

MODELING AND ANALYSIS OF REDUNDANCY IN REMOTE MONITORING AND CONTROL SYSTEMS VIA PETRI NETS

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Abstract: This paper presents techniques that enable the modeling and analysis of redundancy in remote monitoring and control systems. Hardware redundancy and software redundancy are both implemented in the proposed system organically. To model and analyze the redundancy, a formalism to derive Petri net (PN) model from state transition diagram is constructed and the monitor compatible condition is considered. Software redundancy mechanism in manager side is also modeled based on PN. This approach makes redundancy modeling and analysis possible in terms of well-developed concepts and methods in PN theory. By the analysis of the PN model, designers can obtain reliable and effective measures that would compare different schema in the early phases of design, and select the best one. Our approach is illustrated and validated on STPNPlay by an example.

1 INTRODUCTION

The remote monitoring and control system is extremely important for most automated manufacturing processes in large scale and long-distance distributed system. It receives signals from sensors, corresponds to exceptional situations, starts up emergent processes and announces alarms. In the past years, rapid development of Internet technology has witnessed monitoring systems changing from centralized form to multi-centre and distributed form. Lots of approaches have been proposed to monitor automated manufacturing systems from a long distance. However, monitoring and control systems are becoming more and more complicated to guarantee its reliability, as more devices are networked in automated manufacturing systems. Using redundant devices is a widely adopted method to ensure the quality when designing high assurance remote monitoring and control systems. That is to say, an effective redundancy structure is crucial to achieve a high-quality system.

This paper presents an effective modeling approach to analyze redundancy schemes with following benefits.

1. Both hardware and software redundancy mechanism are modeled in a generalized method.
2. By formalism and monitor compatible condition, the modeling approach is built up with well-developed concepts.
3. PN theory offers many effective methods to evaluate the performances of our model.
4. The approach presented in this paper can be performed in an automatic way.
5. Designers can obtain reliable and effective measures in the early design phases to compare different schemes and select the best one.

State transition diagrams are used to illustrate basic components' functions of both the agent side and the manager side. Then, corresponding PN models are proposed to use configurable graphical interface and mathematical analysis methods of PN to verify the redundancy structure before the implementation of the system. During the design process, the PN models are analyzed by performing algorithms which statistically assume probabilities of systems assurance at different levels.

The paper is structured as follows. In section 2 we discuss some related works. Section 3 describes the redundancy schemes in remote monitoring and

control systems. The modeling and analysis approach is outlined in section 4. Section 5 presents an illustrative example. Then the paper is closed by a short conclusion.

2 RELATED WORKS

Remote monitoring and control systems can be usually divided into two components. One is agent side and the other is manager side. Currently, more and more agent side devices are embedded with web server software to be conveniently monitored by manager side devices, using web browsers through the hypertext transfer protocol.

Petri nets (PN), first introduced in 1963, is widely used to model and analyze systems with parallel and concurrent activities. As a graphical-mathematical tool, several new types of PN have been developed to analyze different properties of systems in the past forty years. Classical PN offers methods to qualitatively analyze system properties such as reachability, boundedness, liveness, and conservativeness. Timed Petri nets (TPN) is used to quantitatively analyze the performance properties. By changing the numerical variables in TPN into stochastic ones to form a Stochastic Petri nets (SPN), Markov Chain Method can be used to analyze performance properties of systems, which offers more analytical ways. PN has not only precise semantics but also powerful analytical methods. Moreover, many approaches have been proposed to analyze various systems via PN automatically. This is why, in this paper, PN is adopted to obtain the analyzable models of redundancy schemes for remote monitoring and control systems. With this approach, both qualitative and quantitative analysis can be applied to achieve reliable long distance distributed systems.

3 REDUNDANCY IN REMOTE MONITORING AND CONTROL SYSTEMS

Generally, redundancy can be implemented in three aspects. The first is hardware redundancy which configures multi-backup for key hardware to enhance system's reliability. The second is software redundancy. By implementing some fault toleration software, systems can automatically return to the normal status from the abnormal one. And the third, information redundancy, adds to system some necessary data to enhance its reliability. Its merits

are lower redundancy requirements, unified treatment of information bit and checkout bit.

In general, the more the redundancy backup is implemented, the higher the system's reliability and cost is, and the more complicated the system's architecture is. Therefore, redundancy should be used properly in the weak parts to find a tradeoff between system reliability and its cost.

In remote monitoring and control systems, hardware redundancy is often applied to make the system work properly without any interruption even when a fault happens. While software redundancy is the most common way to enhance reliability of distributed software. In our work, hardware redundancy and software redundancy are implemented organically. In the agent side, hardware redundancy is the solo choice since basic and major components such as sensors, motors, and programmable logic controllers do not support high-grade software programming. Whereas, both hardware and software redundancy can be adopted in the manager side due to the advanced capability of the management stations, often computers.

Our approach develops high assurance systems

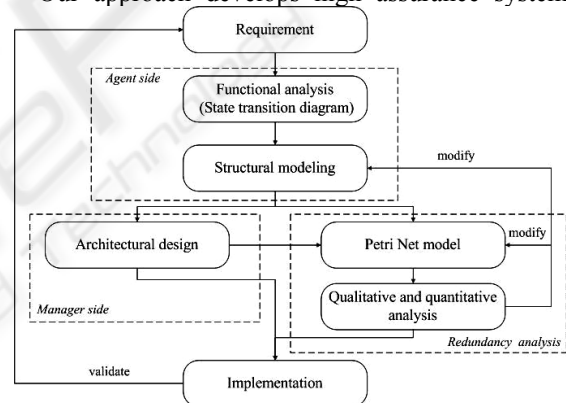


Figure 1: The development procedure for system.

with PN model and analysis. As is shown in Fig. 1, at the stage of functional analysis, state transition diagrams are used to depict the requirements corresponding to the purposed system. Then a model of detailed structure is set up to describe relationships of the agent side at the stage of structural modeling. Subsequently, at the architectural design stage, the approach is completed by finishing the design of the manager side. By constructing PN models, we can perform both qualitative and quantitative redundancy analysis when designing the agent side and manager side. Finally, the obtained schema is implemented and validated. If it does not meet the requirements, the procedure will return to the beginning. Thus the system is developed in an iterative and incremental way.

4 REDUNDANCY MODELING AND ANALYSIS

In this section, our redundancy architecture of the remote monitoring and control system is introduced first. Then, a formalism to build PN is constructed to represent the working process of sensors, motors, and other components of agent side. PN model about software redundancy is also derived from the manager side. At last, analysis of redundancy is discussed.

4.1 Redundancy architecture

Remote monitoring and control system with redundancy architecture can run properly even when some parts have faults. The redundancy architecture presented in our work which implements both hardware and software redundancy is shown in Fig. 2.

In the agent side, each sensor and motor connects with two agent nodes with completely the same type. Application program works in parallel, and realizing the data sampling and communication tasks. The comparison algorithm is used by management stations to automatically find the abnormal agent node. When the two agent nodes run normally, they send the same sampling data to network from the same sensor. Once one of them is wrong, the comparison program would find it by comparing data and diagnosing status information. Then the management station would dynamically remove the abnormal node, and inform the system manager.

Software redundancy is more complex and harder to implement compared with hardware backup of

parallel-style. But it needs less resource. Since the management station is power enough to run advanced software, software redundancy technology is a good choice in the manager side. In software redundancy architecture, tasks are performed by service processes dynamically generated by fault toleration program. The states of stations and the fault toleration program will decide which station would perform the task. If a task fails, the software redundancy mechanism will invoke error recovery method to avoid single task failure. If a station fails, the fault toleration software will automatically assign another station to take over the faulted node and announce fault alarm immediately. The UPS should be used as power supply of management stations in real application.

4.2 Modeling of redundancy structure

To outline our work in a formal way, we introduce the following definitions of state transition diagram and Petri net.

Definition 1: A state transition diagram is a 4-tuple $STD = \{Q, E, \delta, q_0\}$, where

1. $Q = \{q_1, q_2, \dots, q_m\}$ denotes a finite set of states,
2. $E = \{e_1, e_2, \dots, e_n\}$ denotes a finite set of transitions,
3. δ denotes the state transition function defined on $Q \times E$ and $\forall q \in Q, \exists e \in E \wedge q' \in Q: \delta^2(q, e) = q' \vee \delta(q', e) = q$,
4. $q_0 \in Q$ is called the initial state.

Definition 2: A Petri net is a 4-tuple $PN = \{P, T, F, M_0\}$, where

1. $P = \{p_1, p_2, \dots, p_m\}$ denotes a finite set of

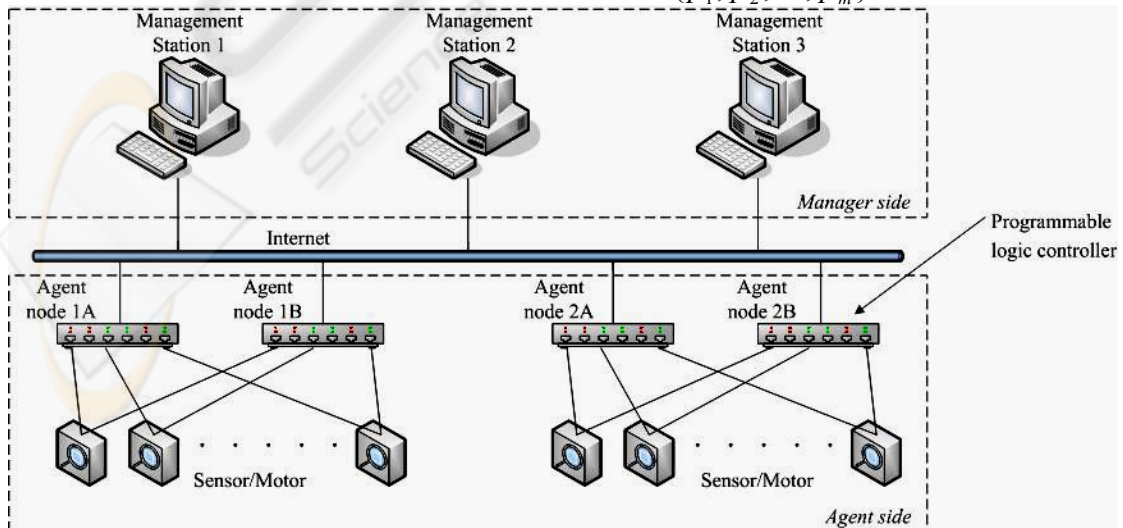


Figure 2: Redundancy architecture.

places,

2. $T = \{t_1, t_2, \dots, t_n\}$ denotes a finite set of transitions,
3. $P \cap T = \emptyset$ and $P \cup T \neq \emptyset$,
4. F is the incidence function defined on $(T \times P) \cup (P \times T)$, and denotes the set of arc links between places and transitions,
5. $\forall p \in P, \exists t \in T : F(p, t) \neq 0 \vee F(t, p) \neq 0$,
 $\forall t \in T, \exists p \in P : F(p, t) \neq 0 \vee F(t, p) \neq 0$
- 6 M_0 is the set of token values defined on P and is called the initial marking.

4.2.1 PN model of sensors and motors

The sensors and motors often have straightforward state transition diagrams since they are designed in a high reliable way with only a few states. The PN model derived from state transition diagram is formally specified as follows.

Definition 3: If $STD = \{Q, E, \delta, q_0\}$ is a state transition diagram, the Petri net of it, $PN(STD)$, is defined to be $PN(STD) = \{P, T, F, M_0\}$ where

1. Places and transitions: $P = Q$, and $T = E$,
2. $F(p, t) = 1$ if $\delta(p, t)$ is defined and $F(t, p) = 1$ if $\delta(t, p)$ is defined,
3. Initial mapping: $M_0(p) = n$ if $p = q_0$, 0 otherwise.

4.2.2 Agent side PN model

Agent nodes are more sophisticated than sensors or motors due to their processing and control interaction between sensor/motors and management stations. They are the most crucial devices having connecting links between the preceding and the following in remote monitoring and control systems. We introduce the following definition to formalize the agent side PN model.

Definition 4: A state transition diagram $S = \{Q, E, \delta, q_0\}$ is a state transition diagram of agent node, if $Q = Q_{io} \cup Q_m \cup Q_c$ and $E = E_{io} \cup E_m \cup E_c$ where $Q_{io} \cap Q_m = Q_m \cap Q_c = Q_{io} \cap Q_c = \emptyset$ and $E_{io} \cap E_m = E_m \cap E_c = E_{io} \cap E_c = \emptyset$, satisfy the following conditions:

1. $q_0 \in Q_{io}$, $Q_c = \{q_{c1}, q_{c2}, \dots, q_{cj}\}$,
 $Q_m = \{q_{m1}, q_{m2}, \dots, q_{mj}\}$, $E_{io} = E_a \cup E_b$,
 $E_a = E_{ai} \cup E_{ao}$, $E_b = E_{bi} \cup E_{bo}$,
 $E_i = E_{ai} \cup E_{bi}$, $E_o = E_{ao} \cup E_{bo}$,
 $E_i \cap E_o = E_{ai} \cap E_{ao} = E_{bi} \cap E_{bo} = \emptyset$, and
 $E_{ai} = \{e_{ai1}, e_{ai2}, \dots, e_{ain}\}$,
 $E_{ao} = \{e_{ao1}, e_{ao2}, \dots, e_{aon}\}$,
 $E_{bi} = \{e_{bi1}, e_{bi2}, \dots, e_{bik}\}$,
 $E_{bo} = \{e_{bo1}, e_{bo2}, \dots, e_{bok}\}$.
2. For any $e \in E_c$, if $\delta(q, e)$ is defined, then $\delta(q, e) \in Q_{io} \cup Q_c$; for any $e \in E_{io}$, if $\delta(q, e)$

is defined, then $\delta(q, e) \in Q_{io} \cup Q_m$ if $q \in Q_{io} \cup Q_m$ or $\delta(q, e) \in Q_{io} \cup Q_c$ if $q \in Q_{io} \cup Q_c$; and for any $e \in E_m$, if $\delta(q, e)$ is defined, then $\delta(q, e) \in Q_{io} \cup Q_m$.

Remark 1: In an agent node state transition diagram S , Q_m represents the set of possible monitor states when the agent node plays the role as a monitor of sensors and motors, Q_c represents the set of possible control states when the agent node plays the role as a control of sensors and motors, Q_{io} represents the set of possible I/O states when the agent node does some communications.

Remark 2: Similarly, E_m represents the set of possible monitor transitions when the agent node plays the role as a monitor, E_c represents the set of possible control transitions, E_{io} represents the set of possible I/O transitions. E_a represents the I/O transitions which communicate with sensors and motors and E_b represents the I/O transitions which communicate with management stations. E_i represents the I/O transitions which receive a message and E_o represents the I/O transitions which send a message. E_{ai} , E_{ao} , E_{bi} , and E_{bo} have the same interpretation with respect to the I/O transitions.

Remark 3: Condition (1) implies that for each monitor state, there is a corresponding control state; and for each transition which send messages to sensors and stations, there is a corresponding transition which receives messages from sensors and stations respectively and vice versa.

Remark 4: Condition (2) indicates that the monitor transitions will always keep the agent node in the monitor state; and that the control transition will always keep the agent node in the control state.

To guarantee that a sequence of messages sent can always be processed, and a sequence of control actions will always correspond to some monitor behaviors, we introduce the monitor compatible condition. To do this, the following notations are introduced: for any state $q \in Q$, its co-state is defined as $\bar{q} = q$ if $q \in Q_{io}$, or $\bar{q} = q_{mk} / q_{ck}$ if $q = q_{ck} / q_{mk}$; for any transition $e \in E$, its co-transition is $\bar{e} = e_{mk} / e_{ck}$ if $e = e_{ck} / e_{mk}$, or $\bar{e} = e_{aik} / e_{aok}$ if $e = e_{aok} / e_{aik}$, or $\bar{e} = e_{bik} / e_{bok}$ if $e = e_{bok} / e_{bik}$; for any sequence of transitions $x = e_1 \dots e_s \in E$, its co-sequence of transitions is $\bar{x} = \bar{e}_1 \dots \bar{e}_s$. Then an agent node is said to be monitor compatible if and only if $\forall x \in (E_c \cup E_{io})^* \cup (E_m \cup E_{io})^*$, $p \in Q$:
 $q = \delta(p, x) \Leftrightarrow \bar{q} = \delta(\bar{p}, \bar{x})$.

Since the agent side is composed of agent nodes, sensors and motors, and two agent nodes with lots of sensors as well as motors are the elementary components, we introduce the following definition to derive the PN model in terms of S and STD .

Definition 5: If S_1 and S_2 are two state transition diagrams of a pare agent nodes, STD_1, \dots, STD_r are r state transition diagrams of sensors and motors, the elementary agent side PN, $PN(S_1, S_2; STD_1, \dots, STD_r)$ is defined to be $PN(S_1, S_2; STD_1, \dots, STD_r) = (P, T, F, M_0)$ where

1. $P = Q_{s1} \cup Q_{s2} \cup Q_1 \cup \dots \cup Q_r \cup C_1 \cup \dots \cup C_r$, $C_j = \{p_{i1}^j, \dots, p_{in2}^j, p_{o1}^j, \dots, p_{on}^j\}$, $T = E_{s1} \cup E_{s2} \cup E_1 \cup \dots \cup E_r$
2. $F(p, t) = 1$ if $\delta_k(p, t)$ is defined or $(p, t) = (p_{iu}^j, e_{au}^j)$, or (p_{ou}^j, e_w^j) ; $F(t, p) = 1$ if $\delta_k(t, p)$ is defined or $(t, p) = (e_{au}^j, p_{ou}^j)$, or (e_w^j, p_{iu}^j) ; otherwise, $F(t, p) = 0$, where $j = 1, \dots, r$; $k = s1, s2, 1, \dots, r$; $l = s1, s2$; $u = 1, \dots, n$; $w = 1, \dots, |E_j|$.
3. $M_0(p) = n_k$ if $p = q_0^k$, 0 otherwise.

$PN(S_1, S_2; STD_1, \dots, STD_r)$ is constructed by connecting S_1, S_2 and STD_1, \dots, STD_r through additional places C_1, \dots, C_r . These new places represent the communication point between the two parts. Message exchange between the two parts can be achieved only through the communication point. The PN model will specify all the possible monitor and control actions between an agent node and sensors by using the execution rule of PN. Thus, the PN model of agent side has been derived.

4.2.3 PN model of software redundancy and the system

Fault tolerant software architecture is widely used to form a redundancy structure in distributed systems. Several approaches have been proposed to build highly available applications. As shown in Fig. 3, fault tolerance is provided by the replication of managers, fault detection and error recovery. The

agent side should not be aware of the faults in the management station or the recovery from faults, nor should it be aware of the fact that the managers are replicated. Local fault detectors are monitored by a global fault detector which detects when a local fault detector is not available. Managers are continuously monitored by local fault detectors which are deployed on each management station. If a fault occurs, then the local fault detector reports the error to the fault notifier. The fault notifier analyzes incoming error reports and sends a notification to the redundancy manager. When the redundancy manager receives a notification, it would initiate the recovery of the manager or assign another manager to handle it.

We are interested in redundancy model in the early phases of system design, so that decisions can be made to choose the best redundancy scheme. Therefore, we focus on the abstract from implementation details. In our approach, we first give a UML model about software redundancy architecture and then a PN model. The most sophisticated part in the redundancy structure is the model of redundancy manager, which should consider the event queue, dispatcher and dependency.

The model proposed here is an object model which can be easily specified by unified modeling language (UML). Lots of approaches have been proposed to derive PN model from UML model automatically, therefore it is easy to get the PN model of the manager side.

Combining the PN model of agent side and the PN model of manager side is similar to combining the PN model of agent node and the PN model of sensors and motors. Here is the definition.

Definition 6: $PNA(P^a, T^a, F^a, M_0^a) =$

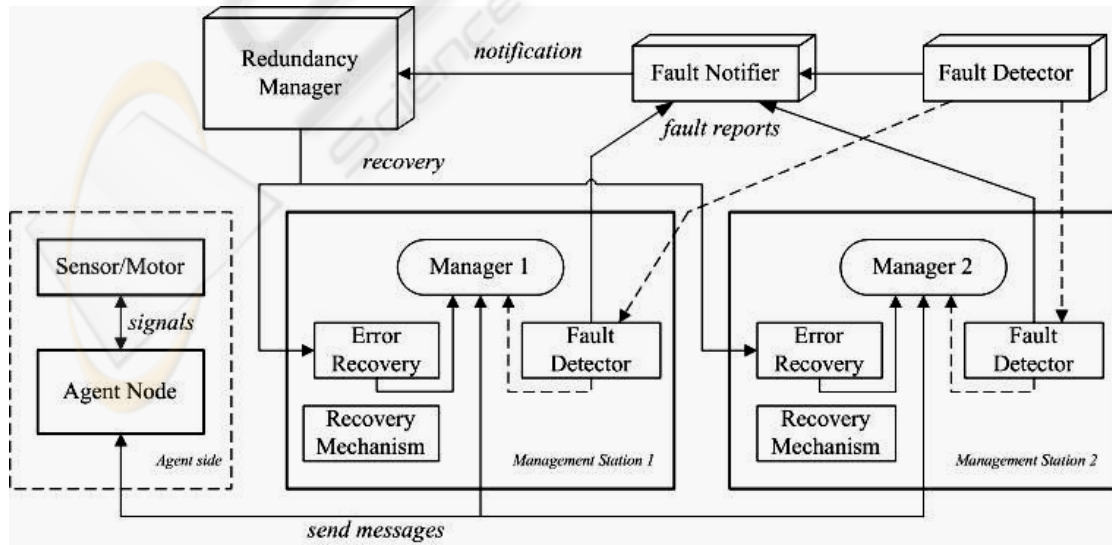


Figure 3: Management side redundancy structure.

$PN(S_1^1, S_2^1, STD_1^1, \dots, STD_n^1) \cup \dots \cup PN(S_1^s, S_2^s, STD_1^s, \dots, STD_n^s)$ is the agent side PN and $PNM(P^m, T^m, F^m, M_0^m)$ is the manager side PN. $T_c \subset T$ is the possible set of transitions when manager side communicates with agent side. Then the system PN $PN(PNM, PNA)$ is defined to be $PN(PNM, PNA) = (P, T, F, M_0)$ where

- $P = P^a \cup P^m \cup D_1 \cup \dots \cup D_s$,
 $D_j = \{p_{il}^j, \dots, p_{ik}^j, p_{ol}^j, \dots, p_{ok}^j\}$,
 $T = T^m \cup T^a$,
- $F(p, t) = 1$ if $F^a(p, t) = 1$ or $F^m(p, t) = 1$,
or $(p, t) = (p_{iu}^j, e_{biu}^j)$, or (p_{ou}^j, t_w) ;
 $F(t, p) = 1$ if $F^a(t, p) = 1$ or $F^m(t, p) = 1$,
or $(t, p) = (e_{bou}^j, p_{ou}^j)$, or (t_w, p_{iu}^j) ; otherwise,
 $F(t, p) = 0$, where $j = 1, \dots, s$; $l = s1, s2$;
 $u = 1, \dots, k$; $w = 1, \dots, |T_c|$.
- $M_0(p) = M_0^a(p) \wedge M_0^m(p) = M_0^m(p)$, 0 otherwise.

4.3 Analysis of redundancy

PN model analysis can be both qualitative and quantitative. Qualitative analysis shows the structural characteristics and qualitative analysis shows performance. Both qualitative and quantitative analysis can be performed in our PN model.

In our qualitative analysis, we consider the liveness and boundedness properties. The liveness property means that the system can be executed properly without deadlocks, and boundedness property means that the system can be executed with limited facilities. For quantitative analysis, appropriate parameters, such as time period or error probability, are assigned for the PN model.

Simulations will show us the critical transitions of the system. Moreover, the sensitivity analysis based on static cycle methods can also find the critical

timed transitions.

5 AN EXAMPLE

Our illustrative example is a model of an application about oil well. In this example, there are 3 wells. Each well, 20 temperature sensors, 20 humidity sensors, 4 power sensors, 4 current sensors, 4 voltage sensors, and 120 binary sensors are connected to a pair of agent nodes to be monitored. As faults occur, corresponding control actions such as power off the motors and reset the sensors are taken. Moreover, there are three management stations for safety in case of managers' crash. In the following presentation we focus on the model of agent nodes and software redundancy.

5.1 PN mode

Based on the state transition diagram, information can be extracted to build a PN model. The model of temperature and voltage sensors have 3 places and 4 transitions each, while the model of power and binary sensors have 2 places and 2 transitions each. The simplified PN of agent node is shown in Figure 4. It consists of 26 places and 30 transitions. This PN model satisfies Definition 4 and monitor compatible condition. That is to say all messages sent will be processed, and all control actions will correspond to monitor behaviours.

Without restricting the interfaces and the implementation of the system, we assume that 4 events, unrecoverable, recovered, task fault, station fault are processed by redundancy manager. Figure 5 depicts the PN model of the manager side with 3 stations and a 4 length buffer. t6 causes task fault, while t7 recovers task fault, and t8, t9 cause station

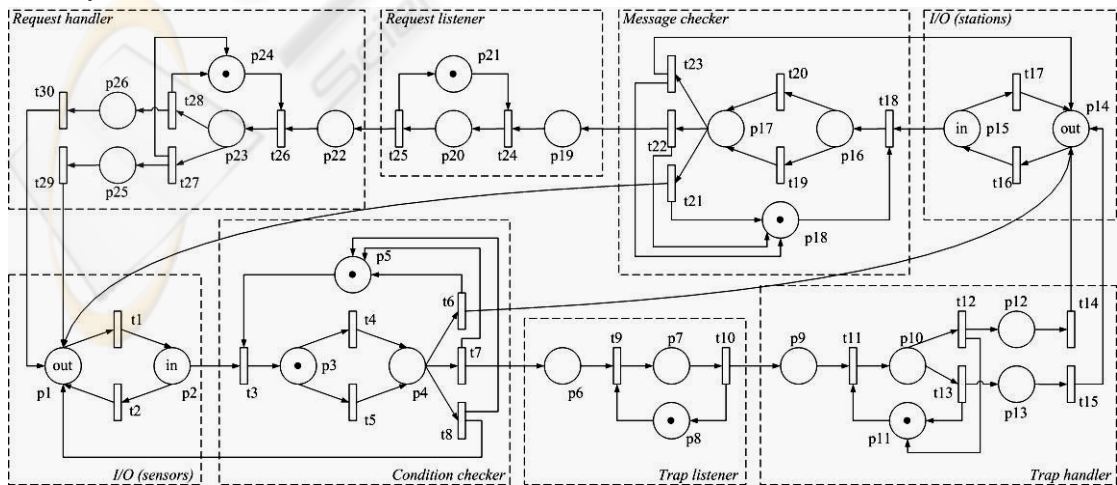


Figure 4: PN model of agent node.

fault. If there are no tokens in p5, t4 will never be triggered. It means that if there are no stations available, manager side will refuse to receive any tasks. The failure of a station is effectual only if a task is deployed on it. t9 and t12 are triggered by administrators which means that both task fault alarm and station fault alarm will cause the administrators to reset the systems. Obviously, these operations will take a long time and degrade the reliability level.

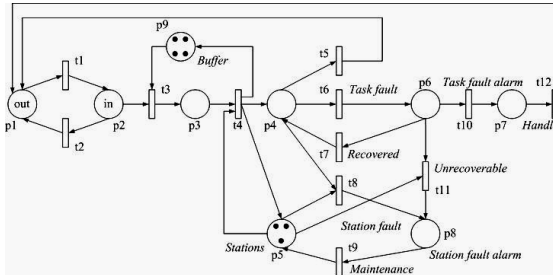


Figure 5: PN model of management side.

By using definition 5 and 6, the PN model of redundancy about the whole remote monitoring and control system can be derived now. The software package STPNPlay is adopted to verify quantitative properties of the PN model because of its graphical representation, ease of manipulation, and ability to perform performance analysis.

5.2 Measurement results

The PN model of the system consists of more than 200 places and 200 transitions. The analysis answers two questions. One is what is the probability of having at least one working station and the other is what is the probability of having at least one working agent node. In the early phase of the design usually timed PN transitions with exponential distribution are used in the model and the designer estimates the parameters of the distributions. This assumption enables an analytical solution of the model. Here we assumed the following parameters:

Modeled occurrence	Average time units
Station failure	10,000
Task failure	1,000
Task recovery	10
Local fault detection	10
Global fault detection	100
Agent node failure	10,000

The simulation on STPNPlay has reached following results. As Fig. 6 shows, the probability of having at least one working station is bigger than 99.99%, of having at least two working stations is 99.9% and of having three working stations is

98.4%. Similarly as Fig. 7 shows, the probability of having at least one working agent node is 99.9%, of having a selected working agent node is 99.6% and of having both working agent node is 99.1%.

In early design phase, a critical question is the comparison of different architectural solutions.

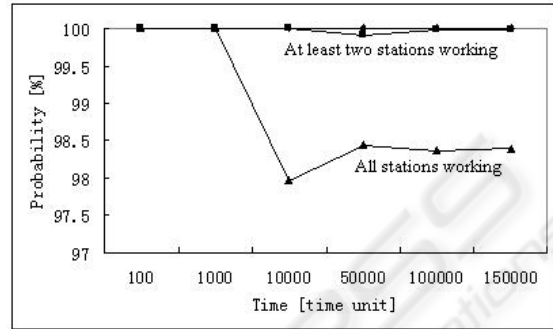


Figure 6: Probability of having working stations

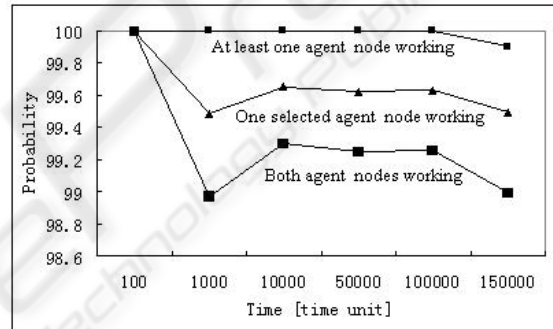


Figure 7: Probability of having working agent .

Designers can reduce the design cycle by comparing different solutions and dwelling on the best fitting one. In our example, the parameter of the number of stations and agent nodes can be used to achieve the required availability. The comparison of systems with different number of stations and agent nodes is quite easy and the required modification of the PN model is straightforward.

5.3 Further work

The results of this study lead to the following discussion. Since the manager side model developed here for application to remote monitoring and control system is based on the object-oriented concept, reusable models can be grouped into a library to make the design process more efficient. Exponential timing is not the most appropriate assumption of fault handling policy. The analysis can be performed correctly by using SRN models with deterministic timed transitions. Security is a prime concern for many network control systems. Improving the security by applying security protocol

should be feasible. Formalism method is becoming popular in developing systems. With its illation and math form, it can guarantee the systems properties in a mathematical way. Thus a powerful and easy usable formalism method would be a great benefit.

6 CONCLUSION

This paper presents a Petri net based approach to achieve design and modeling of redundancy in remote monitoring and control systems. The complex redundancy architecture can be analyzed automatically. The analysis can be performed in early design phase when the system structure and redundancy behaviour is defined. The manager side model is object-oriented, which describes software redundancy architecture. While the agent side model is more detailed, describing hardware redundancy architecture. The state transition diagram is transformed to a PN model which is analyzed by off-the-shelf tools. The optimal redundancy architecture can be selected by modeling different redundancy architectures, considering monitor compatible condition and subsequent property analysis.

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