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Development of an Automated Operating Procedure System using Fuzzy Colored Petri Nets for Nuclear Power Plants

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Abstract

In this work, AuTomated Operating Procedure System (ATOPS) is developed. ATOPS is an automation system for operation of a nuclear power plant (NPP) which can monitor signals, diagnose statuses, and generate control actions according to corresponding operating procedures, without any human operator's help. Main functions of ATOPS are anomaly detection function and procedure execution function, but only the procedure execution function is implemented because this work is just the first step. In the procedure execution function, operating procedures of NPP are analyzed and modeled using Fuzzy Colored Petri Nets (FCPN), and executed depending on decision making of the inference engine. In this work, an ATOPS prototype is developed in order to demonstrate its feasibility and it is also validated using FISA-2/WS simulator. The validation is performed for the cases of a loss of coolant accident (LOCA) and a steam generator tube rupture (SGTR). The simulation results show that ATOPS works correctly in the emergency situations.

1. Introduction

In large and complex machine systems, many operations have become more difficult for users, resulting in a greater potential for operation errors. Such mistakes may cause serious accidents, especially in aircraft industries and power plants. Hence, many machine systems have been automated through the introduction of modern computer and information technologies [1]. A computerized procedure system is an example of such an automated system. Various computerized procedure systems have been developed during the past decade [2]. They support systems which supply necessary information to a human operator quickly and conveniently in order to reduce human errors through easy and accurate decisions. Owing to recent progress in computer control, information processing, and human interface devices, the design of instrumentation and control (I&C) systems for various plant systems is rapidly moving toward fully digital I&C systems with an increased proportion of automation [3],[4].

In modern nuclear power plants (NPP), many computerized operating procedure systems have been developed and some of them have been already installed in real plants. They convert text-based operating procedures to a procedure database in a computer and show the procedure database to human operators through a graphics or text-based display. They also support an operator's interactions with the system, procedure maintenance, and configuration control.

There are also other researches which focus on an automation system. One of them is a "virtual collaborator," an agent robot, which is realized in virtual reality [1]. The virtual collaborator is a new type of human-machine interface, which works as an "intelligent interface agent" to help machine operators manipulate large scale machine systems such as a power plant. It is a kind of "virtual robot" that behaves like an intelligent agent robot in virtual reality space and communicates naturally with humans akin to the manner in which humans do with each other. It can behave like a plant operator in a simulated control room of a nuclear power plant in virtual reality space.

These systems appear to be similar to AuTomated Operating Procedure System (ATOPS) developed in this work, but they are very different in many aspects. The crucial difference is that they are only operator-supporting systems, whereas ATOPS is an automated system which does not need the help of a human operator.

In this work, operating procedures of NPP are converted to a procedure database and it used in ATOPS through Fuzzy Colored Petri Nets (FCPN). And an inference engine which consists of fuzzy functions, the time versus cognitive reliability (TCR) curve, and a knowledge database performs a decision making instead of human operators in NPP. A prototype of ATOPS is developed and simulated using FISA-2/WS simulator. ATOPS is a prototype of a system that will help a NPP become fully automated for next generation NPP operation. Moreover, ATOPS is a very long-term research project. This study, in which the feasibility of ATOPS is verified, is just the first step.

2. AuTomated Operating Procedure System (ATOPS)

ATOPS is a kind of automation system that operates a machine system according to prescribed procedures without any human operator's help. Since ATOPS is not an operator supporting system but rather an automation system, a man-machine interface (MMI) is not considered. Operators in the MCRs of NPPs monitor signals, diagnose current status, and perform suitable actions according to corresponding operating procedures. ATOPS performs such actions as the operators do: It monitors the plant status, detects anomalies, diagnoses the status, and operates the plant according to corresponding operating procedures in order to maintain the plant in a stable state.

Main functions of ATOPS are anomaly detection function and procedure execution function. The anomaly detection function includes plant status monitoring and anomaly status detecting when alarms occur. In an anomaly status, a human operator sees an alarm and considers the potential causes of the alarm, mostly using his own knowledge and experience because it is impossible to search all of the possible anomaly status cases. In contrast, a computer-based system cannot think, but it can search all possible cases in a short time due to its very fast calculating speed compared to a human operator. When another alarm occurs, the anomaly detection function cuts off cases which do not relate to the alarm in order to reduce possible cases. If any anomaly status is detected, the procedure execution function starts operating the plant itself according to the corresponding operating procedures. That is, the most important role of the procedure execution function is to perform a procedure perfectly and guarantee integrity. A procedure execution function consists of four components: a procedure database, an inference engine, a real factor database, and a knowledge database. In the procedure execution function, text operating procedures are converted to a procedure database, and then a procedure database and an inference engine are implemented using FCPN.

Human operators can always potentially cause an unexpected error, and this is a serious problem. On the other hand, an unexpected error related operations are negligible for ATOPS. For ATOPS, validation and verification is an important problem for applying ATOPS to NPP, because it is a software. In this work, a prototype ATOPS is constructed through implementation of the procedure execution function only. A simulation of the prototype ATOPS is performed for the cases of a loss of coolant accident (LOCA) and a steam generator tube rupture (SGTR) using accident mode-simulation with FISA-2/WS, which is the simulator of the KORI 2 NPP unit.

3. Procedure Analysis

The NPP operating procedures consist of five components. Operators in an NPP operate the plant according to the system operating procedures (SOP) and the general operating procedures (GOP) in normal state. When an alarm occurs, the operators monitor necessary signals and manipulate appropriate devices through the alarm response procedure (ARP). When multiple alarms occur, the operators act through the abnormal operating procedures (AOP). If the reactor is tripped and safety injection (SI) is operated in an abnormal state, the operators monitor necessary signals and manipulate necessary devices to put the NPP in a hot standby (HSB) state through the emergency operating procedure (EOP).

In this work, the target operating procedures of the ATOPS are the EOP. The EOP outlines the procedures for emergency situations such as LOCA or SGTR. If the reactor is tripped, SI begins, operators should operate the plant according to the E-0 procedure. The E-1 procedure is for LOCA, and the E-2, E-3 procedures are for SGTR.

The EOP consists of “If-then-else” statements. And the types of statements are classified into four categories. The first type is a simple confirms which require checking the values or states of instruments. The second type is simple controls, which require manipulating devices such as valves. The third type is ambiguous statements, which includes vague and ambiguous information such as “increase”, “decrease”, and “keep”. The last type is statements that require supplementary data.

3. Operating Procedure Modeling using Fuzzy Colored Petri Nets

This work uses FCPN in order to model text-based operating procedures. FCPN is a kind of Petri nets (PN), and there have been many studies on fuzzy Petri nets (FPN) that are used to represent uncertain knowledge about a system state, combining fuzzy set theory and PN theory [15].

Definition (FCPN): FCPN is a ten-tuple FCPN = (Σ, P, T, A, N, C, G, G', E, I) satisfying the requirements as follows:

- Σ is a finite set of non-empty types, called color sets.
- P is a finite set of places.
- T is a finite set of transitions.
- A is the set of arcs such that $P \cap T = P \cap A = T \cap A = \emptyset$.
- N is a node function. It is defined from A into $P \times T \cup T \times P$.
- C is a color function. It is defined from P into Σ.
- G is a guard function. It is defined from T into expressions such that $\forall t \in T$: $[Type(G(t)) = Bool \wedge Type(Var(G(t))) \subseteq \Sigma]$
- E is an arc expression function.
- I is an initialization function.
- The definitions of Σ, P, T, A, N, C, G, E, and I are the same as those for CPN described in the previous subsection and [14].
- The definition of G' is newly introduced for FCPN. It is defined from T into SGE = {N→F, F→N(Method), F→F, IntF(DOI)}, which is a set of special guard expressions that denote characteristics of transitions. N represents 'normal', F does 'fuzzy', and DOI does the degree of importance of evaluation items. In order to distinguish from the special guards, we call the guards defined by G as general guards.

FCPN has special transitions shown in Figure 7. FCPN can handle transitions from normal places to fuzzy places and those from fuzzy places to normal places. Therefore, we can implement fuzzification and defuzzification with FCPN. Figure 7 (a) describes a normal to fuzzy transition that represents the fuzzification and Figure 7 (b) describes a fuzzy to normal transition that represents the defuzzification. The fuzzy to fuzzy transition shown in Figure 7 (c) represents the transformation from a fuzzy variable to another fuzzy variable. Figure 7 (d) represents an integral fuzzy transition for the integration of FCPN models [8].

Current operating procedures still have vague and ambiguous expressions which are difficult to represent in a computer. To cope with this problem, the FCPN in this work has four types of place according to the complexity of the tasks which operators should do. The first type is the normal places which does nothing or only has a jump action. The second type is the basic place which has simple actions requiring no inference. The third type is the simple place which has actions including ambiguous information such as “if – increase - ” and “if – decrease - ”. This type requires human operators’ judgments. The last type is the complex place which has actions including information needs supplementary data such as “properly” and “if needed”. This type requires supplementary data or human operator’s judgments or both. Each place of the FCPN has a color, and the color represents a place type, which is one of the following four types:

Definition (Places)

Type 1 : Normal place
Color : gray
Execution : Jump to next place following transition

Type 2 : Basic place
Color : blue
Execution : Execution FCPN of basic decision
Jump to next place following transition

Type 3 : Simple place
Color : red
Execution : Execution FCPN of simple decision
Jump to next place following transition

Type 4 : Complex place
Color : green
Execution : Execution FCPN of complex decision
Jump to next place following transition

In the FCPN graphics, the token movement shows the current executing step; also the token color shows the types of executing step. The types of executing steps are given as follows:

Definition (Tokens)

Type 1 : Black – Normal execution
Type 2 : Orange – Continuously execution

Type 3 : White – Stop

The FCPNs for a part of E-2 procedure are shown in Figure 1 and Figure 2, as examples.

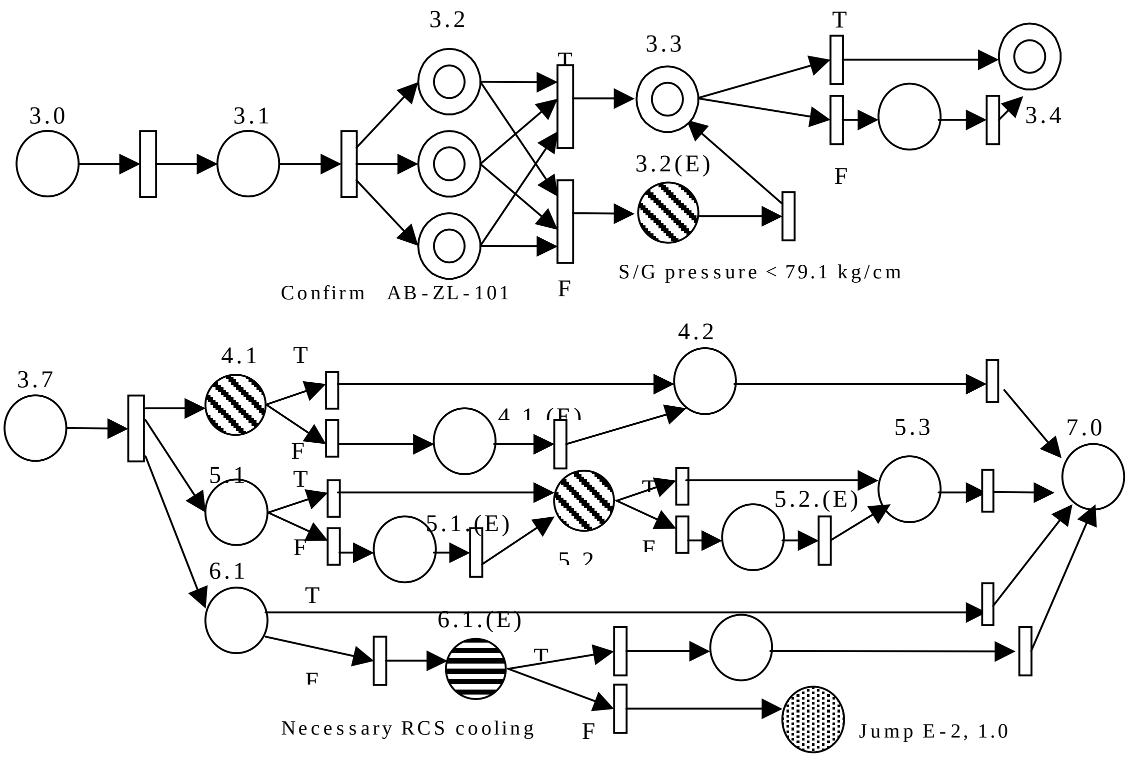

Figure 1. Example of procedure modeling using FCPN

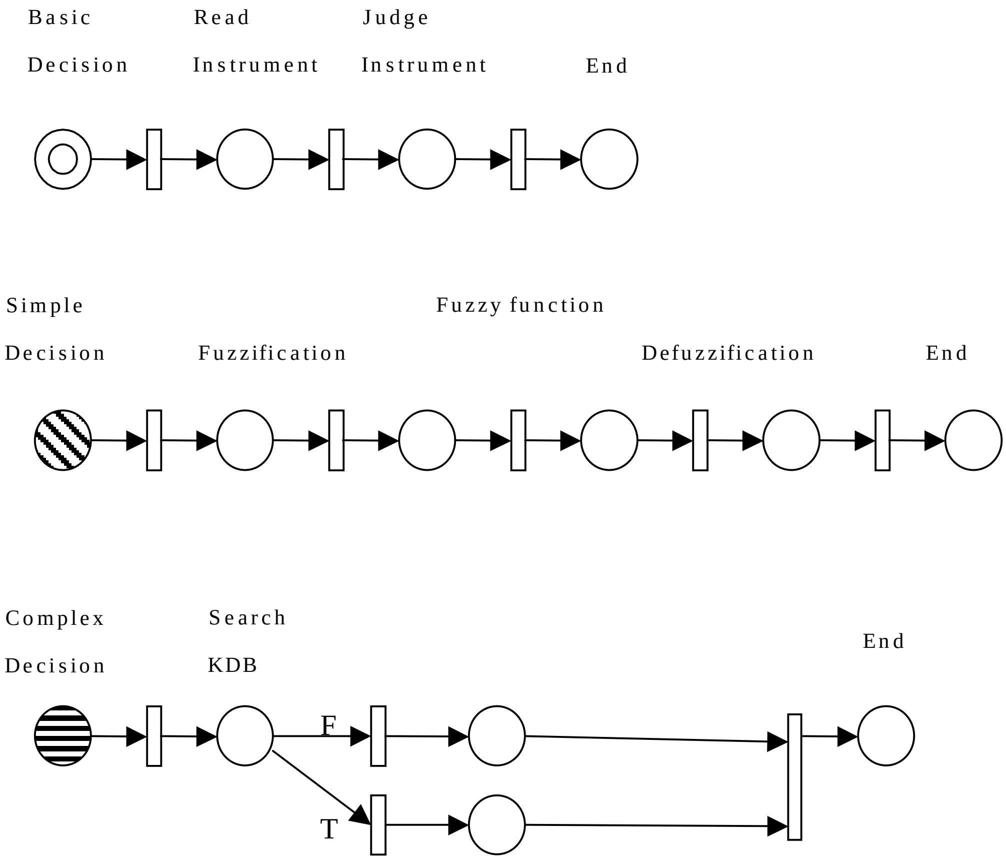

Figure 2. Three decisions using FCPN

4. Inference Engine

ATOPS has an inference engine, because the procedure still has ambiguous information that cannot be handled without the inferences of a human. The inference engine in ATOPS uses two databases. The first is the real factor database, which stores plant signal data, and the second is the knowledge database, which stores supplementary data such as appendices of operating procedures.

ATOPS has three types of decisions (basic decision, simple decision, and complex decision). A basic decision is a decision that needs no judgment. A simple decision is an action that has ambiguous information for a computer such as “if – increase - ”, “if – decrease - ”, and so on. Human operators can handle such information through their own judgments or experiments, but a computer cannot. Simple and easy expressions for human operators can be difficult expressions for computer. Therefore, such statements are handled by a fuzzy membership function and time versus cognitive reliability (TCR) curve [6]. Lastly, the complex decision is an expression that requires some supplementary data or information such as “properly”, “if needed”, and it is handled by a knowledge database. Thus, ATOPS has fuzzy membership functions and a knowledge database to judge unclear expressions.

The knowledge database is the storage for additional information or data. ATOPS can handle a variety of information using the knowledge database. In the procedures, there are expressions that need supplementary data or information. Almost all of the supplementary data is in the appendices of the operating procedures.

5. A Prototype of ATOPS using the Proposed Method for Nuclear Power Plant Operation

In this section, the prototype of ATOPS, as shown in Figure 3, is developed in order to validate procedure using FISA-2/WS simulator. Validation of the prototype is performed for the cases of LOCA and SGTR using accident mode-simulation of FISA-2/WS, which is the simulator for the KORI 2 NPP unit and has a graphic user interface (GUI). And LOCA and SGTR are covered by procedures E-0, E-1, E-2 and E-3. If LOCA or SGTR occurs, the reactor is tripped and SI operates. Then, E-0 procedure should be executed in order to diagnose the NPP and establish stable status. If LOCA occurs, E-1 procedure should be executed. If SGTR occurs, procedures E-2 and E-3 should be executed. In the LOCA and SGTR simulations, the prototype ATOPS operated the FISA-2/WS simulator by searching the corresponding operating procedures, and generating adequate control signals. Most of the actions were fairly exact.

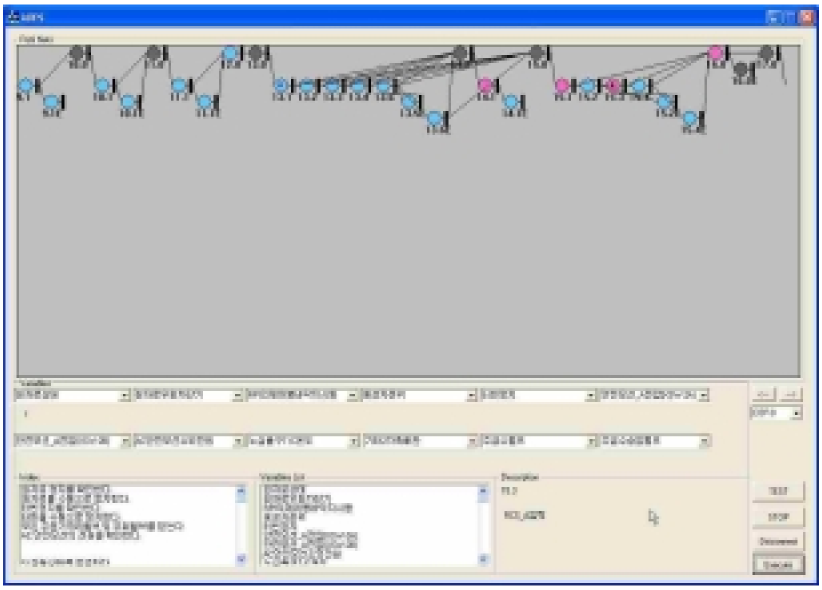

Figure 3. LOCA executing screen of AOTPS prototype

6. Conclusions

In this work, ATOPS is developed. ATOPS is an automation system to operate a NPP by monitoring signals, diagnosing statuses, and generating control actions according to corresponding operating procedures, without any human operator's help. An ATOPS prototype is developed in order to demonstrate its feasibility and it is also simulated using FISA-2/WS simulator. The simulations are performed for LOCA and SGTR. The simulation results show that ATOPS works correctly in emergency situations. In LOCA and SGTR situations, ATOPS operates the FISA-2/WS simulator by searching for corresponding operating procedures, judging the current status, and generating adequate control signals. Most of the actions were fairly exact.

ATOPS is a prototype of a system that help a NPP integrate a fully automated system for next generation NPP operation. This work is merely the first step in a lengthy and ongoing research project. In this work, the feasibility of the ATOPS was verified. In the next step, the ATOPS function will be implemented in a wider scope, such as the AOP, the GOP, and the SOP. There are many problems and issues that remain to be considered and thus much further research must be conducted.

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