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Development of Machine-Maintenance Training System using Petri Net and Virtual Environment

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Abstract

In this study, VR-based machine-maintenance training system was developed. The salient feature of this system is the utilization of Petri net for representing the procedures of machine assembly and disassembly in virtual environment. The utilization of the Petri net model realized the environment where the trainee can behave freely, and also made it possible to equip the system with the function that shows the next action to do to the trainee whenever he wants. The size of Petri net, however, usually becomes very large. Therefore, the support system for constructing Petri net was developed so that a large Petri net can be constructed easily. Through the application to a check valve, the effectiveness of using Petri net for the VR-based machine-maintenance training system was demonstrated.

Introduction

The nuclear power plant in Japan is inspected almost every year. In the inspection major parts of the plant are disassembled, inspected and then reassembled. Operation tests are executed after these maintenance procedures. To improve the skill on the machine maintenance at the training center today only the leaders of the maintenance groups can be trained by using the real machines or the real-size mockups. It is a serious problem of the maintenance in the nuclear plants that the capacity of these training facilities is very limited.

Virtual reality (VR) technology makes it possible for anyone to experience various kinds of operations in the virtual environment just like in the real world. And the machine-maintenance training is considered to be one of the fields to which VR technology can be applied effectively.

The expected effects through the VR-based machine-maintenance training system are as follows:

1) It will increase the chance of training for every worker.
2) When compared with the training based on the real machines or real-size mockups, the VR-based training will be economical and safe for the trainees.
3) If the VR-based training system includes a instruction function, the workload of the instructors at the training center can be also reduced.

NASA (National Aeronautics and Space Administration) succeeded in the mission for the repair and maintenance of the Hubble Space Telescope in 1993 and the VR-based training system was used as a part of the mission training. According to the questionnaire response after the mission, it was very effective for the team members to get the VR training in advance (Loftin and Kenny, 1995). Miwa et al. (1995) developed the learning environment for the maintenance of plants and equipments based on VR. They investigated the performance of the system through the application to the maintenance of the gas-insulated power-substation.

Although the availability of VR in the field of training has been recognized, one of the problems of the training system in virtual environment (VE) developed before is that the behaviors that the trainee can do are very restricted.

The aim of this study is to develop a new type of machine-maintenance training system in VE where the trainee can behave rather freely and, furthermore, can get advices about what to do next whenever he wants. The system is developed by combining the VR-based simulation of disassembling machines and the Petri net model for representing the disassembling procedures.

Petri net is a general tool for describing the behavior of simultaneous discrete events(Peterson, 1981). In the field of factory automation, Petri net is often used for representing the states of the machine-assembling lines in a factory (Nakashima et al, 1994). This study proposed a new method to use Petri net as a tool for representing and controlling the states of the parts on disassembling process in VE. The utilization of the Petri net model realized the environment where the trainee can behave freely, and also the function that shows the next action to do in VE to the trainee whenever he wants. The size of Petri net, however, usually becomes very large. Therefore, the support system for constructing Petri net was also developed so that a large Petri net can be constructed easily. Through the application to a check valve and other types of equipments, the effectiveness of using Petri net for the VR-based machine-maintenance training system was demonstrated.

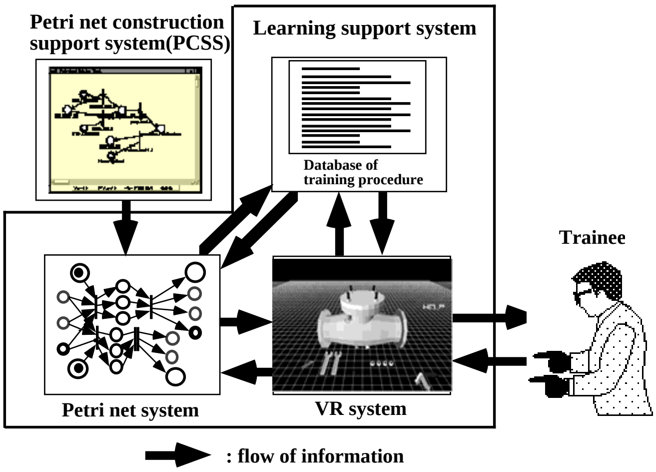

Figure 1: The whole system for training.

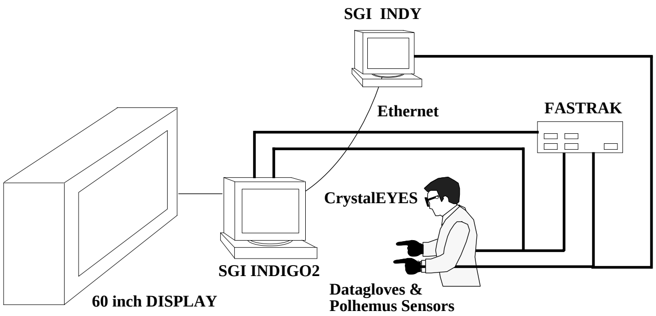

Figure 2: The whole VR system.

In this paper, the configuration of the training system is outlined first. And then the method to represent the disassembling/assembling procedures by using the Petri net model is explained. The basic idea and configuration of the Petri-net construction support system (PCSS) is described in the latter part of this paper.

Configuration of VR-based Training System

The configuration of the VR-based training system developed in this study is shown in Fig. 1. This system consists of four systems, i.e., VR system, Petri net system, Learning support system and Petri-net Construction Support System.

VR (Virtual Reality) System

The VR system shown in Fig. 2 measures the trainee's actions and produces various simulations in VE. This system consists of graphic workstations which produce graphical simulations using WorldToolKit as a programming library, 60 inch display, Crystal Eyes which provides a trainee with 3 dimensional images, Datagloves which measure the gestures of the trainee's hands, and Polhemus sensors which measure the location of the trainee's hands in 3 dimensional space. This system exchanges the information only about the name of the transition, which has fired or should fire, with Petri net system and Learning support system. See Mitani et al.(1995) for the detail of this system.

Petri Net System

The Petri net system restricts the change of the states of the objects in VE. This system is installed in the computer independent of the one which deals the VR system, and these two computers are connected through ethernet. This system identifies the names of the transitions which can fire and sends them to the VR system. According to this information and the trainee's actions the VR system determines the transition which should fire and sends its name to the Petri net system. And then, the states of Petri net change in the Petri net system.

Learning Support System

From the viewpoint of the training system, the function which offers appropriate advices to the trainee is very important. The training system developed in this study is equipped with the function that offers in VE the automatic performance of the task to be executed next whenever the trainee wants. This system accepts the name of the transition which has fired from the VR system and decides the proper transition which should fire next. And in response to the request from the VR system, this system sends the name of the proper transition to the VR system. In determining the transition which should fire in the next step, this system can use the information about the location of the tokens in Petri net, but the information about right procedure of assembly and disassembly cannot be obtained from the Petri net. The Petri net has only information about the tasks executable in the next step. Therefore, the additional information is necessary for the automatic performance. In this study the database about the right procedures is prepared besides the Petri net. See Ishii et al. (1997) for more discussion.

Petri Net Construction Support System (PCSS)

This support system makes it possible even for the novice regarding Petri net to make the objective large Petri net easily only by selecting Petri net parts prepared in advance. The detail of this system is mentioned in the latter part of this paper.

Petri Net Representation of Assembly/ Disassembly Procedures

In this section, the method to represent the disassembling/ assembling procedures of machines by using Petri net model is explained. This method is originally proposed in this study.

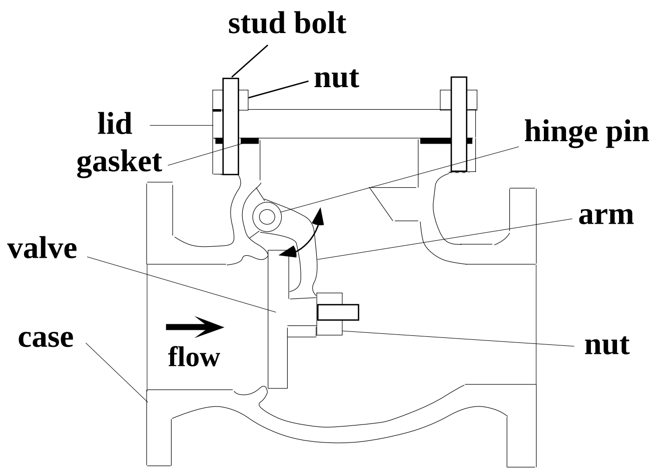

Figure 3: Check-Valve.

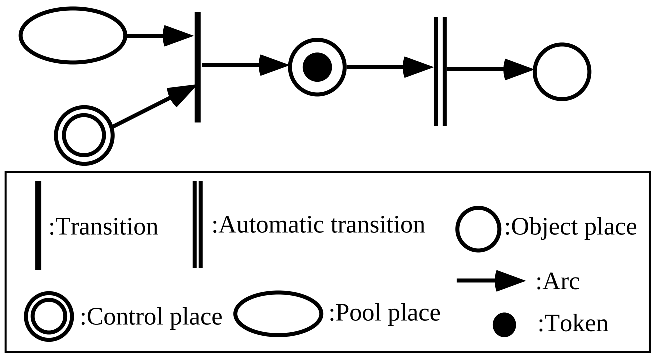

Figure 4: A simple example of Petri net.

The disassembling procedure of a check valve is adopted as an example.

Disassembly Procedure of Check Valve

The configuration of a check valve is illustrated in Fig. 3. According to the description of the textbook used in the training center, the whole procedure is summarized as follows:

1) Mark both the lid and the case with a marker pen in order to put the lid at the right position in the reassembly procedure.
2) Loosen a bit all the nuts on the lid with a spanner. The nuts should not be removed completely from the bolts at this stage to avoid an accident, because the internal pressure of the check valve might remain high.
3) Lift up the lid to confirm that the internal pressure be normal.
4) Get rid of all the nuts with a hand (and put them on an appropriate place).
5) Get rid of the lid.
6) Get rid of the stud bolts by double-nut method.
7) Get rid of the gasket with a spatula.
8) Hold the arm and pull the hinge pin out of the arm.
9) Get rid of the valve and arm.
10) Separate the valve from the arm.

The assembly procedure is just in the reverse order.

Characteristics of Petri Net Model

Petri net is a method of describing a relation between conditions and consequences of certain discrete events schematically. Figure 4 shows a simple example of this net. In this figure, 'transition' represents an event which occurs. The occurrence of an event is called 'fire' of transition. 'Places' are on both sides of a transition and are connected with the transition by arcs. The place, from which an arc starts, is called 'input place' and represents a condition for the fire of the transition, while 'output place' is the place where an arc ends and means the resultant states of the fire. The satisfaction of conditions is represented by a 'token' in input place. The condition for transition to fire is that each of its input places has one or more tokens. When a transition fires, a token in each input place disappears and appears in each output place. This is an outline of basic Petri net. Many variations of Petri net have thus far been proposed according to the objective of usage, and in this study, some new rules are adopted in applying Petri net to the training system:

1) An 'object' in VE corresponds to a token uniquely in the net. It is important that the number of tokens which correspond to the objects is conserved through the fire of transition. This kind of Petri net is called 'colored' Petri net.
2) A probable state of any object is represented by a place which is called 'object-place', and a token in an object-place means the current state of the object that corresponds to the token.
3) Change of object's state by trainee's action is represented by a transition, and executing the action triggers the fire of the transition.

Some more definitions about Petri net are introduced in this study as follows:

1) Pool place

'Pool place' permits plural tokens to enter at the same time and is represented by an oval. This place is necessary for the case that plural nuts are on a desk and that any of the nuts can be pinched, for example.

2) Control place

'Control place' is used to control actions of complicated Petri net, and is represented by 'double circle'. This place does not correspond to an object in VE.

3) Automatic transition

The transition described above represents trainee's intentional action. It is called 'manual transition'. But the state of the objects sometimes changes without the trainee's intention. Free-fall of objects is the typical example.

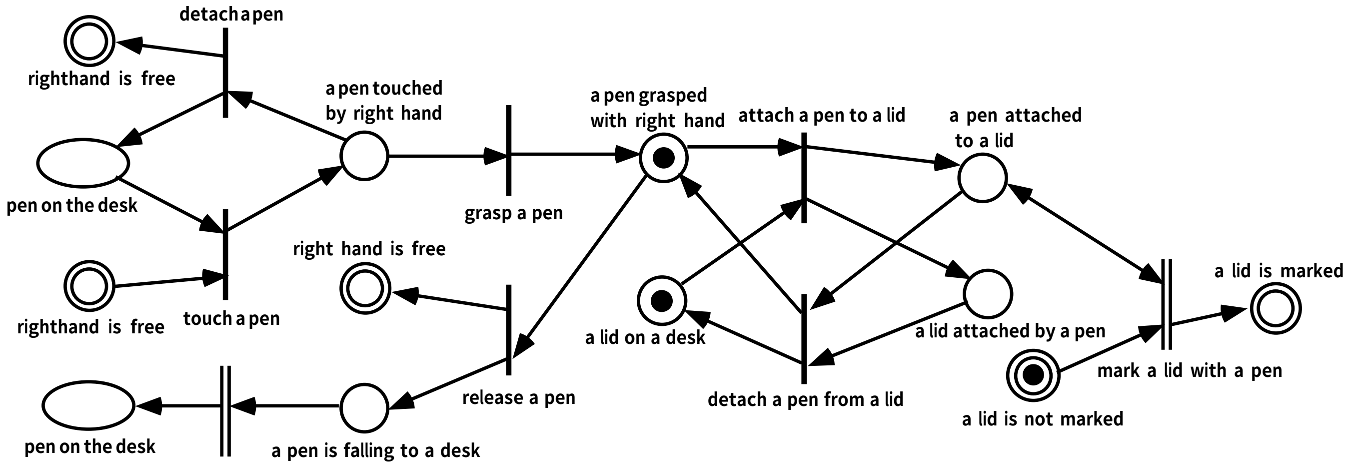

Figure 5: The Petri net representation of the procedure to mark a lid with a pen.

Table 1: The basic tasks in VE

Basic Tasks	
bt-1	Touch an object1 with hand1 (or a tool).
bt-2	Grasp (pinch) an object1 with hand1 (or a tool).
bt-3	Attach an object1 to object2 with hand1.
bt-4	Turn an object1 around by using an object2 with hand1
bt-5	Mark an object1 by object2 with hand1.
bt-6	Detach a hand1 (or a tool) from an object1 with hand1.
bt-7	Release an object1.
bt-8	Separate attached objects.
bt-9	Put an object1 into a hole of object2.
bt-10	Push an object1 by something.
bt-11	Pull an object1 by something.
bt-12	Examine something about objects.

'Automatic transition' is introduced to represent this kind of events and is represented by two parallel bars.

Based on above-mentioned definitions, the disassembly and assembly procedure of the check-valve can be represented by Petri net as is shown in the following subsections.

Basic Tasks in Assembly and Disassembly Procedures

The disassembling procedures of check valve can be decomposed into 'basic tasks'. The basic tasks, which are necessary to represent the assembly and disassembly procedure in VE, are generally shown in Table 1. Let us take two tasks, 'loosen a nut with a spanner in right hand' and 'mark the lid with a pen in left hand', as simple examples. These tasks can be decomposed into the basic tasks as is shown in

Table 2: Loosen a nut with a spanner in right hand

	Task	Basic task
1	Touch a spanner with right hand	bt-1
2	Grasp a spanner with right hand	bt-2
3	Attach the spanner to a nut with right hand	bt-5
4	Turn the nut around by using the spanner with right hand	bt-9
5	Detach the spanner from the nut with right hand	bt-3
6	Release the spanner with right hand	bt-11

Table 3: Mark a lid with a pen in left hand

	Task	Basic task
1	Touch a pen with left hand	bt-1
2	Grasp a pen with left hand	bt-2
3	Attach the pen to a lid with left hand	bt-5
4	Mark the lid by a pen with left hand	bt-4
5	Detach the pen from the lid with left hand	bt-3
6	Release the pen with left hand	bt-11

Table 2 and 3. The basic tasks used in both examples are only 7, because the same basic tasks are used in both examples. It should be noted that the basic tasks necessary to represent various procedures are expected to be very limited. The basic idea of Petri-net construction support system (PCSS) is based on this expectation. As is explained in the next section, PCSS modifies and combines the sub-nets of the basic tasks.

An Example of Petri-net Representation

The Petri-net representation of the procedure, 'mark a lid with a pen in right hand', is shown in Fig. 5. In this figure, there is a token in the place whose name is 'a pen grasped with right hand'. So it is understood that in VE the trainee has a pen in his right hand. And as both places whose names are respectively 'a pen grasped with right hand' and 'a lid on a desk' have a token, the transition whose name is 'attach a pen to a lid' can fire. And it is also understood that the trainee can attach a grasped pen to the lid.

The example shown above is rather simple, but in the case of 'with a pen on the right hand and a spanner on another hand' the possible tasks are of wide variation. Therefore, indispensable is the tool which supports the supervisors to construct Petri net easily.

Connection of Trainee's Action, Petri Net and VE

If a trainee does the action, e.g., 'grasp a pen' in VE, the transition whose name is 'grasp a pen' must fire in the constructed Petri net. But the constructed Petri net alone can not decide which transition should fire according to the trainee's action. In this study 'task functions' are prepared in advance. 'Task function' takes a role of connecting trainee's actions, VE and Petri net. Task function recognizes the trainee's actions and prepares information necessary for the control of VE and Petri net. When the trainee does an action in VE, the task function and also the transitions to fire are correspondingly selected according to the action. And when the action finishes, i.e., the transition fires, the states of the objects change in both VE and Petri net at the same time.

Petri Net Construction Support System (PCSS)

It is very important that the large Petri nets for the training system can be constructed in a mechanistic way. In this section PCSS(Petri net Construction Support System) developed in this study is explained. By this system, even novice users for Petri net can construct a large Petri net system very easily.

The Fundamental Concept on PCSS

The noticeable characteristics of the Petri net which represents the procedures for assembling and disassembling machines is that the sub-nets with the same or similar structure would often appear in the net. The typical example of this sub-net is already shown in Table 2 and 3. The procedures, that is, 'mark the lid with the pen' and 'loosen a nut with the spanner', appear many times in these tables, but it is evident that the former procedure, for example, can be constructed only by changing 'object1' ,'object2' and 'hand1' of bt-4 in Table 1 into 'pen' ,'spanner' ,'right hand' or 'left hand', respectively. Therefore, if someone who is familiar with Petri net very well has once constructed the sub-nets which represent the fundamental action in VE as is shown in Table 1, the others can use the net only by slightly modifying and combining the sub-nets. And from the view point of human-interface, it is desirable that the sub-nets can be modified visually. Therefore, the support system based on GUI (Graphical User Interface) is expected to make it much easier to construct the whole Petri net. In this study Tcl/Tk, that is a language for developing GUI, is used in PCSS so that the user can construct Petri nets visually.

The Functions for PCSS to equip with

In combining sub-Petri nets which are prepared in advance in order to construct a whole Petri net, the following problems should be considered:

1) How to connect sub-nets?,
2) How to modify the structure of sub-nets? and
3) What kind of sub-nets should be prepared in advance?

The problems, 1) and 2), can be solved by making rules as follows:

R-1) The places which have the same name are regarded as the same place.

R-2) The naming for the places should strictly follow some rules, so that the place can be recognized uniquely only by name.

Owing to these two rules, one can connect the plural nets and also modify the prepared net to get the objective net easily. The problem ,'what Petri net should be prepared in advance?', is discussed in the end of this section.

An Example of Using PCSS

In the following, explained is how to use PCSS by taking a task, 'mark a lid with a pen in right hand' as an example.

1) Input names of objects which exist in VE through key board. In this case, the names are 'lid', 'pen', 'desk' and 'right hand'.
2) Select appropriate nets from the set of the sub-nets prepared in advance. The name-list of the sub-nets are displayed on CRT whose scene is shown in Fig. 6. In this case, the sub-nets which represent 'grasp (pinch) an object1 with hand1 (or a tool)' and 'mark an object1 by object2 with hand1' are selected by using a mouse.
3) Input the relation among the objects according to the questions asked by the support system, such as 'What is the name of object1 which marks object2 ?'. In this case, the answer is 'pen' and 'pen' is selected by a mouse. (Fig. 7)
4) The support system finally connects the basic nets and expand into the necessary nets. (Fig. 8)
5) Include the constructed Petri net in the training system.

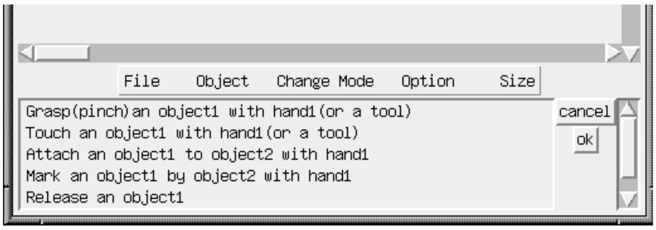

Figure 6: The scene of selecting aprepared net.

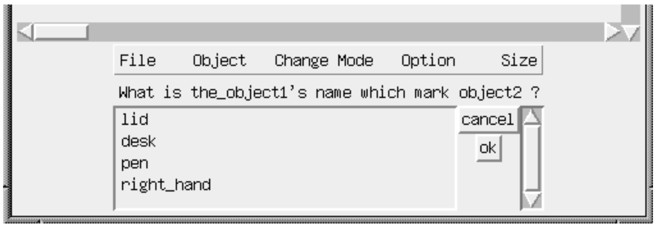

Figure 7: The scene of inputing the relation among the objects.

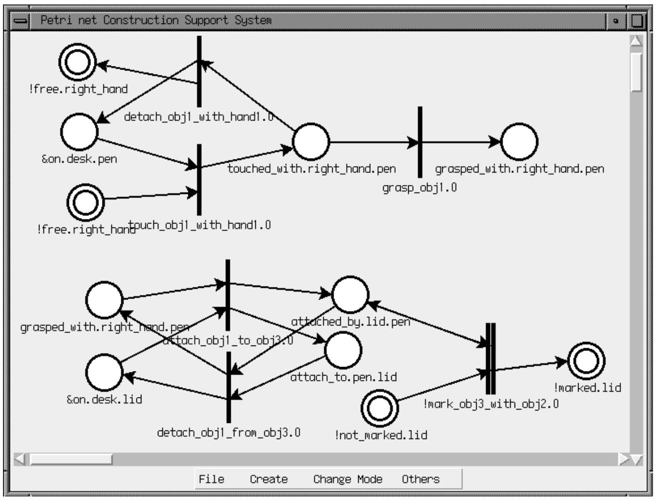

Figure 8: The evolved Petri net by PCSS.

The Effect of Using PCSS

As is understood from the above discussion, it is very important to decide what kind of Petri net should be prepared in PCSS. The number of sub-nets prepared for representing the disassembly procedure of check valve was 16, and each sub-net was composed of about 5 transition and 10 places. This number may be thought too large for the simple disassembly procedure. In constructing the net for the procedure of disassembling the other two types of value, however, the number of the newly constructed sub-nets was only 4. Therefore, once the sub-nets are prepared for some procedures of assembly and disassembly, the net necessary for the application to similar equipments can be constructed rather easily. This fact shows PCSS can remarkably reduce the load for constructing Petri net. And even a novice who are not so familiar with Petri net can develop the Petri net by using PCSS.

Conclusion

In this paper, the machine-maintenance training system which is based on Petri net is outlined. The representation method of various tasks by using Petri net is proposed, and the Petri net construction support system(PCSS) is explained. It is concluded that the effectiveness of applying Petri net to the machine-maintenance training system in VE is shown through simulation study.

There remain some problems for future study. The current system does not have the function which offers alarms and/or advices when the trainee executes an improper task. Also, making the database for the function which identifies the proper tasks to be executed takes much time now because it is done manually. Therefore, the support system for making the database should also be developed. For this purpose, it will be effective to use the concept of hierarchical Petri net which regards a group of transitions such as 'grasp a pen and mark a lid with the pen' as a macro-transition,.

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