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Research Article

Failure Effects Evaluation for ATC Automation System

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ATC (air traffic control) automation system is a complex system, which helps maintain the air traffic order, guarantee the flight interval, and prevent aircraft collision. It is essential to ensure the safety of air traffic. Failure effects evaluation is an important part of ATC automation system reliability engineering. The failure effects evaluation of ATC automation system is aimed at the effects of modules or components which affect the performance and functionality of the system. By analyzing and evaluating the failure modes and their causes and effects, some reasonable improvement measures and preventive maintenance plans can be established. In this paper, the failure effects evaluation framework considering performance and functionality of the system is established on the basis of reliability theory. Some algorithms for the quantitative evaluation of failure effects on performance of ATC automation system are proposed. According to the algorithms, the quantitative evaluation of reliability, availability, maintainability, and other assessment indicators can be calculated.

1. Introduction

ATC (air traffic control) is a service provided by ground-based controllers who direct aircraft on the ground and through controlled airspace and provide advisory services to aircraft in noncontrolled airspace. The main objectives of air traffic control (ATC) are to ensure flights safety and an efficient organization of traffic flows [1, 2]. ATC automation system is a kind of complex electronic system combined with computer and information technology. It is usually used to maintain the air traffic order, guarantee the interval, and prevent aircraft collision [3]. It is essential for regional control and terminal airspace control. The reliability of ATC automation system has direct effects on air traffic safety.

In recent years, the air traffic control efficiency has been improved due to the employment of various types of ATC automation systems. But the majority of imported ATC automation systems have been used for many years. The hardware and software have declined gradually. And because the serve time of homemade systems is relatively short, there is obvious uncertainty in the evaluation of failure and risk. So the collection of failure records and evaluation of the failure effects are especially urgent. Lots

of researches are aimed at reliability forecasting of ATC software. Wang and Liu collected the 36-month failure data of ATC automation system, and Markov chain is employed to predict its reliability [4]. Ternov and Akselsson proposed a new method for identifying hazards in a complex system based on DBE (disturbance, effect, and barrier) analysis and applied it to an air traffic control unit in Malmoe, Sweden [5]. Gómez et al. illustrated a recommender framework for assisting flight controllers, which combines argumentation theory and model checking in the evaluation of trade-offs and compromises to be made in the presence of incomplete and potentially inconsistent information [6]. Zhang et al. established the air traffic management system safety evaluating indicator system considering person-equipment-environment-management [7]. Woltjer et al. described the approach taken and results to develop guidance and to include resilience engineering principles in methodology for safety assessment of functional changes, in air traffic management [8]. Mayer developed an integrated aviation and ATC modeling platform for comparing and evaluating proposed aircraft flight operations and ATC procedures [9]. Flavio Vismari and Camargo Junior proposed a methodology for safety assessment of ATC system by combining “absolute” and

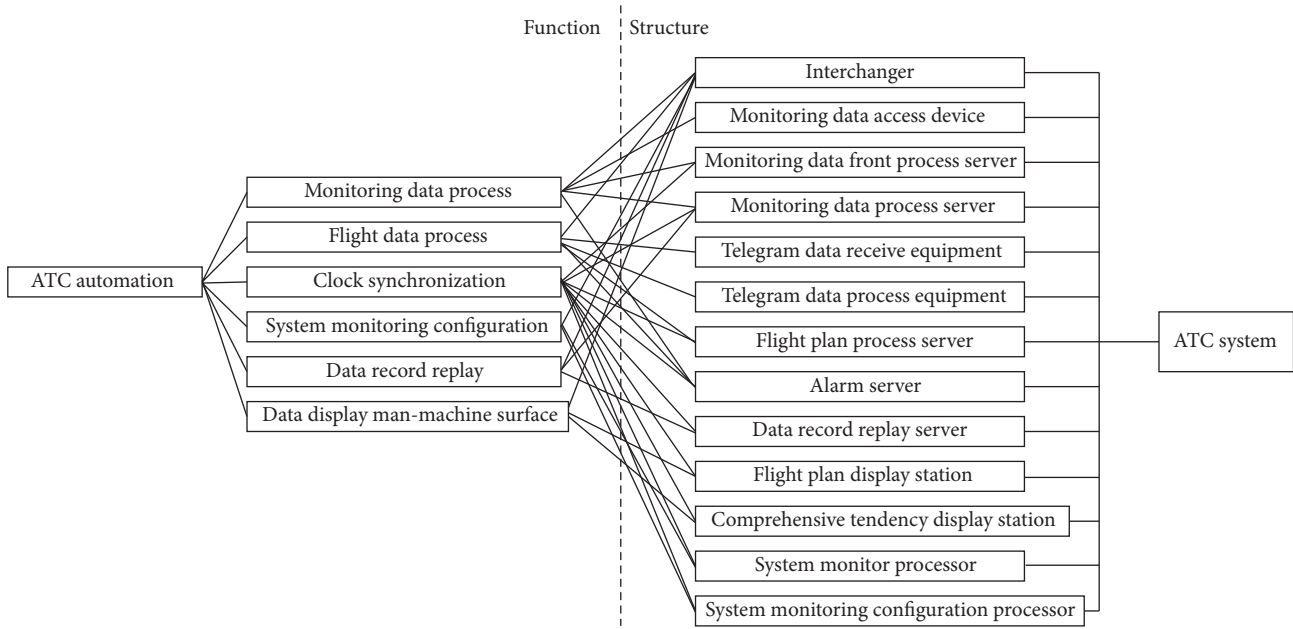


FIGURE 1: The structure and function corresponding diagram of ATC automation system.

“relative” safety assessment methods, using Fluid Stochastic Petri Nets (FSPN) as the modeling formalism [10]. Moon et al. had evaluated the relationship between air traffic volume and human error in air traffic control (ATC) on the basis of reviews of existing literature and interviews and surveys of ATC safety experts [11]. Vanderhaegen [12] also considered the effects of human errors on the ATC system.

The aim of this paper is to establish an available framework to evaluate the effects of failures of subsystems or components to the whole ATC system, so common reliability theory is utilized, such as reliability logic diagram and FMECA (Failure Mode, Effects, and Criticality Analysis), rather than the abstruse algorithms. A general structure of ATC automation system is used as the research object. The relationship between structure composition and functions is analyzed. An evaluation framework is established for failure effects appraisal according to performance effects and function effects. Section 2 gives the structure and function corresponding diagram of ATC automation system. In Section 3, evaluation framework of failure effects on performance is discussed and, in Section 4, evaluation framework of failure effects on function is proposed.

2. Basic Concept of ATC Automation System

An ATC automation system can deal with different types of radar data and form the flight path by information fusion. The autorelation of radar target and flight plan can be realized. The subsystems of a general ATC automation system include RFP (radar data front processing subsystem), RDP (radar processing subsystem), FDP (flight data processing subsystem), SDD (situation data display), FDD (flight data

processing terminal), DRP (data record play), and CMD (condition monitoring display). The structure and function corresponding diagram is shown in Figure 1.

Among the subsystems of ATC automation system, RFP, RDP, FDP, and DRP have two redundancies. When the main equipment fails, the spare one will be switched as main equipment. SDD and FDD are display terminals; the breakdown of a single SDD or FDD will not affect others. CMD is used to set up system parameters. Failures of each subsystem have effects on the function and performance of the whole ATC automation system.

3. Evaluation of Failure Effects on Performance of ATC Automation System

On the basis of the past records and history data, the reliability, availability, maintainability, system load, and system response time can be quantitatively evaluated using proper mathematical models. The diagram of performance evaluation is shown in Figure 2.

3.1. Evaluation of Failure Effects on Reliability. The redundant configuration of ATC automation has diversity in different manufactures, for example, single-redundancy, two-redundancy, or three-redundancy. The model for evaluating reliability should be established according to the actual redundant configuration. A general reliability based on diagram of ATC automation system is shown in Figure 3.

In Figure 3, the same redundant subsystems are parallel connection. The different redundant subsystems are serial connection. Supposing that there are n work points in the

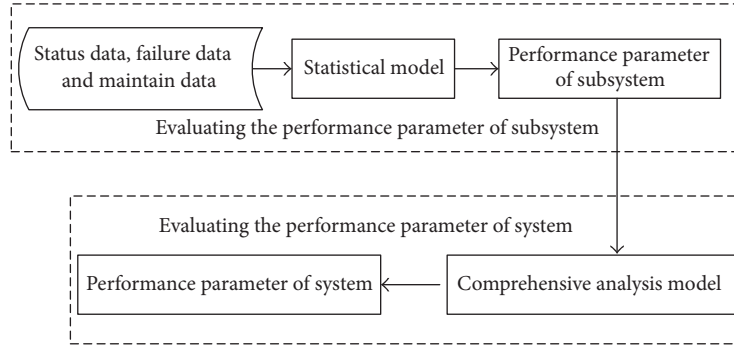
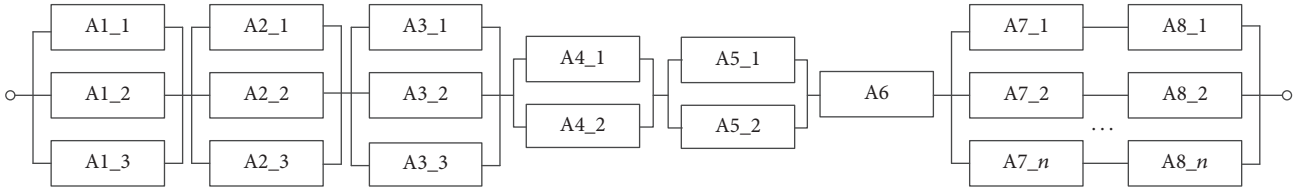


FIGURE 2: The diagram of performance evaluation.



A1_1~A1_3: 3 RFPs; A2_1~A2_3: 3 RDPs;
 A3_1~A3_3: 3 interchangers; A4_1~A4_2: 2 FDPs;
 A5_1~A5_2: 2 DRPs; A6: CMD/DMS;
 A7_1~A7_n: n SDDs; A8_1~A8_n: n FDDs;

FIGURE 3: General reliability based on diagram.

whole system, the system reliability can be calculated as follows:

$$R_s(t) = \left\{ \prod_{i=1}^3 \left[1 - \prod_{j=1}^3 (1 - R_{i-j}) \right] \right\} \cdot \left\{ \prod_{i=4}^5 \left[1 - \prod_{j=1}^2 (1 - R_{i-j}) \right] \right\} \cdot R_6 \cdot \left\{ 1 - \prod_{j=1}^n \left[(1 - R_{7-j} \cdot R_{7-j}) \right] \right\}, \quad (1)$$

where R_{i-j} is the reliability of the subsystem A_{i-j} .

3.2. *Evaluation of Failure Effects on Availability.* The indexes of availability of ATC automation system can be estimated on the basis of maintenance records and statistical models. For example, the stable availability of ATC automation can be calculated using

$$A = \frac{MTBF}{MTBF + MTTR}, \quad (2)$$

where MTBF is mean time between failures and MTTR is mean time to repair. MTBF can be calculated by

$$MTBF = \frac{\text{the sum of time between failures}}{\text{times of maintain}}. \quad (3)$$

3.3. *Evaluation of Failure Effects on Maintainability.* The indexes of maintainability of ATC automation system (e.g., repair rate, MTTR) can also be estimated on the basis of maintenance records and statistical models. The stable availability of ATC automation can be calculated using

$$MTTR = \frac{\text{the sum of time of maintain}}{\text{times of maintain}}. \quad (4)$$

The mean repair rate of ATC automation is

$$\mu = \frac{1}{MTTR}. \quad (5)$$

And the maintainability of ATC automation is

$$M(t) = 1 - \exp(-\mu t). \quad (6)$$

3.4. *Evaluation of Failure Effects on System Load.* When some redundant modules are broken down but at least a redundant

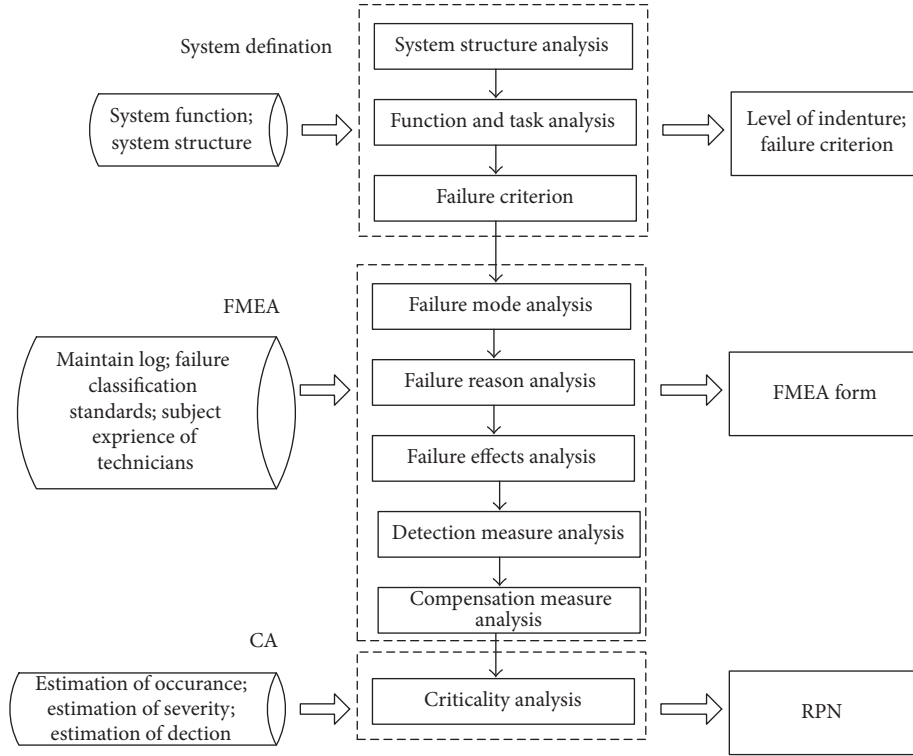


FIGURE 4: Procedure of FMECA for ATC automation system.

module is normal, the ATC system can work normally. But the loading of normal modules must be increased. For example, the occupancy rate of CPU, RAM, and hard disk of server may be increased and so is the network flow. According to historical data, the change of occupancy rate of each subsystem should be considered, and then the load-time curve can be plotted.

The equipment load in time t is the weighted sum of its single index $Li(t)$ (e.g., RAM occupancy rate), as shown in

$$LE(t) = \sum_{i=1}^n [\alpha_i L_i(t)], \quad (7)$$

where $LE(t)$ is the load of equipment in time t and α_i is the weight of the i th single index. The load of subsystem and the whole system are calculated as follows:

$$\begin{aligned} LS(t) &= \sum_{i=1}^n [\beta_i LE_i(t)], \\ LSS(t) &= \sum_{i=1}^n [\gamma_i LS_i(t)], \end{aligned} \quad (8)$$

where $LS(t)$ and $LSS(t)$ are the load of subsystem and the whole system in time t , respectively. β_i is the weight of the i th equipment and γ_i is the weight of the i th subsystem.

3.5. Evaluation of Failure Effects on System Response Time. According to the operating data of ATC automation system,

response time of each typical operation is statistically calculated. And then the mean system response time is

$$\bar{y} = \frac{1}{N} \sum_{i=1}^N y_i, \quad (9)$$

where \bar{y} is the mean response time of system. N is the number of typical operations. y_i is the response time of the i th typical operations.

4. Evaluation of Failure Effects on Function of ATC Automation System

The failure effects on function of ATC automation system are evaluated by using FMECA. FMECA (Failure Mode, Effects, and Criticality Analysis) is generally employed to analyze all the possible failure modes of components in a complex system in its whole lifetime [13]. The reasons of each mode and its effects to every layer are found out. And then improvement measures can be put forward. The procedure of FMECA for ATC automation system is shown in Figure 4.

4.1. Failure Modes Analysis. The purpose of failure mode analysis is to find out the possible failure modes of the ATC system from the requirement of the function and the failure criterion of the system definition.

Common failure modes are determined according to standard for failure classification of ATC equipment. The uncovered failures modes can be found out of maintain log or subjective experience of technicians.

TABLE 1: FMEA table of correlation between target trajectories and flight plans.

Number	Project	Function	Failure mode	Failure cause	Failure impact
1	Radar data	The basis of generating radar track	Radar track position is not accurate	Radar precision is insufficient Air complex environment causes interference	Radar track position causes the deviation
			SSR code error	Radar signal interference that can lead to inaccurate SSR code	Wrong correlation
			The repeated SSR code	Double SSR code appears to be caused by mountain reflection, radar fault, false target, fusion algorithm, and so on	Unable to correlate with each other
			The radar flight number error of ADS or S model	ADS data or S mode's radar data transmission and processing is wrong	Wrong correlation
2	Flight telegraph	The basis of the flight plan	Poor timeliness of flight telegraph	Manually send flight telegraph delay	ATC system did not receive the message within prescribed time. Time deviation is too large, autorelated error, or wrong correlation
			The sequential variation of flight telegraph	Network communication link quality is poor	The receiving and dispatched flight telegraph do not match the time order
			The format and content of flight telegraph are not accurate	Human error	The format and content of flight telegraph are wrong.
			Lost the flight telegraph	Network communication link quality is poor	Unable to get the correct route and calculate the flight status. Unable to automatically correlate with each other
3	Basic data	Provide the information of airport, airlines, aircraft, beacon, and punctuation	Basic data is not accurate	Network communication link quality is poor	Unable to get accurate route and calculate the flight status. Unable to automatically correlate with each other
			Basic data is not complete	Basic database did not update the information of routes and beacon adjusted Not existing Code duplication	Unable to establish accurate flight route. Unable to calculate accurate 4D track. Autorelated error or wrong correlation
4	4D track prediction	Establish the precise 4D track model of whole flight process	The calculated time deviation that through each way point is too large	4D track prediction algorithm is not accurate	State of the flight plan is not correct. The deviation between the planned track position and real target position is large. Unable to automatically correlate with each other or wrong correlation
			The calculated planned flight direction is far away from the actual direction	4D track prediction algorithm is not accurate	Unable to automatically correlate with each other or wrong correlation

TABLE 2: The Classification failure incidence.

Classification	Classification basis	Examples
A	Control unit cannot provide air control service	(1) Backbone of communication networks of control unit failure. (2) Internal phone communication system (very high frequency system) failure. (3) Main and backup functional automation device overall paralysis
B	Failures decline the control capability of air control service and greatly reduce the flight capacity	(1) The whole or part of the automation system cannot be recovered in a short time. (2) Failure of automatic transfer system. (3) Partial control seats at the same time failure or other equipment failure which leads to air to ground communication failure.
C	Failures cause the degradation of service quality on monitoring communication and navigation and reduce the control efficiency	(1) Short time main device or automatic transfer system performance degradation leading to failure of flight plan processing function. (2) Control coordination/transfer of telephone failure due to various causes.
D	Failures have no effects on flight and traffic control	(1) Single machine or single network of redundant system fault. (2) Transient control over telephone or other equipment performance degradation and rapid recovery does not affect the control operation.

4.2. Failure Reason Analysis. The failure reason is divided into direct causes and indirect reasons. The direct cause is the physical and chemical process of the ATC system itself, which leads to the failure or potential failure of the system, while the indirect failure is caused by the failure of other products, environmental factors, human factors, and so forth.

Failure reason analysis helps to identify the factors of the design, manufacture, usage, and maintenance that cause the failure. And then improvement measures and compensation measures can be taken into account to prevent or reduce the possibility of failure.

Before analysis, firstly the features of the ATC automatic system should be classified, and the relevant description should be determined. Analysts must be able to accurately describe each function and its related modules and failure mode.

The FMEA form of ATC automation system correlation between target trajectories and flight plans is shown in Table 1. Table 1 is established on the basis of the analysis of the anomalies of the track [14] and the causes of wrong correlation between target trajectories and flight plans [15], from the perspective of flight plan track related technology principle [16], radar system, and multiradar data processing system.

4.3. Failure Effect Analysis. Failure effect refers to the effects of each failure mode of the ATC system on its usage, function, and status.

When the failure mode of a module is affected by the failure of the other modules of the system, it is usually carried out according to the predefined system level structure. The structure and function corresponding diagram of ATC

TABLE 3: Scoring method of occurrence degree.

Score	The possibility of failure		Reference value of failure probability
1	Rare	Low possibility of failure mode	1/106
2	Low	Possibility of failure mode is relatively low	1/20000
3			1/4000
4			1/1000
5	Middle	Middle possibility of failure mode	1/400
6			1/80
7			1/40
8	High	High possibility of failure mode	1/20
9			1/2
10	Extremely high	Extremely high possibility of failure mode	1/8

TABLE 4: Scoring method of severity degree.

Score	The influence degree of the failure	
1	Slight	No impact on the performance of the system.
2	Low	A slight effect on system performance.
3		
4		
5	Middle	General failure: the system performance is affected; it can be settled through the implementation of the corresponding treatment.
6		
7		
8	High	Serious failure: the system performance is seriously affected.
9		
10	Extremely high	Critical failure: system failure.

automation system is shown in Figure 1. According to the hierarchical structure of ATC automatic system, it can be divided into inverted tree type structure. Through the hierarchical structure diagram and the structure and function corresponding diagram, the modules failure effects on ATC automation system capability can be analyzed.

The effects of failure are clarified into four levels based on different incidence of single equipment to control unit, as shown in Table 2.

4.4. Criticality Analysis. A failure assessment follows the failure analysis, and RPN (Risk Priority Number) number is generally used. RPN is the product of *O*, *S*, and *D*. With the RPN, a ranking of the identified failure causes and their failure connection to the failure effect can be done.

O, which indicates occurrence, estimates how probable the occurrence of the failure cause is. According to Table 3, the scoring criteria for the occurrence probability grade are given. The value of failure probability is corresponding to the rating of expected number of failures in the product life cycle.

S, which indicates severity, describes the severity of a failure effect. It used in the evaluation of the eventual impact

on the failure mode of the analysis. Usually, the description of failure mode to the users should be visible. According to Table 4, the scoring methods of the severity are given.

D, which indicates detection, determines how successful the detection of the failure cause is.

According to Table 5, P_D is the probability of the failure mode and cause.

After completing the above steps, the number of RPN could be calculated. For the high harmful failure mode, we should put forward improvement measures.

5. Conclusion

In order to evaluate the effects of subsystem failures to ATC automation system, a framework considering effects on performance and function is established. On the basis of the framework, failure effects on system performance are calculated considering reliability, maintainability, availability, system load, and response time. The mathematical models for each index are given according to the reliability theory. The failure effects on function of ATC automation system are evaluated using FMECA. The procedure of FMECA of ATC

TABLE 5: Scoring method of detection degree.

Score	The difficulty of fault is detected	
1	$P_D \approx 1$	Can completely find failure mode and causes
2	$3.3 \times 10^{-1} < P_D$	May find failure mode and causes
3	$5 \times 10^{-2} < P_D \leq 3.3 \times 10^{-1}$	May find failure mode and causes
4	$2 \times 10^{-2} < P_D \leq 5 \times 10^{-2}$	May find failure mode and causes
5	$1 \times 10^{-2} < P_D \leq 2 \times 10^{-2}$	May find failure mode and causes
6	$2 \times 10^{-3} < P_D \leq 1 \times 10^{-2}$	May find failure mode and causes
7	$2 \times 10^{-4} < P_D \leq 2 \times 10^{-3}$	May find failure mode and causes
8	$2 \times 10^{-6} < P_D \leq 2 \times 10^{-4}$	May find failure mode and causes
9	$P_D \approx 2 \times 10^{-6}$	May find failure mode and causes
10	$P_D < 2 \times 10^{-6}$	May find failure mode and causes or may be unable to detect them

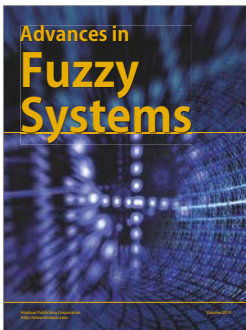
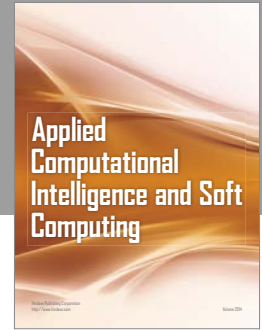
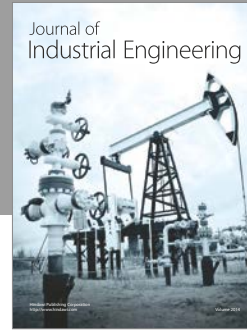
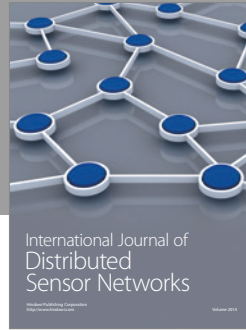
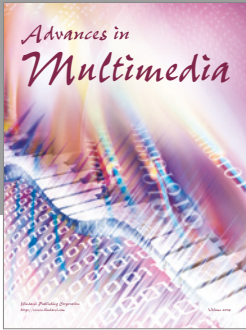
automation system is proposed. The framework can be used to guide the reliability analysis procedures of ATC.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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