani por meio de uma métrica do Matlab (tempo de processamento). Após a discussão de resultados esse trabalho se encerra com uma conclusão e sugestão de futuras investigações.
PALAVRAS-CHAVE: Fuzzy Cognitive Maps, Controle Adaptativo. Misturador Industrial.

ADAPTATIVE DYNAMIC FUZZY COGNITIVE MAPS APPLIED IN INDUSTRIAL PROCESS

ABSTRACT: This work will present a version of a driver based on Fuzzy Cognitive Maps. (FCM) However, the Dynamic Fuzzy Cognitive Maps in this work were adaptive. That is, the weights of their cause and effect relationships are refined according to the output error. A brief introduction about adaptive control, FCM theory, and a description of the process will be supported to compress the proposal better. The results are compared with a Fuzzy Mandani version, already validated in the literature, to clarify the control actions of the proposed controller. It emphasizes the low complexity of the FCM compared to the classic version of Fuzzy Mandani through a Matlab metric (processing time). After discussing the results, this work ends with a conclusion and suggestion for future investigations**.**
KEYWORDS: Fuzzy Cognitive Maps, Adaptive Control, Industrial Mixer.

1 I INTRODUCTION

In modern control systems, it is noticed that linear control becomes insufficient when the operating conditions of a system are not fixed. Thus, adaptive control is used. One of its objectives is to compensate variations in the parameters of nonlinear control systems (K. J. ÅSTRÖM, B. WITTENMARK, 2008) which, in general, are an interconnection of components forming a configuration that produces a desired response (K. OGATA, 2010).

An alternative is to use heuristic models or semi-quantitative methods like Fuzzy Cognitive Maps (FCMs), which encode experts' knowledge about the connections among the different parameters of the studied industrial process control. In other words, Fuzzy cognitive maps (FCMs) are a very convenient, simple, and powerful tool for simulation and analysis of dynamics systems (MENDONCA et al., 2019).

These methods could be preferred to other alternatives as they allow modeling of complex system dynamics, without the need for capturing the functional relationships be-tween concepts of the real system by means of com-plex mathematical equations.

In this way, FCMs can encode control tactics that are imprecise in nature, commonly expressed in linguistic terms, which is helpful when it is difficult to obtain a mathematical model of the process.

FCMs allow dealing with subjective and vague linguistic variables used by domain experts and handling uncertainties due to their approximate knowledge using Fuzzy Logic (K. M. PASSINO, S. YURKOVICH, 1998), such as the heuristic process used in this work.

There are many applications of FCMs in process control. In the work of Mendonça (M. MENDONÇA, et al, 2013), the authors used a Fuzzy-PID controller development of an alcoholic fermenter process proposed in Maher (M. MAHER, 1995). Also, Lima and Serra (F. LIMA, G. SERRA, G., 2015) proposed a robust Fuzzy controller implemented for visualization and control of a thermal process.

In this work, the objective is to investigate the application of systems based on FCMs, designed using experts' knowledge and compare their results with the more classical methods. We present three examples of industrial processes in this work. Intelligent control methods were used to tune the gains of a classical PID controller of an alcoholic fermenter, were directly applied as controllers in a heat exchange process (Heatex) and a Dynamic Fuzzy Cognitive Map (DFCM) with two weight's adaptation methods: Hebbian learning algorithm (DFCM-Heb) and a weight-scheduling configuration (DFCM-WS).

The paper is organized as follows. Section II describes the processes and presents a brief background about Fuzzy Logic and FCM, presenting our contribution in the intelligent control area. In Section III, we show the obtained results and compare the other techniques. Finally, in Section IV, we outline some conclusions and directions for future work.

2 | BACKGROUND AND PROCESSES' DESCRIPTION

A Fuzzy Cognitive Maps (FCM) is a soft computing technique that combines the advantages of Artificial Neural Networks (ANNs) and Fuzzy Logic, using existing knowledge and hu-man experience to model complex systems (E. I. PAPAGEORGIOU, 2014). Due to their simplicity, support for ambiguous (Fuzzy) knowledge, they are applicable in many areas, such as medicine, engineering, software development, etc. FCMs emerged from Kosko's work (B. KOSKO, 1986), which expanded the concepts of Axelrod's (R. AXELROD, 1976) and Tolman's (E. C. TOLMAN, 1948) previous Cognitive Maps works. FCMs introduced fuzziness to Cognitive Maps, by using numeric descriptions (fuzzy binaries) of causal influences instead of positive or negative symbols.

In a FCM, the value $Ai^{(k+1)}$ of each concept *Ci* at iteration *k+1* is calculated as a function of the sum of *Ai(k)* at iteration *k*, with the product of *Aj(k)* of the concept *Cj* by *wij*, which is the value of the causal link between *Cj* and *Ci*, given in the range [-1 1]. The mathematical representation of FCM inference is given by equation (1).

$$A_i^{(k+1)} = f(A_i^{(k)} + \sum_{\substack{j=1 \\ j \neq i}}^{N} A_j^{(k)} * w_{ji}) \qquad (1)$$

In (1), *f(.)* denotes a threshold function like sigmoid to squash the values within the range [0 1], as shown in equation (2), where λ is a real positive number, which determines the steepness of *f(.)*, and *x* is the value of *Ai* at the equilibrium point.

$$f(x) = {}^{1}/_{(1+e^{-\lambda x})} \quad (2)$$

It is not scope of this work to analyze the stability of the FCM. However, these equations combined suggest stability similarly to the work from Boutalis and Kottas (Y. BOUTALIS, T. L. KOTTAS, M. CHRISTODOULOU, 2009), which shows that threshold sigmoid functions have interval previous defined and are continuous differentiable. Also, the calculated values and causes their convergence to the same specific value (V. ELENI, G. PETROS, 2017).

The stability initials analysis and results have been presented by the same authors (V. ELENI, G. PETROS, 2017). This study was done by using an appropriately defined contraction mapping theorem and the non-expansive mapping theorem. In other way, Kosko examined Associative Memories stability by identifying a Lyapunov or energy function with associative memory states (Y. BOUTALIS, T. KOTTAS, 2008), (B. KOSKO, 1988), (M. A. S. MARTCHENKO, et al, 2003).

For the Heatex control, a Fuzzy controller (FLC) and a FCM controller were developed, and were compared to the original PI controller in Matlab®, similarly as seen in Mollon (M. F. MOLLON et al, 2017), which the FCM controller was compared with ANN-FCM and other techniques.

Due to the low complexity of this system, it was unnecessary to use the error integral as expected. For the FCM controller, Simulink® was used to modify the structure of the controller used in Puheim et al. (M. PUHEIM, J. VAŠČÁK, L. A. MADARÁSZ, 2015). The Fig 1 show adaptative architecture.

The causal relationships of the FCM were defined heuristically. The causal weight values were chosen as W_{13}=0.75 and W_{23}=0.2.

The second step was to create the FLC. In this process, the rule base used was the same as the one proposed by Passino and Yurkovich (K. M. PASSINO, S. YURKOVICH, 1998), to control an inverted pendulum, with 25 rules, three triangular (center) and two trapezoidal (borders) pertinence functions. The inputs, like in the FCM controller, are *Error* and $Error_{diff}$ and the output is the control signal.

We designed an adaptive PID controller with FCM and Fuzzy adjustment mechanisms using Maher's approach (M. MAHER, 1995). Subsequently, as in the Heatex process, the results were compared with the PID controller used as the basis for the tuning mechanisms.

In this work, we used a maximum tank volume (*V*) of 4.75 l and a minimum volume of 1 l. Accordingly, if the former case occurs, the F_{in} valve is completely closed, and if the latter case occurs, the valve F_{out} is closed (M. MENDONÇA, et al, 2013). As discussed in this work, equations (4) to (8) were used to simulate this process in Matlab®.

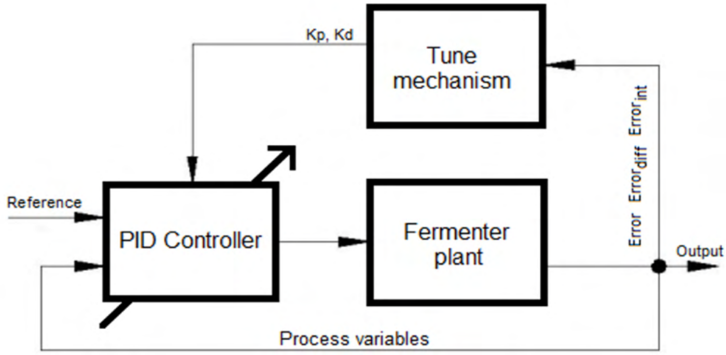

Fig. 1. Auto tune architecture.

The inputs (absolute errors) range from 0 to 1 (100% positive error). The *Kp* output range is [0 1.5] and *Kd* is [0 2], both adjusted heuristically, obtaining the Fuzzy surfaces, two of which are shown in Fig. 8.

As can be seen in Figs. 4 and 8, in this work the FCM corresponds to a simple acyclic graph, different from Kosko's original proposal (B. KOSKO, 1986). In this way, according to Miao et al. (Y. MIAO, et al, 2001) and Mendonça (M. MENDONÇA, et al, 2013) the construction of large cognitive maps by steps always generates smaller maps usually acyclic, which correspond to well de-fined cause-effect relations. Thus, based on the concepts of repulsive artificial pheromones, this work presents an optimization of the robots' trajectory, thus increasing the search area without increasing the distance traveled. In other words, when a robot detects high concentrations of pheromones – whether they are left by the other robots or itself – it will deflect its course so as not to become trapped in relatively more difficult navigational zones such as narrow corridors.

The proposal of control via FCM is to control an industrial mixer that, due to the low complexity of FCM mathematics for its inference, allowed the controller to be embedded in a low-cost controller, such as Arduino and PIC for example. Figures 9 and 10 show the process and the Adaptive FCM due to its weight adjustment being dynamic with the HEBB rule.

Process description

To demonstrate the evolution of the proposed technique (DFCM) we will use a case study well known in the literature as seen in (MENDONÇA et al., 2020) and others.

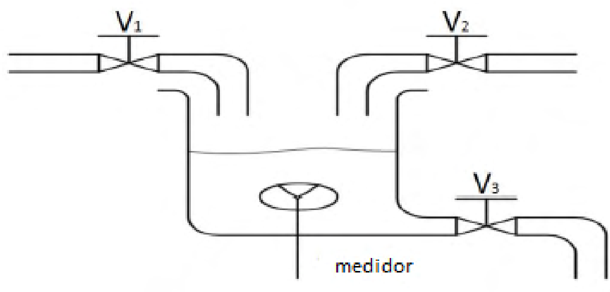

Fig. 2. Industrial Mixer Process.

Valves (V1) and (V2) insert two different liquids (specificgravities) in the tank. During the reaction of the two liquids, anew liquid characterized by its new specific gravity value is produced. At this time, the valve (V3) empties the tank in accordance with a campaign output flow, but the liquid mixture should match the specified levels of the volume and specific gravity. Although being relatively simple, this process is a TITO (Two Inputs and Two Outputs) type with coupled variables. To establish the quality of the control system of the produced fluid, a weighting machine placed in the tank measures the specific gravity of the liquid produced. When the value of the measured variable G, liquid mass, reaches the range of values between the maximum and minimum [Gmin, Gmax] specified, the desired mixed liquid is ready. The removal of liquid is only possible when the volume (V) is in a specified range between the values [V_{min} and V_{max}]. The control consists of to keep these two variables in their operating ranges, as:

$$V_{mim} < V < V_{max} \quad (1)$$

$$G_{mim} < G < G_{max} \quad (2)$$

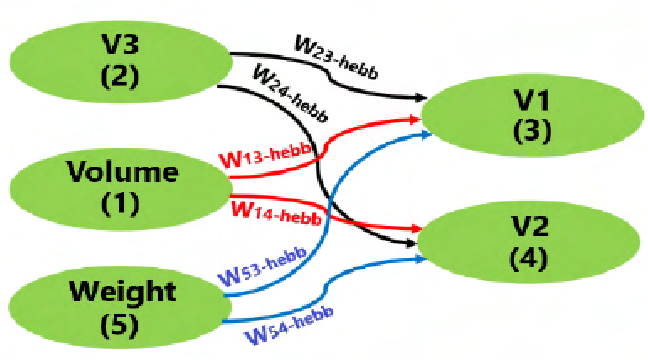

Fig. 3. Industrial Mixer Controller.

In short, In this figure it is possible to observe that we have three valves, two inlet (V1 and V2) for the inlet of two different liquids, such as water and milk in a food process and one for outflow (V3). Two variables must be controlled by range, the weight and the volume of the mixture; what makes the MIMO processs. Figure 4 shows the D-FCM controller.

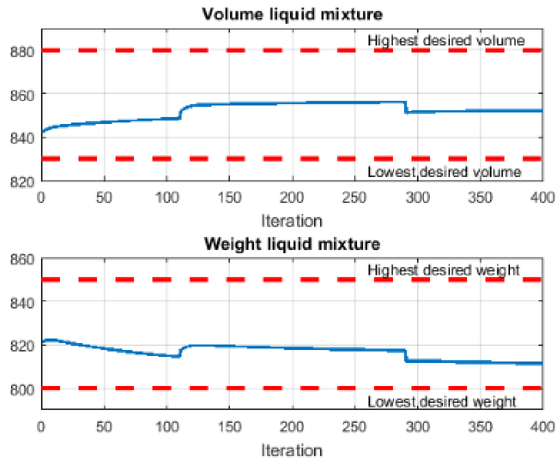

Fig. 4. Valves and results of the DFCM Controller with disturbances.

Já a figura 12* mostra um exemplo de campanha com distúrbios.

To establish a correlation and a future comparison between techniques, a Fuzzy controller was also developed. The Fuzzy rules base uses the same heuristic control strategy and conditions. Fuzzy logic has proved being able to provide satisfactory non-linear controllers even when only the nominal plant model is available, or when plant parameters are not known with precision (M. MENDONÇA, et al, 2017), (M. MENDONÇA, et al, 2016). Fuzzy Control is a technique used for decades, especially in process controlling (E. H. MAMDANI, 1974). It is a motivation to validate DFCM, so in this study it was used the same approach for two controllers, with two different formalisms. It is not in the scope to discuss the development of the Fuzzy controller, but some details of the structure are pertinent: functions are triangles and trapezoidal and 6 rules are considered in its base. The Fuzzy controller surfaces are shown in Fig. 2. Moreover, the rules are symmetric and similar by two output valves; in this specific case, the surface of valve 1 is the same as in valve 2. The rules base examples rules and its respective weighted weights are:

1. If (Level is low) then (V1 is medium) (V2 is medium)(1);

3. If (Level is high) then (V1 is low) (V2 is low) (1);

5. If (Weight is medium) then (V1 is low) (V2 is low) (0.5);

The figure 5 show Fuzzy Superficial….

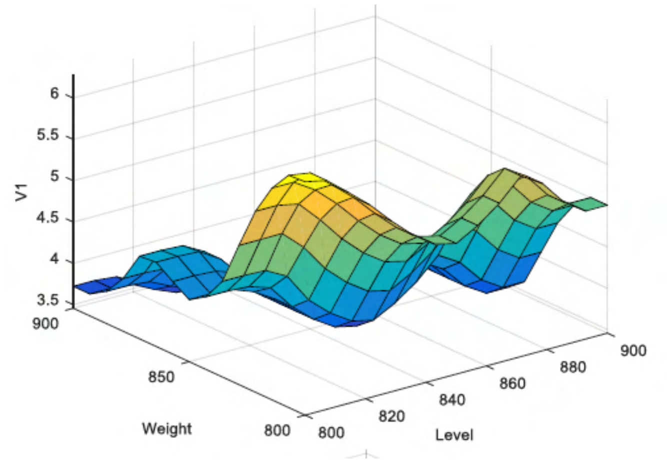

Fig. 5. A shows the nonlinearity of the process with an example of a Fuzzy surface.

Finally, a computational results and complexity metric will be presented in the next figures..

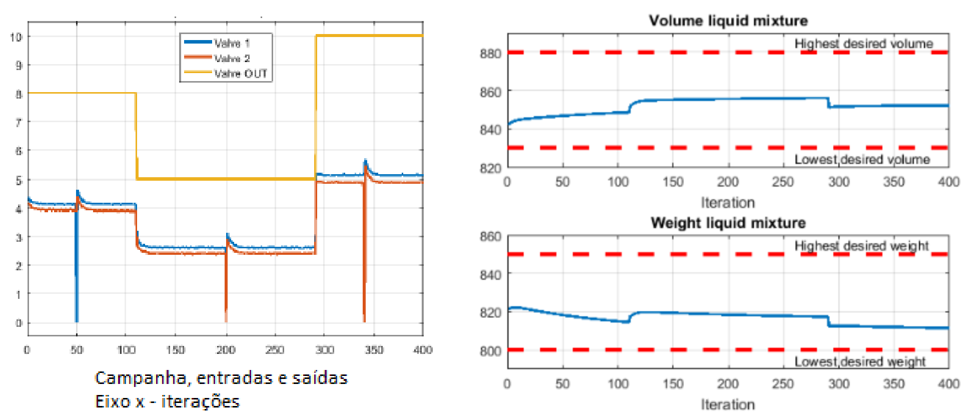

Fig. 6. Example D-FCM campaign with disturbances.

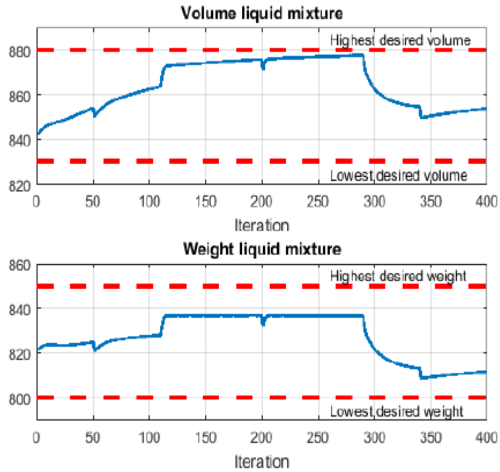

Fig. 7. Example FLC-Mandani campaign with disturbances.

The Fuzzy controller managed to place the variables in the pre-determined ranges, but with a greater variation than the proposed adaptive D-FCM. Table 1 shows the quantitative results of this experiment with disturbance.

	DFCM		*Fuzzy Logic*		*DFCM-Arduino*		*Fuzzy-ANN*	
	Max-min		**Max-min**		**Max-min**		**Max-min**	
Campaign	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Volume mix (mL)	13.82	14.79	35.51	38.12	24.79	26.05	36.69	38.10
Weight mix (mg)	14.69	14.31	28.02	20.64	13.05	11.49	25.28	25.29

.Tabble 1. Quantitative results with disturbances.

Finally, a computational complexity metric will be presented in the next figure.

Function Name	Calls	**Total Time**	Self Time*	Total Time Plot (dark band = self time)
dfcm_tanque_revista_icas_c1_comruido	1	4.911 s	1.556 s	
close	1	1.438 s	0.002 s	
close>request_close	1	1.298 s	0.028 s	
legend	2	1.252 s	0.012 s	
legend>make_legend	2	1.238 s	0.032 s	
closereq	3	1.225 s	0.850 s	

Fig. 8. Matlab results with time processing.

3 I RESULTS AND DISCUSSION

In this section, we discuss the results of multi robot inspired in swarm robotics system to rescue victims. Inspired by the organization of social insects, such as ants, bees and termites, and the formation of schools of fish and birds in flight, swarm robotics is a field of study that seeks the best computational paths for robots to exchange information and act together, according to a common objective for which they were programmed. They are computational solutions that are in the field of study of several groups of researchers in the world.

Still without commercial examples, swarm robotics has the prospect of use both in closed and open places, such as at sea, in the inspection and repair of underwater platforms, in maritime surveillance and in the air, with drones equipped with systems to monitor borders, for example.

In the third study, by Mendonça et al. (M. MENDONÇA, et al, 2017), the architecture was scaled for its use in systems based on swarm robotics, also applying concepts of Ant Colony Optimization (ACO) for the evolution of the robots trajectory. The approach uses only one robot released into the environment at a time, leaving pheromones along the way. The next robot is released when the previous robot ends the route or collides with obstacles. Finally, the last two contributions use both FLCs and Fuzzy Cognitive Maps (FCMs) for a group of homogeneous robots working simultaneously. The results of both approaches were compared in two simulation scenarios, with 1 and 4 robots operating (M. MENDONÇA, et al, 2016), (M. MENDONÇA, et al, 2019).

4 I CONCLUSIONS

In the mixer's control, the results were satisfactory because the variables were within the desired ranges even with disturbances in the process.

In the case of the alcoholic fermenter process, the FCM-PID mechanism obtained the best responses according to the analyzed parameters, obtaining the lowest values in all of them considering the analyzed campaign.

Finally, These aspects suggest that the DFCM control can be successfully used in autonomous robots since this controller presented optimized results compared to FLC.

Future research will focus on exploiting the potential of the soft computing techniques in industrial process control, including disturbances, new setpoint, and others changes in the processes addressed. Three important research topics are considered. First, we would like to embed all the developed controllers in other platforms, like Raspberry PI, Toradex, and others, to verify the low computational complexity, time response, and software portability of the FCM-based controllers. Secondly, addressing a real-time MIMO controller for temperature and level in an actual tank prototype, for example.

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