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FAULT DIAGNOSIS ON THE HIGHWAY SURVEILLANCE AND CONTROL SYSTEM BASED ON PETRI NET MODEL

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ABSTRACT

Highway Surveillance and Control System (HSCS) is the critical system to improving the traffic safety and efficiency of highway. In this paper, the fault diagnosis model of HSCS based on Petri Net Model is provided in line with the composition, fault types and features of HSCS, and subsequently the fault diagnostic algorithm is given. In the end of this paper, the fault diagnosis of Microwave Vehicle Detector (MVD) in HSCS is presented to verifying the proposed fault diagnosis model and algorithm.

1 INTRODUCTION

Highway Surveillance and Control System (HSCS) is the critical system to improving the traffic safety and efficiency of highway. It can monitor and control the traffic information through the real-time acquiring and processing of highway traffic status and environment parameters, and therefore, it can achieve the safe and high efficient running of highway.

In practice, HSCS is composed of the following four sub-systems: Information Acquisition Sub-system (IAS), Information Transmission Sub-system (ITS), Information Processing Sub-system (IPS) and Information Distribution and Control System (IDCS). These subsystems have obvious interaction and complex performance topology, and thus lead to great difficulties on the faults diagnosis of HSCS.

At present, the fault diagnosis technical for complex system can be divided into the following three categories, Analytical Model Diagnosis Method (AMDM), Signal Processing Diagnosis Method (SPDM) and Intelligent Fault Diagnosis Method (IFDM) (Isermann R., 2005). AMDM is the earliest development system fault diagnosis method, which can execute real-time diagnosis by the establishment of precise mathematical model and understanding of the dynamic nature of the diagnostic object. For AMDM, its advantage is that the fault can be directly diagnosed without the knowledge of historical experiences because of the clear description on the fault propagation diagnostic model. However, the disadvantage is that the accurate diagnostic model is difficultly obtained due to the modeling error, disturbance, and the presence of noise etc, and which leads to the lower fault diagnostic rate. SPDM execute the fault diagnosis by extracting the features and relations of the measurable input and output signal through the following analysis method such as the correlation function, higher-order statistics, and autoregressive moving average wavelet technology etc. IFDM, which is particularly suitable for non-linear system and complex system, diagnoses the system faults based on the knowledge and diagnostic object model, and does not depend on the analytical model. Normally, the main intelligent fault diagnosis method includes Expert System, Fuzzy

Logic Method, Neural Network Method, Fault Tree Analysis Method and Petri Net Model etc (Zhu L. et al, 2008, Zhang L. et al, 2010, Doan X. et al, 2008).

In the above intelligent fault diagnosis method, because it can effectively describe the dynamic performance of the faults' generation and propagation, Petri Net Model has been increasingly applied in the fault diagnosis of the following complex dynamic system, such as power system, complex electro-mechanical system, industrial process state supervision and so on (Kano M. et al, 2008, Liu Z. 2008, Zhang H. et al, 2010, Ghainani A. T. et al, 2012).

In this paper, the fault types and features of HSCS are firstly analyzed, the fault diagnosis model of HCSC based on Petri Net Model is provided and subsequently the fault diagnostic algorithm is given according to the provided fault diagnosis model. Finally, as the end of this paper, a typical application is presented to verifying the proposed fault diagnosis model and algorithm.

2 FAULT TYPES AND FEATURES OF HSCS

As previously mentioned, HSCS is composed of the following sub-systems: IAS, ITS, IPS and IDCS. Thereamong, IAS acquires the following traffic information such as traffic flow & status parameters, traffic incidents, traffic environments parameters, and so on. ITS which simultaneously integrates the computer network and other communication median realizes the high reliable and effective transmission of acquired information by IAS. IPS generates the optimized traffic control strategy and control program according to the acquired information from IAS. IDCS is the implementer of generated traffic control strategy, which includes information issue devices (such as Changeable Message Signs, Changeable Speed Limiting Signs, etc.) and traffic control devices (such as Traffic Signal Lamps and Power Supply Devices, etc.). According to the traffic control strategy generated by IPS, IDCS gives the information of traffic status and environment parameters, and issues the traffic control commands to the traffic control device, so as to realize the high traffic efficiency and running safety of highway. In a word, HSCS has a wide range of equipments and there is complex performance interaction & topology among these equipments. So, in order to diagnosing the fault of HSCS, the fault types and features in the operation of HSCS should be firstly determined.

According to the investigation, statistic and analysis of the failures in the operation of HSCS, the main faults and its characteristics are determined, which are given as follows:

1) The failure rate of the sub-system in HSCS is given in figure 1. As shown in figure 1, the failure of IAS accounts for 50% of the total failures in HSCS, the failure in ITS is 7.14% of total failures in HSCS, the failure of IPS is 11.90% of total failures, and the failure of IDCS accounts for 30.95%.

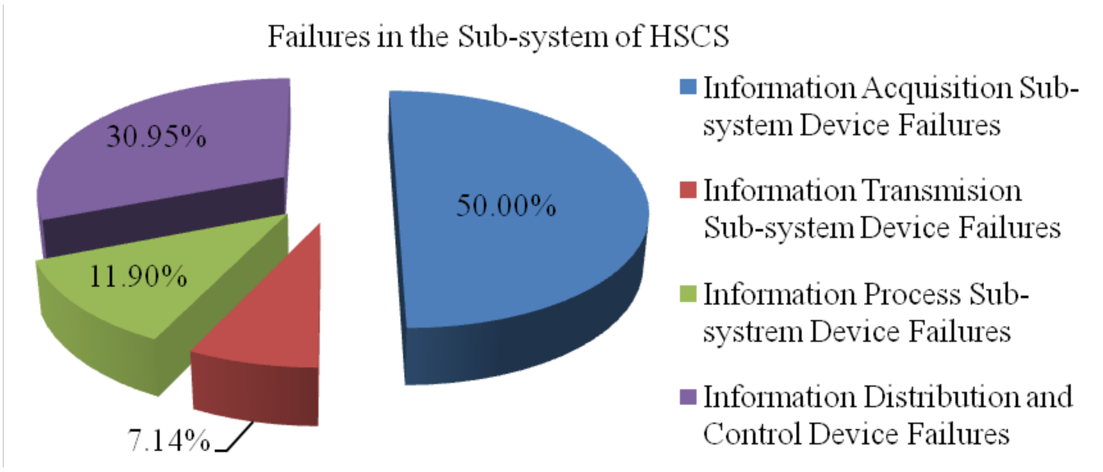


Figure 1: Failures in the Sub-system of HSCS

2) According to the position of failures, the failures of HSCS can be classified into the following four categories:

(1) Device Unit Failures, which mainly include the information collection unit device failure, data processing unit failure and information processing software failure, etc.

(2) Transmission Unit Failures, which include transmission device failure, communication port failure, network connection failure and transmission cable failure, etc.

(3) Power Supply Unit Failures, which include power supply facility failure, power supply failure, power supply cable failure, etc.

(4) Occasional failures.

The failure types of HSCS and its proportion is shown in Figure 2.

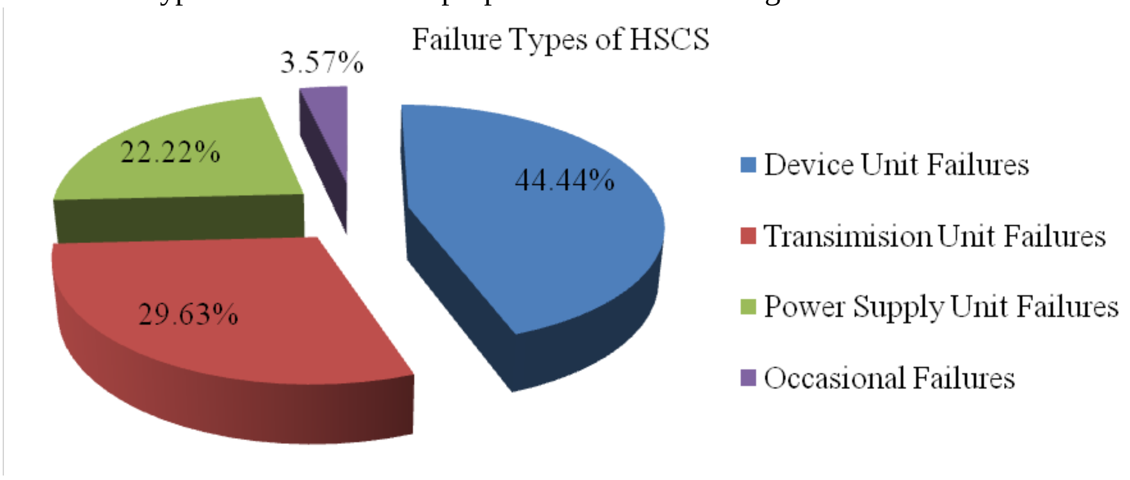


Figure 2: Failures Types of HSCS

The description of the abovementioned failures and its features in HSCS are listed in Table 1.

Table 1: Failures description and its Features

No.	Failure Type	Failure Description	Failure Features
1.	Device Unit Failures	the failures of HSCS devices	1) device has no output 2) the output data of device is abnormal
2.	Transmission Unit Failures	transmission device failures	1) the output data is normal 2) surveillance and control center cannot receive the output data
3.	Power Supply Unit Failures	the failures of power supply sub-system devices	1) surveillance and control center cannot receive the output data 2) the output data is normal 3) the transmission device is working properly
4.	Occasional failures	accidental failures	1) HSCS devices work properly 2) transmission device works properly 3) power supply unit works properly 4) unexplained failure

3 FAULT DIAGNOSIS MODEL OF HCSC BASED ON PETRI NET MODEL

As mentioned above, the devices of HSCS have relative fixed installation, interaction and running route and function topology, and therefore the fault propagation of HSCS has obvious law. Thence, in HSCS, according to the function topology, traffic information data flow and fault propagation route, the fault propagation model can be established. Whereas the fault diagnosis of HSCS is the inverse process of fault propagation, its process is determined the cause and their propagation path based on the known fault of HSCS. Therefore, in order to diagnosing the failures of HSCS, the fault diagnosis model should be given based on the fault propagation model.

According to the failure feature and fault propagation characteristic of HSCS, the fault diagnosis model based on Fuzzy Petri Nets is defined as the following eight-tuple:

$$DM=\{P,T,D,I,O,f,\alpha,\beta\} \qquad (1)$$

Where, P={p_1, p_2,…, p_n} describing a finite set of places ($n \geq 0$), which indicates the running status of HSCS devices; T={t_1, t_2, …, t_m} describing a finite set of transitions ($m \geq 0$), such that P $\cap$ T = $\varnothing$, which indicates the process or condition of the failures in HSCS; D={d_1, d_2, …, d_t } describing a finite set of tokens ($t \geq 0$), which indicates the fault symptoms in the running status of HSCS devices; I $\subseteq$ {P x T} is the input set that defines the set of directed arcs from places to transitions; O $\subseteq$ {T x P} is the output set that defines the set of directed arcs from transitions to places; f: T→[0,1] describing the credibility distributed to each transition; α: P→[0,1] describing the credibility assigned to each place; β: P→[0,1] describing the credibility assigned to each token.

In the above model, a transition can be fired (or the fault can be triggered) in the following conditions:

For a given threshold value λ, the transition will be fire when the token value is greater than λ, otherwise, the transition cannot be fired.

That is, when $\alpha(p_i)\geq\lambda$, the transition t will be fire, the fault will happen; when $\alpha(p_i) \not\geq \lambda$, the transition t cannot be fired, the fault will not happen.

In the provided diagnosis model of HSCS, there are four basic types and corresponding diagnosis rules, which are given as follows:

1) Antecedent Token is "AND"

As shown in Figure 3, when the antecedent Token is "AND", which means multiple input paths result in a singular output. In other words, when conditions exists to place a token d_1, d_2, …, d_n at p_1, p_2, …, p_n, the transition fires and synchronizes the antecedent paths to the beginning of d_k at p_k.

The diagnosis rule can be described as,

$$\text{if } d_1 \text{ AND } d_2 \ldots \text{AND } d_n \text{ THEN } d_k,$$
$$CF(d_k)=\min(\theta_{d1}^0, \theta_{d2}^0, \ldots, \theta_{dn}^0)\times\mu_i \quad (2)$$

Where, $\theta_{d1}^0, \theta_{d2}^0, \ldots, \theta_{dn}^0$ describing the corresponding credibility, μ_i describing the credibility of transition t_i.

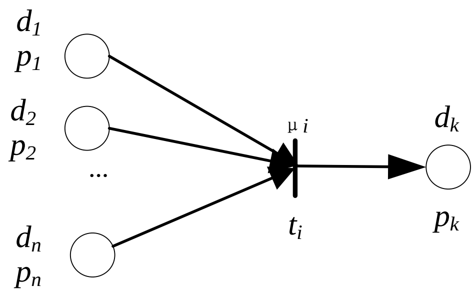


Figure 3: The rule when the antecedent token is "AND"

2) Conclusion Token is "AND"

As shown in Figure 4, when the conclusion token is "AND", the diagnosis rule can be described as,

$$\text{if } d_i \text{ THEN } d_{k1} \ldots \text{AND } d_{kn},$$
$$CF=\mu_i \quad (3)$$

Where, d_i describes the antecedent token; d_{k1}, d_{k2}, …, d_{kn} means the tokens at the places d_{k1}, d_{k2}, …, d_{kn}; μ_i describing the credibility of transition t_i.

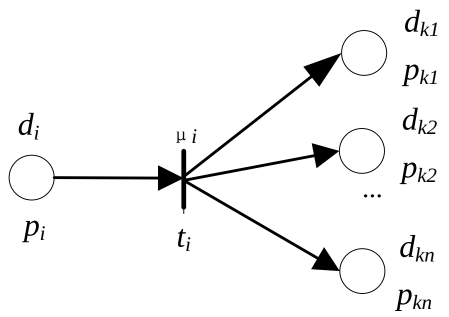


Figure 4: The rule when the conclusion token is "AND"

3) Antecedent Token is "OR"

As shown in Figure 5, when the antecedent token is "OR", the diagnosis rule can be described as,

$$\text{if } d_1 \text{ OR } d_2 \ldots \text{OR } d_n \text{ THEN } d_k,$$

$$CF(d_k) = \max(\theta^0_{d1}\mu_1, \theta^0_{d2}\mu_2, \ldots, \theta^0_{dn}\mu_n) \quad (4)$$

Where, $\theta^0_{d1}, \theta^0_{d2}, \ldots, \theta^0_{dn}$ describing the corresponding credibility, μ_1, μ_2, …,μ_n describing the credibility of transition t_1, t_2, …,t_n.

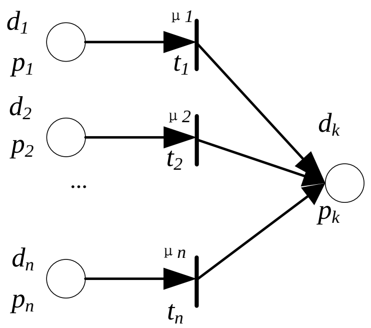


Figure 5: The rule when the antecedent token is "OR"

4) Conclusion Token is "OR"

As shown in Figure 5, when the conclusion token is "OR", the diagnosis rule can be described as,

$$\text{if } d_i \text{ THEN } d_{k1} \ldots \text{OR } d_{kn}$$

$$CF = \mu_i \quad (5)$$

Where, d_i describes the antecedent token; d_{k1}, d_{k2}, …, d_{kn} means the tokens at the places d_{k1}, d_{k2}, …, d_{kn}; μ_i describing the credibility of transition t_i.

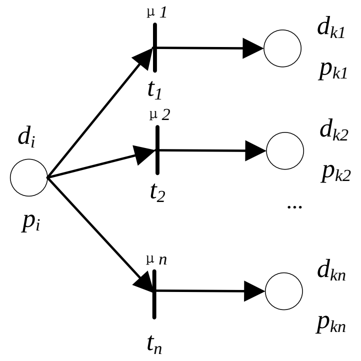


Figure 6: The rule when the conclusion token is "OR"

Because of the Reachable, Structurally Bounded and Live of Petri Nets, the diagnosis model of HSCS can be constituted as a directed graph (reachable marking graph) which the vertices set and the relationship arc set. Therefore, through the reachability tree and covering tree analysis, the failures of HSCS can be effectively diagnosed.

4 FAULT DIAGNOSIS ALGORITHM OF HSCS

According to the fault diagnosis model, the node in fault propagation path is defined as a three-tuple:

$$\left(p_k, \partial\left(p_k\right), IRS\left(p_k\right)\right) \tag{6}$$

Where, p_k describing the k[th] place, $p_k \in P$; $\partial\left(p_k\right)$ is the credibility of p_k; $IRS\left(p_k\right)$ is the Immediate reachability set of p_k. Let λ_k indicate the credibility threshold of p_k.

The fault diagnosis algorithm of HCSC is given as follows:

STEP1: Push $\left(p_k, \partial\left(p_k\right), IRS\left(p_k\right)\right)$ into the non-terminal node stacks and sign it as root node. The diagnosis is begun at root node and the root node is non-terminal node.

STEP2: For each non-terminal node $\left(p_i, \partial\left(p_i\right), IRS\left(p_i\right)\right)$,

STEP2.1 If $IRS\left(p_i\right) = \phi$, sign it as terminal node, put this node into terminal node set;

STEP2.2 Else,

STEP2.2.1 If exists node $p_1, p_2, \cdots, p_m \in IRS\left(p_i\right)$ and $p_1, p_2, \cdots, p_m$ is non-visit node, Let $\partial\left(p_k\right) = Max\left\{\partial\left(p_1\right), \partial\left(p_2\right), \cdots, \partial\left(p_m\right)\right\}$, create node $\left(p_k, \partial\left(p_k\right), IRS\left(p_k\right)\right)$ and the directed arc signed as $CF_{ik} = \mu_{ik}$, the direction of this arc is from $\left(p_i, \partial\left(p_i\right), IRS\left(p_i\right)\right)$ to $\left(p_k, \partial\left(p_k\right), IRS\left(p_k\right)\right)$, where $\left(p_k, \partial\left(p_k\right), IRS\left(p_k\right)\right)$ is non-terminal node and is pushed into non-terminal node stack;

STEP2.2.2 Else sign $\left(p_i, \partial\left(p_i\right), IRS\left(p_i\right)\right)$ as visited node;

STEP 3: For the non-terminal node stack,

STEP 3.1 If non-terminal node stack is not empty, pop the top data of non-terminal node stack, and go to STEP 2;

STEP 3.2 Else non-terminal node stack is empty, go to STEP 4;

STEP 4: For $\left(p_j, \partial\left(p_j\right), IRS\left(p_j\right)\right)$ in terminal node set, if $\partial\left(p_j\right) \geq \lambda_j$ calculate the credibility of corresponding place $\partial\left(p_s\right)$ according to the diagnosis path, and then this node is the cause of fault. Through sorting the calculated credibility $\partial\left(p_s\right)$, the diagnosis results will be obtained.

The fault diagnosis algorithm is given in Figure 7.

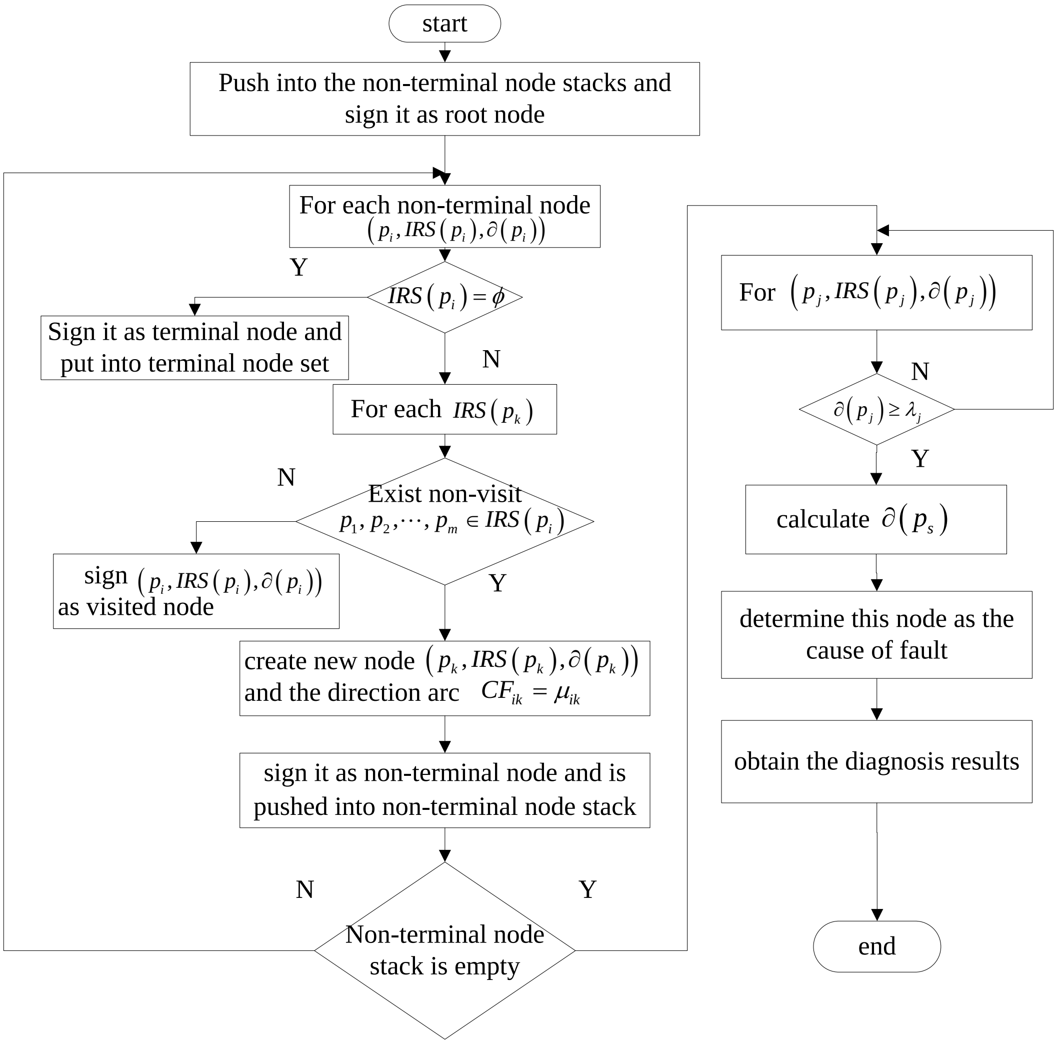


Figure 6: The fault diagnosis algorithm

5 EXAMPLE AND RESULT

In order to verifying the proposed fault diagnosis model and algorithm, a fault diagnosis example of Microwave Vehicle Detector (MVD) is given. In HSCS, MVD is the key device of IAS, which detects the speed and flow of vehicles based on the Doppler Shift Principle. As shown in Figure 7, the compositions of MVD is MVD device (which is composed by microwave emitter/receiver unit, CPU, Data Transmission Unit, Data Storage Unit, Data Process Unit and Power Supply Unit, etc.), power supply unit, optical transceiver, switch, communication equipment and the surveillance & control workstation, etc. In practical applications, the data acquired by MVD is firstly transmitted to the nearby communication station, and then transferred to Surveillance and control center by communication system, where the data is processed and formed to the surveillance and control information of issue devices or traffic control devices in HSCS.

The main failure of the MVD is the loss of data detected by MVD in the Surveillance & Control Center. Based on the analysis of the composition and its function topology of MVD, the mentioned failure propagation knowledge rules are as follows:

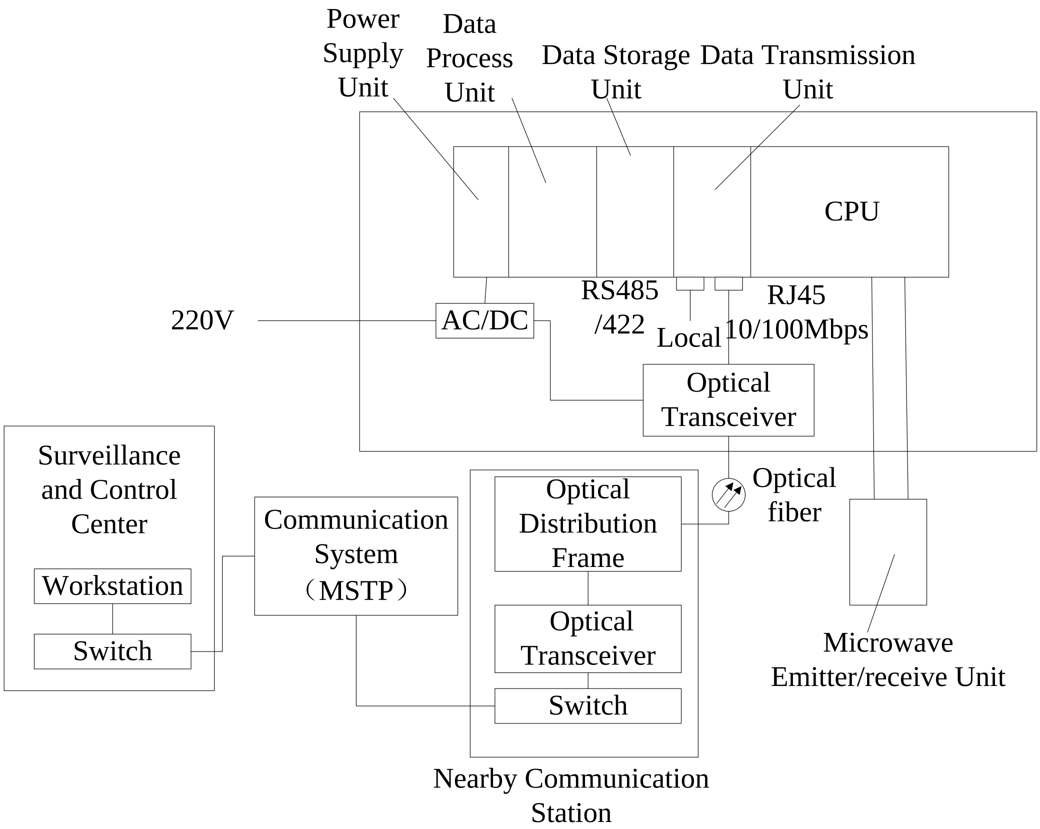


Figure 7: The composition of Microwave Vehicle Detector (MVD)

Rule 1: IF Microwave Emitter/receiver Unit failure THEN MVD no output (where the confidence level is 0.99, the probability threshold of Microwave Emitter/receiver Unit failure $\lambda = 0.020$ and its confidence level is 0.85);

Rule 2: IF Data Process Unit failure THEN MVD no output (where the confidence level is 0.98, the probability threshold of Data Process Unit failure $\lambda = 0.005$ and its confidence level is 0.76);

Rule 3: IF Data Transmission Unit failure THEN MVD no output (where the confidence level is 0.99, the probability threshold of Data Transmission Unit failure $\lambda = 0.050$ and its confidence level is 0.90);

Rule 4: IF the Power Supply Unit of MVD failure THEN MVD no output data (where the confidence level is 0.99, the probability threshold of Power Supply Unit failure $\lambda = 0.050$ and its confidence level is 0.90);

Rule 5: IF Optical Transceiver failure THEN the Optical Transceiver no output (where the confidence level is 0.98, the probability threshold of Optical Transceiver failure $\lambda = 0.050$ and its confidence level is 0.85);

Rule 6: IF the Power Supply Unit of Optical Transceiver failure THEN the Optical Transceiver no output (where the confidence level is 0.98, the Power Supply Unit of Optical Transceiver failure $\lambda = 0.050$ and its confidence level is 0.85);

Rule 7: IF Switch failure THEN the Switch no output (where the confidence level is 0.95, the probability threshold of Switch failure $\lambda = 0.002$ and its confidence level is 0.90);

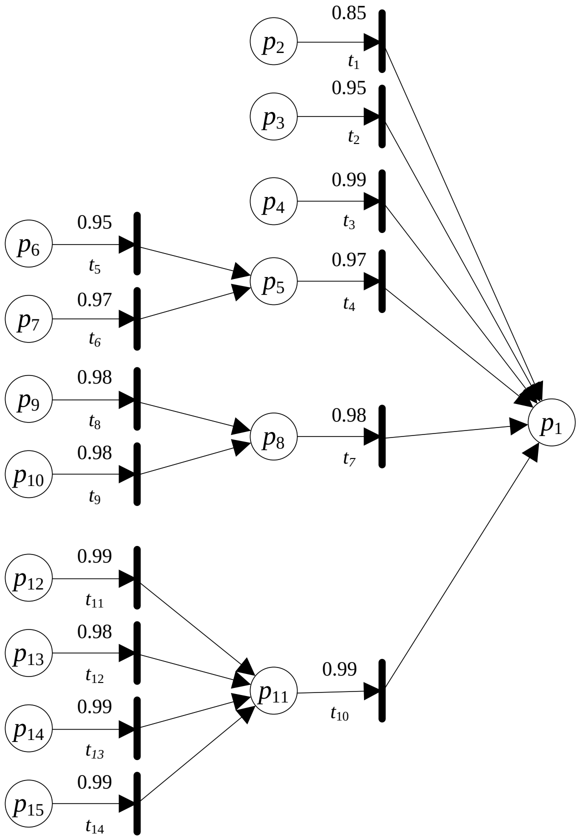
Rule 8: IF the Power Supply Unit of Switch failure THEN the Switch no output (where the confidence level is 0.97, the probability threshold of Power Supply Unit of Switch failure $\lambda = 0.050$ and its confidence level is 0.85);

Rule 9: IF Communication System (MSTP) failure THEN the data detected by MVD cannot be obtained (where the confidence level is 0.99, the probability threshold of MSTP failure $\lambda = 0.001$ and its confidence level is 0.90);

Rule 10: IF Surveillance and Control Workstation failure THEN the data detected by MVD cannot be obtained (where the confidence level is 0.95, the probability threshold of Surveillance and Control Workstation failure $\lambda = 0.010$ and its confidence level is 0.90);

Rule 11: IF Surveillance and Control Software failure THEN the data detected by MVD cannot be obtained (where the confidence level is 0.85, the probability threshold of Surveillance and Control Software failure $\lambda = 0.061$ and its confidence level is 0.90).

In the above Rules, the confidence level and the probability threshold value is determined based on the National and Industry standards related to electronic production and software, relevant technical requirements and fault experiment of MVD. According to the function topology of MVD and above rules, the fault diagnosis model based on Petri Nets is shown in Figure 8.



where p_1 means the data detected by MVD cannot be obtained; p_2 means the Surveillance and Control Software failure; p_3 means the Surveillance and Control Workstation failure; p_4 means the Communication System (MSTP) failure; p_5 means Switch no output; p_6 means Switch failure; p_7 means the Power Supply Unit of Switch failure; p_8 means the Optical Transceiver no output; p_9 means Optical Transceiver failure; p_{10} means the Power Supply Unit of Optical Transceiver failure; p_{11} means MVD no output; p_{12} means Microwave Emitter/receiver Unit failure; p_{13} means Data Process Unit failure; p_{14} means Data Transmission Unit failure; p_{11} means Power Supply Unit of MVD failure.

Figure 8: the fault diagnosis model based on Petri Nets

According to the fault diagnosis model and algorithm, if the data detected by MVD cannot be obtained (place p_1 in Figure 8), the fault tree will be created in the following order: p_4, p_{11}, p_8, p_5, p_3 and p_2. Through calculating the credibility of transition in the fault tree and determining whether the credibility of places in Figure 8 is larger than the probability threshold, if the credibility is larger than the probability threshold the corresponding places is the cause of fault.

On the basis of the proposed algorithm, the mentioned places and its related set are given in Table 2 and subsequently one of the fault diagnosis paths is provided in Figure 9.

Table 2: the places and its related set in the fault diagnosis of MVD

Places (p_i)	$IRS(p_i)$	$RS(p_i)$
p_1	$\{\phi\}$	$\{\phi\}$
p_2	$\{p_1\}$	$\{p_1\}$
p_3	$\{p_1\}$	$\{p_1\}$
p_4	$\{p_1\}$	$\{p_1\}$
p_5	$\{p_1\}$	$\{p_1\}$
p_6	$\{p_5\}$	$\{p_5, p_1\}$
p_7	$\{p_5\}$	$\{p_5, p_1\}$
p_8	$\{p_1\}$	$\{p_1\}$
p_9	$\{p_8\}$	$\{p_8, p_1\}$
p_{10}	$\{p_8\}$	$\{p_8, p_1\}$
p_{11}	$\{p_1\}$	$\{p_1\}$
p_{12}	$\{p_{11}\}$	$\{p_{11}, p_1\}$
p_{13}	$\{p_{11}\}$	$\{p_{11}, p_1\}$
p_{14}	$\{p_{11}\}$	$\{p_{11}, p_1\}$
p_{15}	$\{p_{11}\}$	$\{p_{11}, p_1\}$

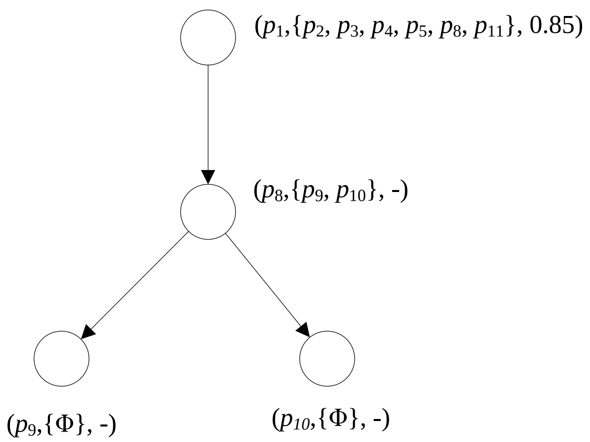


Figure 9: one of the fault diagnosis paths

6 CONCLUSION

Based on the composition, fault types and features of HSCS, the fault diagnosis model of HSCS based on Petri Net Model is provided, the fault diagnostic algorithm is given and subsequently the fault diagnosis of MVD in HSCS is presented to verifying the proposed fault diagnosis model and algorithm. The proposed fault diagnosis model and algorithm is based on the function topology and the physical structure of HSCS devices, and meanwhile takes advantage of the virtue of the Petri nets such as graph description, rule mapping, knowledge analysis, inference and decision etc. In a word, the proposed model and algorithm provides the effective method on the fault diagnosis of HSCS. In the next step, the proposed diagnosis model needs to be improved according to the running data of HSCS, the probability threshold and the credibility need to be optimized by the further diagnosis experiment results, reliability parameters such as the MTBF, MTTR and so on.

ACKNOWLEDGEMENTS

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REFERENCES

Isermann, R. (2005). *Model-based fault-detection and diagnosis – status and applications.* Annual Reviews in Control, 2005, Vol. 29, pp. 71-85.

Zhu, L., Zhang Z. and Bao Z. (2008). Performance Assessment of Highway Tunnel Surveillance and Control System by Fault Tree Analysis. *Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems*, pp. 346-350.

Zhang L., Luo S., Liang J., and Pang Y. (2010). Research on Fault Diagnosis Expert System of Weapon Equipment Based on Rules-Ratiocination, *Proc. IHMSC*, Vol. 1, pp. 157-162.

Doan X. and Srinivasan R. (2008). Online monitoring of multi-phase batch process using phased-based multivariate statistical process control. Computers and Chemical Engineering, Vol. 32, pp. 230-243.

Kano M. and Nakagawa Y. (2008). Data-based process monitoring, process control, and quality improvement: Recent developments and applications in steel industry. *Computers and Chemical Engineering*, Vol. 32, pp. 12-24.

Liu Z. (2008). *Study on methodology of industrial process state supervision (Dissert).*

Zhang H. and Xia F. (2010). Improved Petri Net Based Fault Diagnosis for Ship Power System. *Marine Electric & Electronic Technology*, Vol. 30, pp. 35-38.

Ghainani A. T., Zin A., and Ismail N. (2012). Fuzzy Timing Petri Net for Fault Diagnosis in Power System. *Mathematical Problems in Engineering*. Volume 2012, doi:10.1155/2012/717195.