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Fuzzy Colored Petri Nets and Their Application to Efficient Design and V&V of Fuzzy Logic Controllers

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Abstract

Generally, FLC design causes the designer to spend too much efforts and time. If a design support is provided to apply various membership functions to and simulate a FLC without coding at the early development stage, the cost problem may be solved to a remarkable degree. In order to offer the systematic approach to support FLC design, Fuzzy Colored Petri Nets (FCPN) is introduced as design support in this work. The feasibility of FCPN is demonstrated through a controller design example.

I. Introduction

It is true that fuzzy logic control (FLC) is one of the most frequently investigated approaches for controlling nuclear power plant (NPP) systems. When it comes to the practical application, however, it is very exceptional that Fugen NPP in Japan adopted FLC for the plant operation. It is a huge challenge to apply fuzzy logic in nuclear industry. One of the main reasons for this may be the fact that FLC is not well proven technology, especially in view of the stability. Thus the well-proven PID controllers are still utilized for the control of most of NPP systems. Of the PID controllers, the adaptive PID controller are more effective than the controllers of which control parameters are fixed during control [1, 2]. For this case, the concept of FLC may be 'safely' applied in NPP industry because the 'fuzzy part' of the controller involves in the performance only.

However, it should be noted that the FLC designer should have an experience and knowledge about an applied system in order to obtain the rules of fuzzy algorithm. This is a serious demerit of fuzzy system in view that the designer has to spend too much efforts and time. Therefore, it is desirable to establish a systematic design support for the efficiency of the FLC design. For the classical controllers, various design supports have been provided at the early development phase. MATLAB® is one of the most popular design supports [3]. In order to play the similar role as MATLAB®, it is important that the design support makes it possible to apply various membership functions and simulate a FLC without coding at the early development stage.

In order to offer the systematic approach to support FLC design, Fuzzy Colored Petri Nets (FCPN) is introduced as design support in this work. FCPN, which is described in section II, is a new Petri net model based on Colored Petri Net (CPN) [4]. FCPN to be presented in this paper is suitable to support the design for FLC systems. The feasibility of the FCPN based design methodology is demonstrated through a controller design example in section III. We discuss the issues related to the verification and validation in section IV, concluding this paper.

II. Fuzzy Colored Petri Nets (FCPN)

Fuzzy Petri nets are proper to modeling and analyzing intelligent systems. There are various approaches for designing fuzzy Petri nets by combining Petri nets and fuzzy set [5, 6, 7, 8]. FLC fills the gap between classical control and artificial intelligence techniques. It should be noted that FCPN is tailored to support the integration of different formalisms – fuzzy logic and CPN – in a common design. As mentioned above, FCPN is a CPN based fuzzy Petri net model. Thus the definitions and behaviors can be formally described based on those of CPN as follows:

Definition (FCPN) : FCPN is a ten-tuple FCPN = (Σ, P, T, A, N, C, G, E, I; L) satisfying the requirements as follows:

- The definitions of Σ, P, T, A, N, C, G, E, and I are the same as the ones for CPN described in [4].
- L is a labeling function. It is defined from T into LS, where LS = $\{N \to N, N \to F, F \to N, F \to F\}$

Definition (Set of Variables of t) :

- $\forall t \in T$: $NVar(t) = \{v \mid v \in Var(G(t)) \lor \exists a \in A(t): v \in Var(E(a))\}$ where Var(expr) means the set of variables in an expression, expr
- $\forall t \in T$: $FVar(t) = \{(v1, v2) \mid v1 \in NVar(t) \land v2 \in FV\}$ where FV is the set of fuzzy linguistic variables that is uniquely defined for a FCPN model. $\forall t \in T$: $Var(t) = NVar(t) \cup FVar(t)$, $NVar(t) \cap FVar(t) = \phi$

Definition (Variable Binding) :

- $\forall t \in T$, $L(t) \in \{N \rightarrow N, N \rightarrow F\}$: a normal variable binding of a transition t is a function nb defined on NVar(t), such that $\forall v \in NVar(t)$: $nb(v) \in Type(v)$ and $G(t)<nb>$. By NB(t), we denote the set of all normal bindings for t
- $\forall t \in T$, $L(t) \in \{F \rightarrow N, F \rightarrow F\}$: a fuzzy variable binding of a transition t is a function fb defined on FVar(t), such that $\forall v \in FVar(t)$: $fb(v) \in Type(v)$ and $G(t)<fb>$. By FB(t), we denote the set of all fuzzy bindings for t. Variable binding $B(t) = NB(t) \cup FB(t)$, $NB(t) \cap FB(t) = \phi$

Definition (Expression Evaluation) :

- $\forall t \in T$, $L(t) = N \rightarrow N$: the expression evaluation $E(p,t)<nb>$ is the multi-set of token colors, which are removed from p when t occurs with the binding nb. The expression evaluation $E(t,p)<nb>$ is the multi-set of token colors which are added to p when t occurs with the binding nb and $nb(v) \in Type(v)$, $v \in NVar(t)$.
- $\forall t \in T$, $L(t) = N \rightarrow F$: the expression evaluation $E(p,t)<nb>$ is the multi-set of token colors, which are removed from p when t occurs with the binding nb. The expression evaluation $E(t,p)<nb>$ is the multi-set of token colors which are added to p when t occurs with the binding nb and $nb(v) \in Type(v)$, $v \in FVar(t)$. $E(t,p)<nb>$ is analogous to the fuzzification. Zadeh called "fuzzification" of an ordinary set A on a universe X as the change of x or $\mu_A(x)$ into a fuzzy set on X or [0, 1], respectively, for every $x \in X$
- $\forall t \in T$, $L(t) = F \rightarrow N$: $E(t,p)<fb>$ is analogous to the defuzzification.
- $\forall t \in T$, $L(t) = F \rightarrow F$: the expression evaluation $E(p,t)<fb>$ is the multi-set of token colors, which are removed from p when t occurs with the binding fb and $fb(v) \in Type(v)$, $v \in FVar(t)$. The expression evaluation $E(t,p)<fb>$ is the multi-set of token colors which are added to p when t occurs with the binding fb and $fb(v) \in Type(v)$, $v \in FVar(t)$.

Definition (Enabling and Occurrence) : The definitions are the same as the ones for CPN

In this paper, we partly describe the formal definitions of nonhierarchical FCPN for convenience. The above definitions could be extended to those of hierarchical FCPN easily as in the work of Jensen [4]. One of the most important properties of FCPN is the fact that, as shown in Figure 1, FCPN could be divided into two different parts, normal part and fuzzy part, owing to the special transitions. This property of FCPN, separation of the two parts, gives a good opportunity to designing FLC as described in the following section. For more details of informal descriptions of FCPN, refer to another work that we have described in [9].

III. Fuzzy Gain Scheduling with FCPN

The discrete time form of PID control is given as follows [1]:

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^{n} e(i) + \frac{K_d}{T_s} \Delta e(k)$$

Here, u(k) is the control signal, e(k) is the error between the reference and the process output, Ts is the sampling period for the controller, and $\Delta e(k) \equiv e(k)-e(k-1)$. Figure 2 shows the PID control system with a fuzzy gain scheduler. The above form corresponds to the 'PID controller' in Figure 2 and the corresponding FCPN model is shown in Figure 3. The FCPN model in Figure 3 represents a 'normal part' of the target system.

According to [1], we need five kinds of membership function that represent e(k), Δe(k), K_p, α and K_d. The fuzzy rules are of the form as follows:

if e(k) is A_i and Δe(k) is B_i, then K_p is C_i, K_d is D_i, and $\alpha=\alpha_i$, i = 1, 2, ···, m.

The above fuzzy rules constitute the 'fuzzy part' of the system model. The fuzzy part can be integrated into the 'normal part', shown in Figure 3, through the fuzzification and defuzzification processes, which also can be modeled with FCPN. The integrated model is shown in Figure 4. It should be noted that the truth value of the i^{th} rule μ_i : $\mu_i = \mu_{Ai}\,[e(k)] \cdot \mu_{Bi}\,[\Delta e(k)]$ in Figure 4. Generally, the membership functions and fuzzy rules may be extracted from operator's expertise and derived experimentally based on a kind of response of the process. However, this situation causes the designer to spend too much efforts and time. If a design support is provided to apply various membership functions to and simulate a FLC without coding at the early development stage, the above matter may be solved to a remarkable degree. For the purpose of it, FCPN is introduced in this work. Through the simulation of the integrated model shown in Figure 4, we could determine the most appropriate type of membership functions and performance parameters. For the performance parameters, we may use rise time, maximum overshoot, settling time, etc.

IV. Results and Conclusions

The simulation was performed with the membership functions presented in [1], following the same process. We have found that the simulated results are very similar to those of [1], as shown in Table 1. The major findings from the application are as follows:

1. FCPN is suitable for the modeling of FLC systems owing to its unique properties.
2. It is valuable to introduce the FCPN simulation in order to determine and improve the performance of a rule-based FLC without coding at each development stage.

Wherever the thorough verification and validation (V&V) for FLC systems is required, FCPN may be used successfully. FLC is mostly implemented with the software-based systems. Particularly in this case, V&V through the entire development cycle have a significant meaning. Formal design approaches have been proposed over last two or three decades. Their aim is to improve the quality (reliability) of software-based systems through formal supports for the entire development cycle V&V. Thus, if an adequate formal design methodology for FLC is provided, V&V for FLC will become practical as reliability assurance in nuclear industry.

There are a few open problems related to the proposed design methodology. One of them is to implement FCPN on Design/CPN. We developed some kinds of techniques for it but they are incomplete. These techniques enable us to be supported by the automated design and V&V environment.

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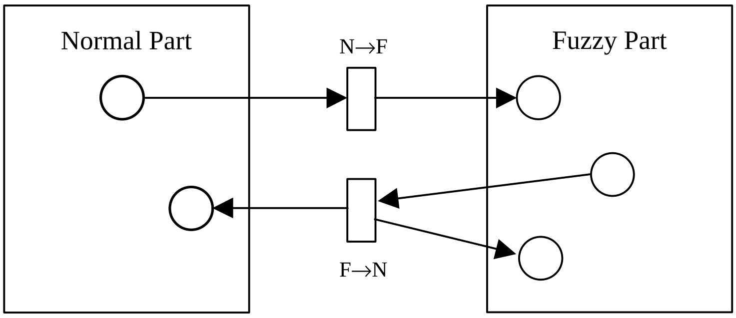

Figure 1. Two Different Parts of FCPN

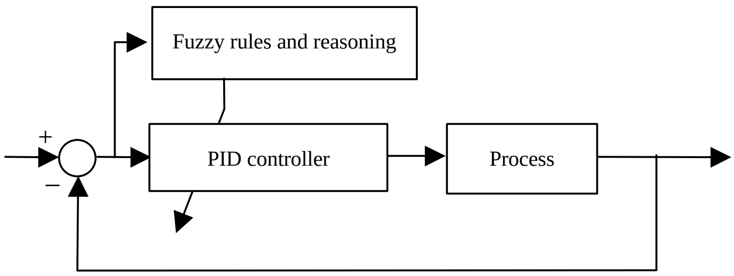

Figure 2. PID control system with a gain scheduler

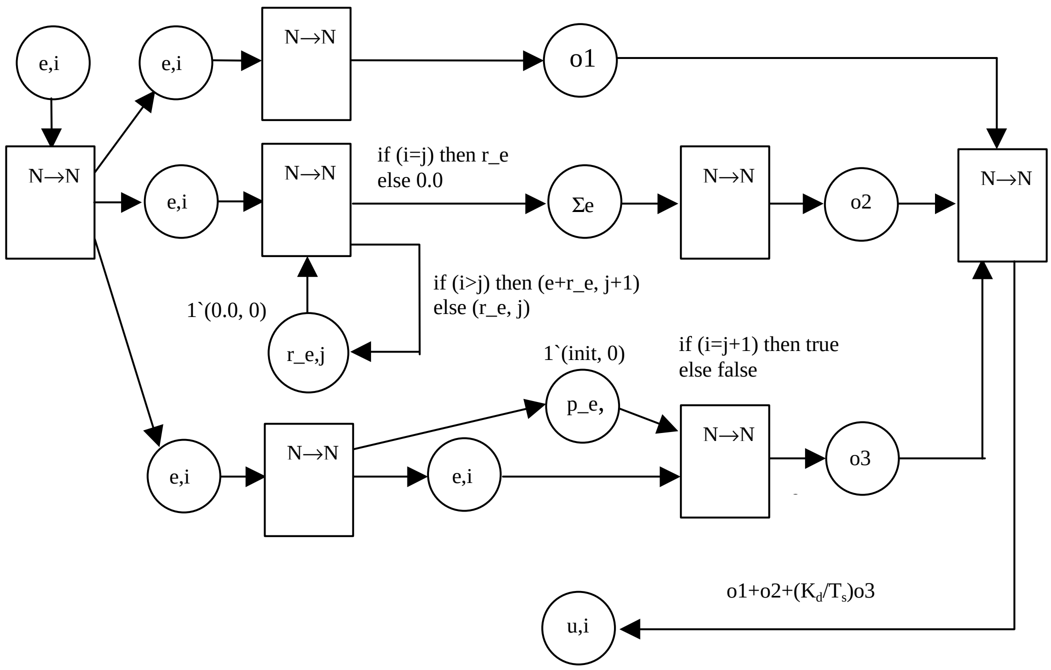

Figure 3. Simplified FCPN model for PID controller

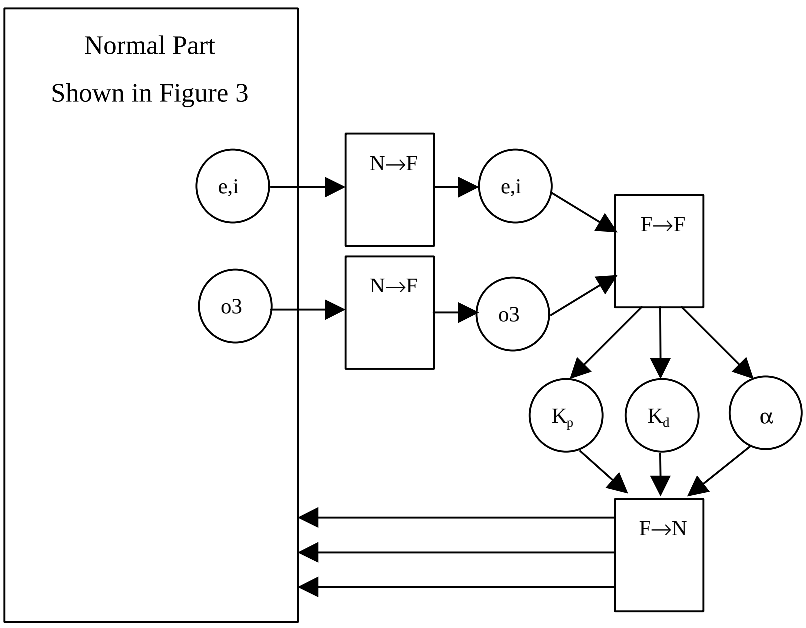

Figure 4. Simplified diagram for the integrated FCPN model

Table 1. Summary of simulation results for step response

Process	Performance Parameters
Second Order	Yos = 6.6%, T5 = 3.2 sec
Third Order	Yos = 6.6%, T5 = 4.9 sec
Fourth Order	Yos = 2.4%, T5 = 2.6 sec