Reliability Model of Integrated Navigation Based on GSPN

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Abstract. It is difficult to describe the dynamic behavior of the repairable system for the traditional reliability modeling methods. To solve this problem, it was built that reliability model of integrated navigation GPS/INS/RA based on generalized stochastic Petri net (GSPN). The model was simulated by TimeNET4.0. The simulation results show that the model is correct, and the method is feasible.

Introduction

Navigation is the science or technology to guide the movement of aircraft or ships. Attitude and heading of the aircraft control and guidance are extremely important. Integrated navigation system has a high navigation accuracy, miniaturization, reliability, it becomes one of the development of modern navigation[1]. Integrated navigation system with a combination of programs according to the different needs of navigation, GPS / INS / RA combination of navigation is one of them. Due to the requirement of high reliability in integrated navigation system, reliability analysis is particularly important[2].

The traditional reliability analysis methods of integrated navigation system are static fault trees, reliability block diagrams and Markov model[3,4]. Traditional reliability analysis methods such as static fault trees, binary decision diagram, and reliability block diagram have nothing to do with the time, and are unable to describe the dynamic behavior of the repairable system. Although dynamic fault tree model and continuous time Markov model can describe the system dynamic behavior, dynamic fault tree model needs to list all the states of the system, and continuous-time Markov model which is computational complexity must be based upon that failure can not be repaired. All above requirements limit the application of the method.[5,6]

Generalized stochastic Petri nets gets more and more applications because of the prominent dynamic modeling and analysis capabilities[7]. In this paper, the reliability model of the GPS/INS/RA integrated navigation is established based on generalized stochastic Petri net (GSPN) and is simulated with the TimeNET4.0. The simulation results show that the model is correct, and the method is feasible. It provides a feasible method for dynamic reliability analysis of integrated navigation.

Definition of Generalized Stochastic Petri Nets

The generalized stochastic Petri net is composed of seven tuples that is GSPN = (P, T, F, K, W, M0, λ). The specific meaning is:

(1) P is set for the library, which represents the system state or resource. The graphical modeling notation is round.

(2) T is a change set, which indicates the change of the state of the system. It is divided into two categories: instantaneous change and timed transition. The time delay of instantaneous change is 0, which symbol is thin strip. The symbol of timed change is hollow rectangle which obeys random distribution. T is used to describe the failure process and repair process of the components in reliability modeling.
(3) F is arc set which is used to connect to the library and changes. Generally speaking, the arcs have a direction. The special forbidden arcs are from the library to changes, which means that the change is forbidden when the library contains the token that is marked in the forbidden arc. In the reliability modeling, it is used to describe the system failure and repair process.

(4) K is a set of capacity functions for the library.

(5) W is a collection of arc weight function. The default value is 1.

(6) M_{0} is a collection of initial identification of the system, which indicates the initial state of the system.

(7) \lambda is a collection of changes in the average implementation rate. Average implementation rate indicates the average number of times that can be implemented within a unit time. The reciprocal meaning is the average implementation delay of the changes or the average service time which is used to represent the component failure rate distribution and maintenance rate in the reliability analysis\cite{[8]}. The schematic diagram of integrated navigation GPS/INS/RA is shown in Figure 1. GSPN is used to establish reliability model of the integrated navigation GPS/INS/RA.

Reliability of Integrated Navigation Based on GSPN

It is assumed that failure and maintenance distribution of integrated navigation units are exponentially distributed.

Description and GSPN Model of GPS

According to the definition of GSPN, seven tuples are needed. Are respectively defined as follows:
Firstly, define the library P_{GPS} = \{RCVR_{on}, RCVR_{off}, PRCSR_{on}, PRCSR_{off}, GPS_{on}, GPS_{off}\}. The RCVR_{on} represents the normal state of the receiver. RCVR_{off} is fault state of receiver. PRCSR_{on} represents the normal state of the processor. PRCSR_{off} is the fault state of processor. GPS_{on} represents the normal state of GPS. GPS_{off} is the fault condition of GPS.

Secondly, define the set of changes and the average rate set of the change. The state transition processes of GPS are the receiver failure process t_{R1} which is transfer from the normal state to the fault state, transport rate \lambda_{R} which is failure rate of receiver; maintenance process t_{R2} which is transfer from the failure state to the normal state, transport rate \mu_{R} which is maintenance rate; failure process of processor is t_{P1}, and transfer rate is \lambda_{P}. Maintenance process is t_{P2}, and the transfer rate is \mu_{P}. Define T_{DG}={t_{R1}, t_{R2}, t_{P1}, t_{P2}}. T_{DG} is timed transition set which is used to describe the process of failure and maintenance. Define T_{IG}={ t_{GPS1}, t_{GPS2}, t_{GPS3}, t_{GPS4}}. T_{IG} is an instantaneous transition set which is used to show GPS state transition that is determined by the receiver and processor status Define \lambda_{G}={\lambda_{R}, \mu_{R}, \lambda_{P}, \mu_{P}} which is transition average rate set. \lambda_{G} shows the number of times of excitation in a unit of time, reciprocal of which means time delay of transition.

Assume that the initial state of GPS is normal; that is to say, the initial state of GPS is M_{G}={1, 0, 1, 0, 1, 0, 1, 0}. Define library capacity function set K_{G}={1, 1, 1, 1, 1, 1, 1}, that is to say, only normal and failure two states to be considered. The weights W_{i} of arcs are all defined as 1.

Because either the receiver or processor is fault, GPS will be fault, so the reliability modeling of GPS is parallel logic. According to the above seven tuples and definition of GSPN, the reliability model of GPS could be obtained as shown in Figure 2.

![Figure 1. Schematic of integrated navigation GPS/INS/RA.](image-url)
Description and GSPN Model of INS

According to the definition of GSPN, seven tuples are needed. Are respectively defined as follows: Similarly, define the library $P_{\text{INS}}=[\text{ACCLRM}_{\text{on}}, \text{ACCLRM}_{\text{off}}, \text{GYRO}_{\text{on}}, \text{GYRO}_{\text{off}}, \text{CMPTR}_{\text{on}}, \text{CMPTR}_{\text{off}}, \text{INS}_{\text{on}}, \text{INS}_{\text{off}}].$ ACCLRM$_{\text{on}}$ represents accelerometer is normal. ACCLRM$_{\text{off}}$ shows accelerometer is failure. GYRO$_{\text{on}}$ represents gyro is normal. GYRO$_{\text{off}}$ shows gyro is failure. CMPTR$_{\text{on}}$ represents computer is normal. CMPTR$_{\text{off}}$ shows computer is failure. INS$_{\text{on}}$ represents INS is normal. INS$_{\text{off}}$ shows INS is failure.

Secondly, define the set of changes and the average rate set of the change. The state change processes of INS components are failure process of accelerometer $t_{A1}$ which is transfer from the normal state to the fault state, transport rate $\lambda_A$ which is failure rate of the accelerometer; maintenance process of accelerometer $t_{A2}$ which is transfer from fault state to normal state, transport rate $\mu_A$ which is maintenance rate of accelerometer. Similarly, fault process of gyro is $t_{G1}$, and $\lambda_G$ is failure rate; maintenance process of gyro is $t_{G2}$, and $\mu_G$ is maintenance rate. Fault process of navigation computer is $t_{NC1}$, and $\lambda_{NC}$ is failure rate; maintenance process of navigation computer is $t_{NC2}$, and $\mu_{NC}$ is maintenance rate. Define a collection of $T_{\text{DI}}=\{t_{A1}, t_{A2}, t_{G1}, t_{G2}, t_{NC1}, t_{NC2}\}$ which is timed transition and used to describe the failure process and maintenance process of INS components. Define a collection of $T_{\text{II}}=\{t_{I1}, t_{I2}, t_{I3}, t_{I4}, t_{I5}\}$ which is immediate transition and represents an event that causes a change in the state of INS. Define transition average rate set $\lambda_{\text{I}}=\{\lambda_A, \mu_A, \lambda_G, \mu_G, \lambda_{NC}, \mu_{NC}\}$ which represents the number of times of excitation in a unit of time. Reciprocal of $\lambda_{\text{I}}$ represents the average time delay of transition.

Assume that the initial state is normal, that is to say, the initial state of INS $M_{I0}=\{1, 0, 1, 0, 1, 0, 1, 0\}$. Capacity function set of library $K_{\text{I}}=\{1, 1, 1, 1, 1, 1, 1, 1\}$ as a result of only two states of component failure and maintenance considered. Arc weights $W_{\text{I}}$ are all defined as 1.

When one of accelerometer, gyro or navigation computer is failure, INS system is fault. Accelerometer, gyro and navigation computer are parallel logical relations when fault is analysed. According to seven tuples: library $P_{\text{INS}},$ transition set $T_{\text{D}}$ and $T_{\text{I}},$ library capacity function $K_{\text{I}},$ arc weights $W_{\text{I}},$ the initial state $M_{I0},$ transition average rate set $\lambda_{\text{I}},$ arc set $F,$ GSPN model of INS can be created as shown in Figure 3.

Description and GSPN Model of RA

Define RA$_{\text{on}}$ which represents the normal state of the radio altimeter and RA$_{\text{off}}$ which represents fault state of the radio altimeter. Failure process is $t_{RA1}.$ Failure rate is $\lambda_{RA}.$ Maintenance process is $t_{RA2}.$ Maintenance rate is $\mu_{RA}.$ Process of failure and maintenance are timed transition. The initial state is normal. The capacity of library is 1. Arc weight is 1. The GSPN model of radio altimeter based on the definition is shown in Figure 4.

Description and GPSN Mode of Integrated Navigation

CS$_{\text{on}}$ represents the normal state of integrated navigation. CS$_{\text{off}}$ represents the fault state of integrated navigation. When INS, GPS and RA are all fault, integrated navigation is fault, so fault logic is series. $T_{\text{Igh}}$ is immediate transition which represents INS, GPS and RA are all fault. $T_{\text{i}}, T_{\text{g}}$ and $T_{\text{r}}$ are immediate transition which represent integrated navigation is normal. Define immediate
transition $t_{CS}$ which represents state change of integrated navigation. GSPN model of integrated navigation can be created according to the GSPN model of GPS, INS and RA as shown in Figure 5.

![Figure 3. INS reliability model.](image1)
![Figure 4. RA reliability model.](image2)
![Figure 5. Integrated navigation reliability model.](image3)

### Analysis of the Reliability Mode of Integrated Navigation

According to the relevant literature[2], it is assumed that the reliability data of integrated navigation components are shown in Table 1. Simulation tools TimeNET 4.0 is used to analyse availability. Availability is shown in Table 2.

| Component     | Failure rate $[10^{-5} \text{h}^{-1}]$ | Repair rate $[10^{-5} \text{h}^{-1}]$ |
|---------------|---------------------------------------|--------------------------------------|
| Receiver      | 6.7                                   | 3.9                                  |
| Accelerometer | 2.6                                   | 6.3                                  |
| Gyro          | 4.2                                   | 8.2                                  |
| INS computer  | 3.2                                   | 5.7                                  |
| RA altimeter  | 8.0                                   | 9.1                                  |

| Component     | Availability                        |
|---------------|-------------------------------------|
| Receiver      | 0.3704071                           |
| Processor     | 0.7739928                           |
| Accelerometer | 0.6986361                           |
| Gyro          | 0.6863542                           |
| INS computer  | 0.6580662                           |
| RA altimeter  | 0.5289989                           |

In TimeNET4.0, $P\{#P_1 > 0\}$ means the probability that the number tokens of library $P_1$ is greater than 0. For example, $P\{#CS_{on} > 0\}$ means the probability that the number tokens of library $CS_{on}$ is greater than 0, that is to say, the probability that the state of integrated navigation is normal. Other expressions are similar in meaning. When INS, GPS and RA are all fault, integrated navigation is fault. The calculation of the availability of the integrated navigation is shown in the formula (1).

$$P\{#CS_{on} > 0\} = 1 - \{1 - P\{#GPS_{on} > 0\}\} \times \{1 - P\{#RA_{on} > 0\}\} \times \{1 - P\{#INS_{on} > 0\}\}$$

(1)

The GPS is normal when the receiver and the processor are all normal. Therefore the calculation of the availability of the GPS is shown in formula (2).

$$P\{#GPS_{on} > 0\} = P\{#RCVR_{on} > 0\} \times P\{#PRCSR_{on} > 0\}$$

(2)

When the accelerometer, gyro and the computer are all normal, INS is normal. Hence, the calculation of the availability of the INS is shown in the formula (3).

$$P\{#INS_{on} > 0\} = P\{#ACCLRM_{on} > 0\} \times P\{#GYRO_{on} > 0\} \times P\{#CMPTR_{on} > 0\}$$

(3)

The availability of the integrated navigation can be obtained according to table 2, formula(1), formula(2) and formula(3). That is to say, $P\{#CS_{on} > 0\} = 0.6974844$. The availability of the integrated navigation is 0.7143278 which is obtained through simulation. It is known that the error is small by comparison which proves the correctness and feasibility of the method.
Conclusion
This paper establishes the reliability model of GPS/INS/RA integrated navigation system based on GSPN. The availability of integrated navigation is obtained by using the simulation tool TimeNET4.0. The analysis results show that the model is correct and the method is feasible, which can improve the dynamic reliability analysis of the repairable integrated navigation system.

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