Reliability Modelling of Automated Guided Vehicles by the Use of Failure Modes Effects and Criticality Analysis, and Fault Tree Analysis*

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Abstract

Automated Guided Vehicles (AGVs) are being increasingly used for intelligent transportation and distribution of materials in warehouses and auto-production lines. In this paper, a preliminary hazard analysis of an AGV's critical components is conducted by the approach of Failure Modes Effects and Criticality Analysis (FMECA). To implement this research, a particular AGV transport system is modelled as a phased mission. Then, Fault Tree Analysis (FTA) is adopted to model the causes of phase failure, enabling the probability of success in each phase and hence mission success to be determined. Through this research, a promising technical approach is established, which allows the identification of the critical AGV components and crucial mission phases of AGVs at the design stage.

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1 Introduction

The concept of an Automated Guided Vehicle (AGV), which travels along a predefined route without an on-board operator to perform prescribed tasks, was first introduced in 1955 [1]. Nowadays, AGVs are being increasingly used for intelligent transportation and distribution of materials in warehouses and/or manufacturing facilities attributed to their high efficiency, safety and low costs. As the AGV systems are getting larger and more complex, increasing the efficiency and lowering the operation cost of the AGV system has naturally become the first priorities, via identifying new flow-path layouts and developing advanced traffic management strategies (e.g. vehicle routing) [2]. For this reason, the previous research effort in the AGV area has mainly focused on route optimisation and traffic management of AGVs. For example, Giuseppe established an approach in 2013 to optimise the flow-path such that the average time for carrying out transportation tasks can be minimised and the utilisation

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degree of AGVs can be maximised at the same time [3]; Wu and Zhou created a simulation model to avoid collisions, deadlock, blocking and minimise the route distance as well with a coloured resource-oriented Petri Net [4]. However, little effort has been made to investigate the safety and reliability issues of the AGV components/subassemblies and their probability of success in completing a prescribed mission. Although Fazlollahtabar recently created a model to maximise the total reliability of the AGVs and minimise the repair cost of AGV systems [5], they considered the AGV as a whole. Hence, fundamental questions, such as 'How could AGVs fail?' and 'What are the possibilities of their failure?', have not been answered.To answer these questions, Duran and Zalewski tried to identify the basic failure modes of the light detection and ranging (LIDAR) system and the camera-based computer vision system (CV) on AGVs in 2013 by the approach of Fault Tree Analysis (FTA) and Bayesian Belief Networks (BBN) [6]. In that work, human injury, property damage and vehicle damage were defined as the top events in the fault tree. However, the research did not cover all components and subassemblies in AGVs. A complete investigation of the safety and reliability issues of all AGV components and subassemblies is important not only to ensure the high reliability and availability of AGVs and their success of delivering prescribed tasks, but also to optimise their maintenance strategies. Research is conducted in this paper to identify the critical risks of all AGV components and the crucial mission phases in an AGV operation. Failure Modes Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA) will be adopted to achieve this. Hence, the contribution of this paper is in developing an efficient approach to investigate the reliability of AGVs taking into account the profiles of the mission undertaken.

The remaining part of the paper is organized as follows. In Section 2, the FMECA-FTA based methodology for AGV safety and reliability analysis is introduced; in Section 3, AGV risk and reliability analysis procedure is developed; in Section 4, the proposed methodology is applied to, assess an AGV's probability of success in completing a prescribed mission, identify the crucial phases of the mission and key AGV components. The work is finally concluded in Section 5 with concluding remarks and the plans for future work.

2 Overview of Methods and Application Area

FMECA and FTA are combined in this paper to develop a methodology for the safety and reliability analysis of an AGV system. To facilitate understanding, a brief introduction to both techniques is given below.

2.1 Failure Modes Effects and Criticality Analysis (FMECA)

FMECA originated from Failure Modes and Effects Analysis (FMEA)which is a well known popular technique used for dealing with safety and reliability issues in complex systems, such as identifying the potential effects that might arise from malfunctions of military, aeronautics and aerospace systems [7]. FMEA can be also used to implement the analysis of component failure modes, their resultant effects and secondary influences on both local component function and the performance of the whole system. A more detailed description of FMEA can be found in the standard [8]. In engineering practice, FMEA is often implemented at the early stage of system development such that the critical system components and potential failures and risks can be identified early.

Conventional FMEA covers the comprehensive analysis of components or subsystem, failure modes, and failure effects which are local and related to the overall system. FMEA can be further extended to rank the failure modes according to their probabilities of failure and severity classifications based on the available data. That is the so-called Failure Modes Effect and Criticality Analysis (FMECA), where, 'criticality' is a terminology used to reflect the combined impact of 'occurrence probability' and 'severity' on the safety and reliability of the system being inspected.

2.2 Fault Tree Analysis (FTA)

Through inspecting the logic between the undesired events that could happen in a system or a mission, FTA allows us to trace back the root cause of a system or mission failure by using a systematic top-down approach. Moreover, the probability of system or mission failure can be computed via Boolean algebra from the tree. FTA provides a straightforward and clear presentation of the logic between various undesired events and is regarded as an effective, systematic, accurate and predictive method to deal with the safety and reliability problems in complex systems, such as the safety issues in a nuclear power plant [9]. In terms of structure, a fault tree is basically composed of various events and gates. In this paper, three basic types of gates, i.e. AND, OR and NOT, are used to depict the logical relations between the events that result in the occurrence of a higher level event. A more detailed description of FTA can be found in [7].

Since FTA ignores the cause of failure modes and FMECA gears towards analysing individual component failure mode occurrences and moreover it is not quantitative, both methods are used in combination in this paper.

2.3 Application AGV System

In this paper, to facilitate the research a typical AGV system is chosen for FMECA-FTA analysis. The AGV system consists of a laser navigation system, safety system, manual button, batteries, AGV software control system (ASCS), drive unit, brake system, steering system and attachments. Among these subassemblies, the laser navigation system, developed by Macleod et al. [10], is in essence a position measurement system to locate the AGV. It comprises a rotating laser installed on the board of the AGV and three beacons mounted along the border of the area to be covered. The safety system, with the aid of a laser detection system installed on the AGV, is designed to avoid obstacles that could appear on the pathway. These, together with the button, input into the control system. This system will then use the information to send commands to the drive unit, brake system, steering system and attachments, where the drive unit, usually a brushless DC electric motor, provides power for motion and operation. Attachments refer to those additional components that are used to assist moving and carrying items and batteries, usually the common lead–acid batteries, are used to supply power to the whole AGV system, see Figure 1.

The AGV that is studied in this paper is required to distribute materials to multiple places in a warehouse according to different requirements. Each time it receives an order it will optimise the routes for completing the whole mission first. Then, the AGV will travel to the material collection port along the optimised route to pick up the materials. After the AGV is loaded, it will travel to the storage station and unload the materials. After successfully distributing the materials, the AGV will travel back to its original parking position. Therefore, the whole mission can be divided into 6 phases in total, namely (1) mission allocation and route optimisation, (2) dispatch to station, (3) loading of item, (4) travelling to storage, (5) unloading and finally (6) travelling back to base. The mission can be regarded as successful only when the AGV is able to operate successfully throughout all these 6 phases without any break due to component and/or system failures and maintenance. Such a period is named as a maintenance-free operational period (MFOP) [11].

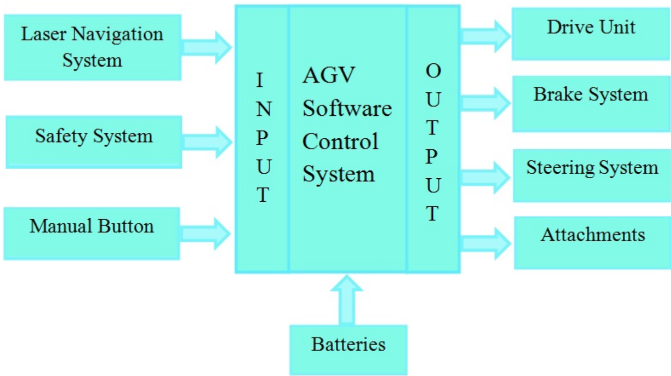

Figure 1 AGV system schematic.

Table 1 Severity assessment.

S_i	Description
1	No loss of any kind
2	Minor property loss (low cost hardware parts), no effect on performance
3	Major property loss, degradation of item functional output
4	Loss of critical hardware, human injuries, severe reduction of functional performance
5	Catastrophic loss of life, loss of the entire AGV system, serious environment damage

3 AGV Risk and Reliability Analysis Procedure

Applying the FMECA process requires the identification of the failure modes of all components in the AGV system, assessment of their local and system effects, evaluation of the severities of their consequences, and carrying out the analysis of their failure rates. The end outcome is the identification of a number of critical components in the AGV system based on the following risk priority number (RPN), i.e.

$$RPN_i = S_i \times F_i \times D_i \qquad (i = 1, 2, \dots, N) \tag{1}$$

where N refers to the total number of failure modes of the AGV components being considered; S_i, F_i and D_i are the severity level, failure frequency and detectability of the failure of the i-th failure mode, respectively. In principle, the larger the value of RPN, the more critical (or important) the corresponding failure mode of the AGV component tends to be. In the calculation, the severity level S_i is assessed using the method depicted in Table 1. The failure frequency F_i is assessed based on the ranges listed in Table 2. The detectability D_i is assessed based on the information described in Table 3.

Once the critical components and their failure modes in the AGV system are identified by using the aforementioned FMECA method, the logical relations of the failure events of these identified critical AGV components will be investigated by the approach of FTA. The resultant fault tree can be constructed by using the following method:

(1) three basic logical gates, i.e. AND, OR and NOT, are used to depict the logical relations between the failure events that result in the occurrence of a higher level event;
(2) mission failure is used as the top event in the fault tree;
(3) phase failures and component/subsystem failures are used as the intermediate events;
(4) the various failure modes that lead to intermediate events are the fundamental events in the fault tree.

Table 2 Failure frequency assessment.

Failure frequency F_i	Range
1	$<$ 0.01 failures/ year
2	0.01-0.1 failures/year
3	0.1-0.5 failures/year
4	0.5-1 failures/year
5	$>$1 failures/year

Table 3 Detectability assessment.

Detectability D_i	Description
1	Almost certain to detect
2	Good chance of detecting
3	May not detect
4	Unlikely to detect
5	Very unlikely to detect

Table 4 Assumed phase lengths.

Phase	1	2	3	4	5	6
Phase Length (minutes)	1.2	12	1.2	9	1.2	6

Herein, it is necessary to note that the following two basic assumptions are presumed in the modelling process in order to simplify the topology structure of the fault tree and therefore model calculations:

(1) the AGV is presumed not to be assigned another mission after unloading; and
(2) the interactions between multiple AGVs, such as AGVs collision and deadlock, are neglected.

Once the fault tree is obtained, the phase unreliability, the failure probability of each AGV subsystem during the period of completing a prescribed mission, and the probability that the AGV is able to complete the whole mission, can be calculated through performing FTA. Hence, the safety, reliability and availability of the AGV system can be readily obtained.

4 Validation of the proposed methodology

In order to validate the methodology proposed in Section 3, the method is applied to identify the key AGV components (by FMECA), crucial phases of mission (by FTA), and assess the AGV's probability of success in completing a prescribed mission (by FTA).

To implement FMECA and FTA, the length (i.e. time duration) of each phase identified in Section 2.3, is prescribed a value as shown in Table 4. The total time duration to complete the whole mission is 30.6 minutes. It is worth noting that the data presented in Table 4 is empirical data, only for demonstration purpose. In reality, these would be different when the AGV implements different types of missions.

A list of the different failure modes of all the components of the AGV of interest are given in Table 5, in which the corresponding severity, failure rate, and detectability are included. The data in the table is based on [12] and expert knowledge and further developed for the AGV. The failure frequencies are given in number of failures per year. The resultant RPN can be determined from equation (1) and hence the criticality of each event failure mode can be ranked.

In the RPN calculation, the failure frequency F_i of each failure mode is derived first from the failure rate listed in Table 5 and the ranges described in Table 2. In table 5, the description of the component function, local and system effects and criticality ranking is not included due to limited space. Once the RPN of a failure mode is obtained, its criticality can be ranked.

From the FMECA results shown in Table 5, it can be found that the manual button has the smallest RPN and hence the lowest rank of criticality. Thus, it will not be regarded

Table 5 FMECA of AGV.

Identity	Sub-item	Failure Mode	S_i	F Rate(f/y)	D_i	RPN
Drive Unit		Unit fails	3	1	1	12
		Circuit connection fails	3	0.5	3	27
ASCS		Control system fails	3	2	4	60
		Control system malfunction	4	4	5	100
LNS	GPS	Fail to locate AGV	3	0.25	4	36
	Transmitter	Disabled communication	3	0.25	4	36
	Laser emitter	Unit fails	3	0.25	4	36
	Laser sensor	Unit fails	2	0.125	4	24
Safety Systems	Laser emitter	Unit fails	3	0.25	4	36
	Laser sensor	Unit fails	4	0.125	4	48
Attachments	Transfer part	Worn, fatigue, Looseness	4	1	2	32
	Holding part	Worn, fatigue, Looseness	4	1	2	32
Batteries		Performance degeneration	2	1	3	24
		Leakage	5	0.125	2	30
		Overheat	5	0.125	1	15
Brake System	Brake shoe	Worn out; Looseness	4	0.2	2	24
Steering System		Unit Fails	3	0.25	4	36
Manual button		Button is stuck	2	0.05	2	8

as key component of the AGV in the process of fault tree construction. Accordingly, for simplicity the fault tree of the AGV is built by only considering those identified key AGV components and the phases that they are involved in, i.e. drive unit, ASCS, laser navigation system, safety system, attachments, batteries, brake system, and steering system.

The construction of fault trees for phased missions is started by identifying the logic of different phases and their effects on the success of mission. Thus, 'mission failure' is chosen as the top event, and the 6 phases defined in Section 2.3 are used as intermediate event below this. The logic between the top event and these branch events is shown in Figure 2. The fault tree is further developed in order to investigate the logic between every phase mission and the failure modes of related AGV components. The resultant fault tree for Phase 2 is shown in Figure 3 as example.

From Figure 3, it is seen that the failure during the phase is used as the top event, the failures of those AGV components that are involved in the phase are basic events. The failures of mechanical parts, system parts for navigation, control and safety, and the power supply are the intermediate events. For example, in Phase 2, the AGV will travel from its parking position to the material collection port. During this period, the ASCS will control the AGV to travel along the optimised route; the laser navigation system (LNS) works over the whole course of the phase to locate the AGV as it moves; the motor is required to drive the vehicle; steering system enables vehicle turning; the safety system performs obstacle scan; and the brake system is responsible to slow down the vehicle when turning and stop the vehicle to avoid collisions. Obviously, the success of phase 2 mission relies on all of these subassemblies working. The fault of anyone of them can lead to the failure of phase 2. In addition, phase 2 can be started only after phase 1 has been completed successfully. In other words, the mission failure in phase $j+1$ is the combined result of successful phases 1 to j and the system failure occurring in phase $j+1$ via an 'AND' gate. This can be seen in Figure 3 where the 'NOT' gate is used to represent system success during phase 1 as NOT failure in

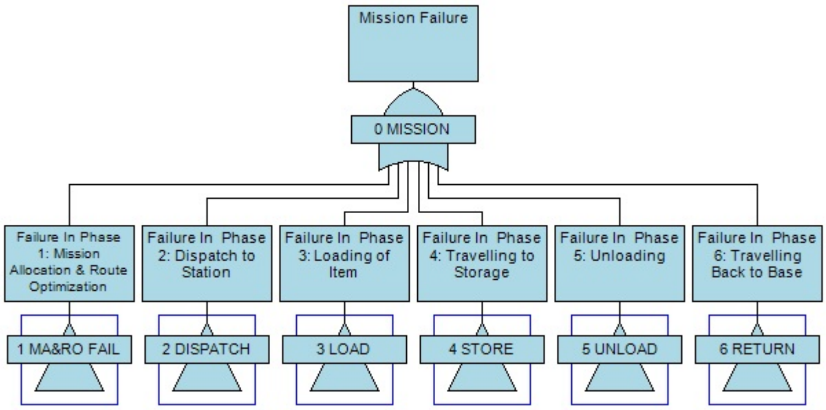

Figure 2 Logic between the top mishap and branch events.

Table 6 Component failures causing system failure at each phase

Phase	Component failures causing system failure at each phase
1	ASCS; LNS; Batteries
2	Drive unit; Brake system; Steering system; ASCS; LNS; Safety system; batteries
3	Attachments; Brake system; ASCS; Safety system; Batteries;
4	Drive unit; ASCS; LNS; Safety system; Attachments; Batteries; Brake system; Steering system
5	Attachments; Brake system; ASCS; Safety system; Batteries
6	Drive unit; ASCS; LNS; Safety system; Batteries; Brake system; Steering system

phase 1. Following this logic, the AGV operation is analysed at each phase. The component failures resulting in the system failure at different phases are identified as shown in Table 6.

Furthermore, in order to complete the FTA, the fault trees for all the identified critical AGV subsystems are further constructed. The corresponding fault trees for the drive unit and the ASCS are shown in Figure 4 as examples.

As a systemic FTA method has been developed in [13] dedicated to modelling phased mission with MFOP, that method is used in this paper to calculate the mission reliability and phased unreliability of the AGV within MFOP based on the phase lengths assumed in Table 4 and the FMECA information obtained in Table 5. The details of the calculation method are given below.

Firstly, the system failure in phase j, i.e. T_j, is calculated by using the following equation

$$T_j = (Phase\ 1\ to\ j-1\ Success).(Phase\ j\ Failure) \tag{2}$$

The probability of failure of basic event A in all phases from i to j (i.e. $q_{A_{i,j}}$) can be calculated using the equation

$$q_{A_{i,j}} = e^{-\lambda_A t_{i-1}} - e^{-\lambda_A t_j} \tag{3}$$

where λ_A refers to the failure rate of a basic event A, t_j is the length of phase j.

The unreliability of phase j can be calculated by

$$Q_j = 1 - R_j = 1 - R_{1,j}/R_{1,j-1} \tag{4}$$

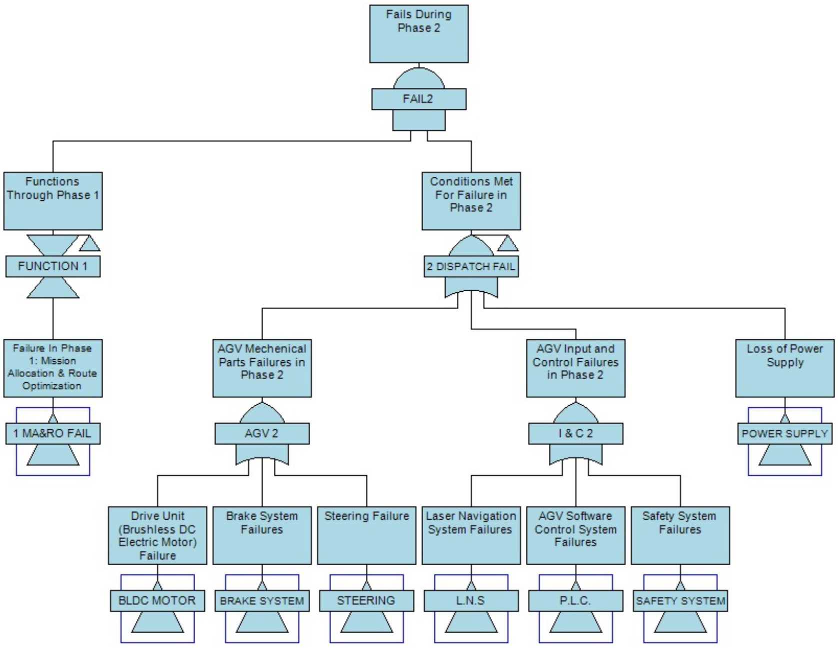

Figure 3 Fault trees for Phase 2.

Table 7 Component failure probability at the end of whole mission.

Description	Failure Probability	Description	Failure Probability
ASCS	0.00034925	LNS	0.00005094
Attachments	0.00009360	Safety Systems	0.00002183
Drive Unit	0.00008725	Steering System	0.00001455
Batteries	0.00007277	Brake System	0.00001164

where R_j denotes the success probability of phase j , $R_{1,j}$ is the success probability till the end of phase j. It should be noticed that the probability of failure is calculated using the exponential distribution since the failure rates are assumed to be constant for simplicity.

In the FTA calculation, the component will be taken into account in a phase only when it is involved in the completion of that phase. It will not be considered if it contributes nothing to the phase. Applying the aforementioned method to calculate the component failure probability, mission reliability, and phased unreliability of the AGV within MFOP, the results are shown in Tables 7 and 8.

From the results shown in Table 7, it is seen that the ASCS, attachments, drive unit and battery have the largest failure probability at the end of the whole mission. That implies these four components are most vulnerable to failure.

From Table 8, it is found that the mission reliability at the end of the 6th phase is 0.99930, which is based on the success of all six phases. This means that the AGV has a greater than 99% chance of successfully completing the mission. Thus, it in fact indicates the overall reliability of the AGV in accomplishing the whole mission. For this reason, it can be concluded that the AGV considered here is a very reliable material distribution vehicle in the warehouse. In addition, Table 8 shows that phase 2 'dispatch to station' and phase 4 'travelling to storage" show the largest phase unreliability values. This means that the AGV is more likely to fail in the completion of these two phases.

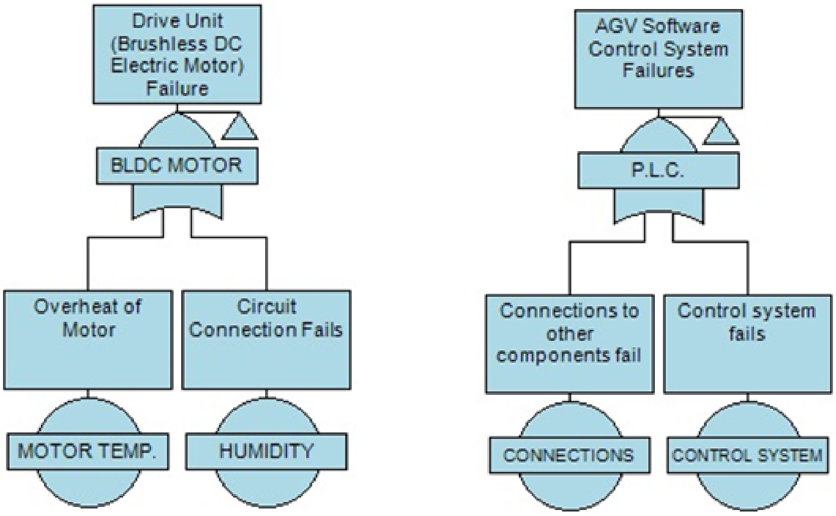

Figure 4 Fault trees for Drive Unit and ASCS.

Table 8 The resultant mission reliability and phase unreliability.

Phase	Mission reliability at phase end	Phase unreliability
1	0.99998	0.00001855
2	0.99974	0.00024386
3	0.99967	0.00007266
4	0.99945	0.00021915
5	0.99942	0.00002243
6	0.99930	0.00012527

Additionally, in this paper the optimum maintenance time of the AGV is also considered by investigating the reliability of the AGV against the number of the missions that the AGV can complete without maintenance. The success probability of the AGV can be calculated by

$$SuccessProbability = \prod_{i=1}^{n} P_i \tag{5}$$

where P_i is the probability that the AGV is able to complete the i^{th} mission successfully, and n is the number of missions the AGV needs to complete. The calculation results are shown in Figure 5. From Figure 5, it is interestingly found that with the increase of the number of missions that the AGV can complete without receiving any maintenance, the success probability shows a monotonous decreasing tendency, thus from which the optimum maintenance time of the AGV can be readily inferred.

5 Conclusions

In order to investigate the safety and reliability issues existing in AGVs that are being increasingly used for intelligent transportation and material distribution in warehouses and/or manufacturing facilities, a promising technical approach has been established in this paper. It has been shown that FMECA and FTA can be adopted to identify the critical

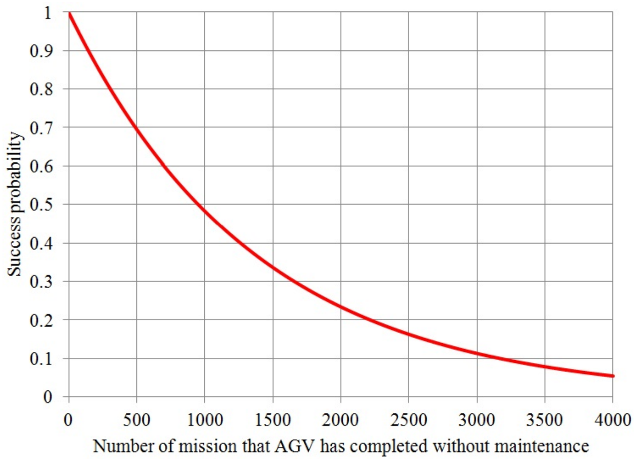

Figure 5 Success probability vs. mission number.

AGV components and the crucial mission phases of AGVs at the design stage. From the research reported, the following conclusions can be reached:

(1) The key AGV components can be successfully identified based on the criticality rank that is obtained through performing FMECA. The calculation results presented in this paper has shown that nearly all AGV components except manual button, such as driving, operating, control and power supply units, are critical components;

(2) The FTA results show that among all identified key components, the ASCS, attachments, drive unit and battery are most vulnerable components to failure because they are found to have the largest failure probability at the end of whole mission;

(3) The FTA calculation has suggested that the AGV is more likely to fail in the completion of the phase ‘dispatch to station’ and the phase ‘travelling to storage’ because these two phases show the largest phase unreliability values. But it is worth noting that such conclusions are based on the assumptions given in Section 3. In reality, the result would be different, depending on the real reliability data collected from the AGVs;

(4) Research has shown that the AGV being inspected is overall a very reliable material distribution vehicle in the warehouse. But Figure 5 has indicated that the reliability of the AGV will degenerate if it completes more missions without maintenance;

(5) Through this research, it can be concluded that the proposed FMECA-FTA approach is indeed a valid method for assessing and evaluating the safety and reliability issues in AGVs.

Nevertheless, the work reported in this paper is only a preliminary research on AGV reliability issues. In the future, the proposed method will be further validated by using real AGV data through the collaboration with relevant industry partners.

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