Research on Fault Diagnosis Method of Tunnel Inspection Robot Based on T–S Fuzzy FTA

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Abstract. Aiming at the intelligent fault diagnosis of tunnel inspection robot, the T-S fuzzy fault tree method was proposed to build the intelligent diagnosis system. Taking positioning system of the robot as an example, the T-S fuzzy FTA model of the system was established. And the T-S importance of each component and fault checking sequence were calculated using the T-S fuzzy gate rule. The example analysis results show that, the method improves the accuracy and practicability of fault diagnosis of the robot system.

1. Introduction

In structural safety monitoring of long and large tunnels, an inspection robot equipped with optical sensors can be used for autonomous monitoring. However, given its complexity the inspection robot system requires an efficient, accurate fault self-diagnosis method to achieve remote maintenance of the robot system. A typical FTA-based diagnosis method gives priority to diagnosis of minimum cut set with a high probability of fault [1, 2], but requires definite event logic and accurate fault rate statistics. Consequently, it is hard to build a fault model and conduct quantitative analysis in application, and minimum cut set with a high probability of fault does not always contribute more to top event. It is therefore difficult to identify prioritized diagnosis object. In order to improve troubleshooting efficiency, literature [3,4] introduces T-S fuzzy model into Fault Tree Analysis (FTA) to describe the links between layers of FTA events using T-S fuzzy gate and thereby addresses event link uncertainty and accurate component fault rate statistics. By building T-S fuzzy FTA, it quantitatively calculates T-S criticality importance of bottom event to identify weak areas of the system. Literature [5] presents a remote fault diagnosis system for road construction equipment using T-S fuzzy FTA method, and determines T-S criticality importance and troubleshooting sequence of each component under each fault condition using T-S fuzzy gate algorithm to effectively improve the practicality of fault diagnosis.

Regarding the fault diagnosis system of a tunnel inspection robot, this paper proposes fault classification and identification based on expertise and introducing T-S fuzzy FTA method to determine self-diagnosis troubleshooting sequence. Engineering example calculation demonstrates the accuracy and effectiveness of this method and its ability to improve fault treatment efficiency and reduce maintenance cost.
2. Inspection Robot Fault Diagnosis Process
The tunnel inspection robot has access via WIFI network to substation server provided in the tunnel and establishes a fault diagnosis system on the server. The system consists of inspection robot, fault self-diagnosis system, expert monitoring center and fault information notification. The structure of the fault diagnosis system is shown in Figure 1.

![Figure 1. Structure of fault diagnosis system](image)

When the inspection robot experiences fault, its state parameters will become abnormal. The diagnosis system will classify and identify the fault according to changes in state parameters using the fault mapping parameter rule, and sort fault cause criticalities using T-S fuzzy FTA model. During execution of the self-diagnosis program, the system will command each module of the robot to complete fault cause check. All fault diagnosis information will be transmitted to the expert monitoring center, and the resulting information will be sent to the mobile terminal of technicians who will treat the fault. Based on the results, the system will update actual probability of fault for each module, and T-S fuzzy FTA model related data and fault classification information to improve the accuracy of building T-S fuzzy FTA model and fault diagnosis.

The diagnosis and treatment process of the fault diagnosis system is presented in Figure 2.

![Figure 2. Fault diagnosis and treatment process](image)

3. Fault Diagnosis Method Based on T-S Fuzzy FTA

3.1. T-S fuzzy FTA
As with a traditional fault tree, T-S fuzzy fault tree consists of top event, basic event and T-S fuzzy gate, as shown in Figure 3. A, B, C and D are basic events; T₂ and T₃ are upper middle events; T₁ is top
event. On the basis of known fuzzy fault probability of basic events, the fuzzy fault probability of upper event is calculated using T-S gate algorithm to obtain the fuzzy fault probability of top event [6].

![Figure 3. T-S fuzzy fault tree](image)

In contrast to traditional FTA which requires accurate failure probability of basic events, T-S fuzzy FTA describes the fault degree of basic events using a fuzzy number in [0,1]. Based on application experience the linguistic variables selected to describe fault degree are small, medium and large (corresponding to fuzzy numbers 0, 0.5 and 1 respectively) for no fault, semi-fault and complete fault. The form of the fuzzy number membership function may be triangular membership function $\mu(x)$, as shown in Figure 4.

![Figure 4. Triangular membership function of fuzzy probability of failure](image)

$$\mu(x) = (x_0, m_l, m_r) \quad (1)$$

where $x_0$ is the center of fuzzy number support set; $m_l$ and $m_r$ are left and right fuzzy zones.

### 3.2. T–S fuzzy gate algorithm

T-S fuzzy model consists of a series of IF-THEN fuzzy rules, assuming all fault degrees of each event in basic event set $X = \{x_1, x_2, \ldots, x_n\}$ and upper event $y$ can be described as fuzzy numbers $x_1^l, x_2^l, \ldots, x_n^l$ and $y^l$ respectively, where $x_1^l, x_2^l, \ldots, x_n^l$ and $y^l$ are fuzzy numbers.

The fault state fuzzy numbers of basic events and upper events satisfy:

$$0 \leq y^l < y^2 < \ldots < y^k \leq 1, 0 \leq x_1^l < x_2^l < \ldots < x_n^l \leq 1 (i=1,2,\ldots,n)$$

Thus the logic algorithm rule for T-S gate is as follows:

With known rule $l(i=1,2,3,\ldots,m)$, if $x_i$ is $x_1^l$ and $x_2$ is $x_2^l$ ... and $x_n$ is $x_n^l$, then the probability of $y$ being $y^l$ is $p^l(y^l); \ldots$; the probability of $y$ being $y^k$ is $p^k(y^k)$. $m$ is total number of rules and $m = k_1k_2\cdots k_n$. T-S fuzzy gate rules are shown in Table 1.
Assuming the probabilities of fault degree of basic events are $P(x_1^i), P(x_2^i), \ldots, P(x_n^i)$ respectively, the probability of executing T-S rule $l$ is:

$$E'_l = \prod_{j=1}^{l} P(x_j^i)$$  \hspace{1cm} (2)

The fuzzy probability of occurrence of upper event is thus inferred as:

$$P(y') = \sum_{i=1}^{n} E'_i P(y^i)$$

$$P(y^i) = \sum_{l=1}^{n} E'_l P(y^i)$$

$$\cdots$$

$$P(y') = E'_n P(y^n)$$  \hspace{1cm} (3)

3.3. Troubleshooting sequence calculation

Similar to traditional two-state system FTA, the proposed method can determine weak components causing system fault by means of qualitative computation of the probability importance and criticality importance of each basic event. For a multi-state system, quantitatively calculated T-S fuzzy importance may be sorted in sequence on which fault check and diagnosis are based [5][7]. T-S criticality importance actually reflects the importance of the fuzzy probability of each fault state of basic event $x_j$ to each fault state of upper event.

From T-S fuzzy gate algorithm it is known that in a multi-state system T-S fuzzy fault tree, the fuzzy probability of fault state $x_j^i$ of a basic event $x_j (j \leq n)$ is $P(x_j^i)(i_j=1,2,\ldots,k_j)$. According to the definition of T-S criticality importance in literature [14], T-S criticality importance of $x_j$ to upper event $T$ being fault state $T_q$ can be calculated from:

$$I_{T_q}^C(x_j) = \frac{\sum_{i=1}^{k_j} I_{T_q}^C(x_j^i)}{k_j} = \frac{\sum_{i=1}^{k_j} P(x_j^i)I_{T_q}^P(x_j^i)}{P(T=T_q)}$$  \hspace{1cm} (4)

where $I_{T_q}^P(x_j^i)$ is T-S probability importance of fuzzy probability $P(x_j^i)$ of $x_j$ in fault state $x_j^i$ to upper event $T$ in state $T_q$, i.e. the probability of system failure when component $x_j$ fails, as calculated from the following equation:

$$I_{T_q}^P(x_j^i) = P(T_q, P(x_j^i) = 1) - P(T_q, P(x_j^i) = 0)$$  \hspace{1cm} (5)

where $P(T_q, P(x_j^i) = 1)$ is the fuzzy probability of upper event in fault state $T_q$ when the probability of basic event $x_j$ in fault state $x_j^i$ is 1; $P(T_q, P(x_j^i) = 0)$ is the fuzzy probability of upper event in fault state $T_q$ when the probability of basic event $x_j$ in fault state $x_j^i$ is 0.

| Rule | $x_1$ | $x_2$ | … | $x_n$ | $y_1$ | $y_2$ | … | $y_n$ |
|------|------|------|---|------|------|------|---|------|
| 1    | $x_1^1$ | $x_2^1$ | … | $x_n^1$ | $p_1(y_1)$ | $p_1(y_2)$ | … | $p_1(y_n)$ |
| 2    | $x_1^2$ | $x_2^2$ | … | $x_n^2$ | $p_2(y_1)$ | $p_2(y_2)$ | … | $p_2(y_n)$ |
| 3    | $x_1^3$ | $x_2^3$ | … | $x_n^3$ | $p_3(y_1)$ | $p_3(y_2)$ | … | $p_3(y_n)$ |
| …   |      |      | … |      |      |      | … |      |
| l    | $x_1^l$ | $x_2^l$ | … | $x_n^l$ | $p_l(y_1)$ | $p_l(y_2)$ | … | $p_l(y_n)$ |

Table 1. Rule of T–S gate

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These two probability values can be obtained by putting $P(x_i) = 1$ and $P(x_i) = 0$ into Eq. (2) and (3) and using T-S fuzzy gate algorithm.

4. Diagnosis Analysis Case

4.1. Modeling T–S fuzzy FTA

The positioning system of the inspection robot is the foundation for distress detection and positioning. Due to high frequency of operation, its components tend to be wearing parts of the robot system and thus the focus of study on robot fault diagnosis system. Its system structure is illustrated in Figure 5. Driven by servo motor the robot moves along the track while performing detection tasks according to control signal and command. Its location information is monitored via the encoder and position detection sensor.

![Schematic diagram of robot positioning system](image)

Figure 5. Schematic diagram of robot positioning system

According to T-S fuzzy FTA method, build a T-S fuzzy fault tree taking actuating cylinder no-load fault as top event, as shown in Figure 6. In the figure, $T_1$ is top event; $y_1$ and $y_2$ are middle events; $x_1 \sim x_5$ are basic events. Basic event $x_1$ is servomotor fault; $x_2$ is driver fault including input power fault; $x_3$ is transmission mechanism fault; $x_4$ is encoder fault; $x_5$ is position sensor fault.

4.2. Fuzzy probability and T-S criticality importance analyses

According to fuzzy fault probability event description and experience of system element fault, assume the fault states of basic events $x_1, x_2, x_3, x_4, x_5$ representing element faults, middle events $y_1$ and $y_2$, and top event $T_1$ are $(0, 0.5, 1)$ respectively; the membership function parameter is $m_1 = m_2 = 0.4$. From expertise and fault statistics T-S fuzzy gate rules can be obtained, as shown in Tables 2 to 4.
Figure 6. T-S fuzzy fault tree of robot positioning system

Table 2. T–S fuzzy gate 1 rules

| Rule | $x_1$ | $x_2$ | $x_3$ | $y_1$ |
|------|-------|-------|-------|-------|
| 1    | 0     | 0     | 0     | 1     |
| 2    | 0     | 0     | 0.5   | 0.2   |
| 3    | 0     | 0     | 1     | 0     |
| 4    | 0     | 0.5   | 0     | 0.1   |
| 5    | 0     | 0.5   | 0.5   | 0.1   |
| 6    | 0     | 0.5   | 1     | 0     |
| 7    | 0     | 1     | 0     | 0     |
| 8    | 0     | 1     | 0.5   | 0     |
| 9    | 0     | 1     | 1     | 0     |
|      |       |       |       | :     |
| 27   | 1     | 1     | 1     | 0     |

Table 3. T–S fuzzy gate 2 rules

| Rule | $x_4$ | $x_5$ | $y_2$ |
|------|-------|-------|-------|
| 1    | 0     | 0     | 1     |
| 2    | 0     | 0.5   | 0.2   |
| 3    | 0     | 1     | 0.8   |
| 4    | 0.5   | 0     | 0.4   |
| 5    | 0.5   | 0.5   | 0.4   |
| 6    | 0.5   | 1     | 0.7   |
| 7    | 1     | 0     | 0     |
| 8    | 1     | 0.5   | 0     |
| 9    | 1     | 1     | 0     |
Table 4. T–S fuzzy gate 3 rules

| Rule | $y_1$ | $y_2$ | $T_i$ |
|------|-------|-------|-------|
| 1    | 0     | 0     | 0     |
| 2    | 0     | 0.5   | 0.5   |
| 3    | 0     | 1     | 0     |
| 4    | 0.5   | 0     | 0.5   |
| 5    | 0.5   | 0.5   | 0.6   |
| 6    | 0.5   | 1     | 1     |
| 7    | 1     | 0     | 0.4   |
| 8    | 1     | 0.5   | 0.3   |
| 9    | 1     | 1     | 0     |

Based on reliability data in each product manual, the fault rates of each component when fault degrees are 0.5 and 1 are identical, as shown in Table 5.

Table 5. Reliability data for component of each bottom event

| Event | Component          | Fault rate ($10^{-6}$/h) | Event | Component                        | Fault rate ($10^{-6}$/h) |
|-------|--------------------|--------------------------|-------|----------------------------------|--------------------------|
| $x_1$ | Servomotor         | 12.6                     | $x_4$ | Encoder                          | 10.2                     |
| $x_2$ | Servo driver       | 50                       | $x_5$ | Position detection sensor       | 0.05                     |
| $x_3$ | Transmission mechanism | 22.8                  |       |                                  |                          |

Using Eq. (2) and (3) calculate the fuzzy probabilities of middle events and top event of the servo hydraulic subsystem, as shown in Table 6. Because the difference between the product of fuzzy probabilities according to T-S fuzzy gate rule 5 and that according to rule 2 is of $10^6$ order of magnitude, this rule can be ignored.

Table 6. Fuzzy probability of the occurrence of middle event and top event

| Fault state | $y_1$ | $y_2$ | $T_i$ |
|-------------|-------|-------|-------|
| 0.5         | 30.42 | 4.14  | 68.6  |
| 1           | 128.3 | 12.27 | 100.446 |

Using Eq. (4) and (5) T-S probability importance and T-S criticality importance for components in different fault states can be derived, as shown in Tables 7 and 8.

Table 7. T–S probability importance of T1 in different fault states of components

| T-S probability importance | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ |
|---------------------------|-------|-------|-------|-------|-------|
| $I_{ps}^{x_i}(x_j')$      | 0.77  | 0.79  | 0.76  | 0.02  | 0.6   |
| $I_{c}^{x_i}(x_j')$       | 0.93  | 1.05  | 0.96  | 1.22  | 1.2   |
Based on T-S criticality importance in the above table, the positioning system troubleshooting sequence is determined as: \( x_2 > x_3 > x_1 > x_4 > x_5 \).

5. Conclusions
This paper has developed a remote fault diagnosis system for a tunnel inspection robot by introducing T-S fuzzy FTA model for quantitative calculation of T-S criticality importance of fault causes and sorting components by probability of causing system fault. This provides accurate troubleshooting basis for fault self-diagnosis and simplifies complex fault diagnosis and treatment into component testing. After determining the troubleshooting sequence for components of the fault diagnosis system, the system will prompt the operator to perform remote fault self-diagnosis and call test program to identify fault causes.

This diagnosis method is effective in addressing engineering equipment fault diagnosis and treatment problems. In addition, T-S fuzzy FTA method is effective in addressing the inadequacy of traditional FTA in multi-state information and fuzzy information processing, and uncertainty of fault mechanism. Using T-S gate fuzzy logic and algorithm it enables FTA of more generic complex systems while improving the accuracy of fault diagnosis analysis.

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