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Novel methodology for optimising the design, operation and maintenance of a multi-AGV system

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ABSTRACT

Automated guided vehicles (AGVs) have long been identified as a potential driver to improve system efficiency and lower labour costs in material handling systems. Accordingly, the reliability and availability of AGV systems is crucial to assure the stability and efficiency of these systems. However, the reliability issues and maintenance strategies of AGVs have not previously been studied sufficiently. This is even more marked in the case of multi-AGV systems that consist of fleets of AGVs. To fill this knowledge gap, research is conducted considering a multi-AGV system, consisting of three AGVs, in order to develop a scientific methodology for optimising the layout design, operation and maintenance of a multi-AGV system. Once an AGV is failed, it will be towed to the maintenance site for repair by a recycle vehicle to prevent deadlock and conflict. The efficiency of the recycling process of failed AGVs in a multi-AGV system, with respect to the change of location of the maintenance site, is analysed by the approach of coloured Petri nets (CPNs). A CPN model simulating the corrective and periodic preventive maintenance processes of failed AGVs is also developed in order to investigate the impact of different AGV maintenance strategies on the operation efficiency of the multi-AGV system. The simulation results obtained clearly show that the location of maintenance sites and maintenance strategies do have significant influence on the performance of a multi-AGV system, where corrective maintenance is an effective measure to maintain the long-term reliability and stability of the system.

1. Introduction

Automated Guided Vehicles (AGVs), a type of vehicles that are driverless and programmed to travel on predefined routes to transfer loads, are being widely used in modern material handling systems due to their ability to improve the efficiency and productivity of the systems and decrease human labour. Accordingly, the design, operation and maintenance of the AGV systems have attracted interest from both academic and industrial communities in recent years. In particular work on improving the efficiency, and lowering the operation cost, of AGV systems has been performed [1, 2]. An approach was developed in [3] to obtain an optimal unidirectional flow path of AGVs. The optimal path design was targeted to minimise the total travel distance of the AGVs in the system. The main performance criteria for the guide-path material handling system were discussed in [4]. The interest of the majority of these pioneering works was focused on the optimization of the travel time and queue length of the AGVs. However, with the continual increasing application of AGVs, it is recognized that more factors should be taken into account to achieve an optimal solution for the design, operation and maintenance of an AGV system. For example, the impact of empty AGVs on system operation was investigated in [5]. This research concludes that ignoring the impact of empty vehicles can lead to an underestimation of the number of AGVs and the time required for completing missions. Other attempts have been made to improve the system performance by various approaches. For example, a method was proposed in [6] to solve the deadlock problem, when AGVs are unable to make further progress, the potential in reducing both the material handling time and the cost was demonstrated by the approach of simulation. The impact of both empty and loaded vehicles on the operation of AGV system was researched in [7] in order to optimise the direction of unidirectional routes.

With the continual scaling up and modernisation of AGV systems in recent years, they are now designed to deliver more complex tasks. Accordingly, more and more uncertainty issues are observed in the systems. For this reason, the failure management and maintenance strategies of AGVs are identified as new challenging issues that need to be addressed. As the rate of application of AGVs continues to increase the need to resolve such issues has become a pressing task. Some studies have been undertaken in the literature to achieve this. For example, the safety requirements and safety functions for a decentralised controlled

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AGV system were discussed in [8]. In this work, three major hazards, i.e. collision with a person, tilting over and falling down, were identified. The effects of the speed of AGVs, the braking distance and detection area requirements, as well as the mean time to dangerous failure and performance were analysed. Considering failure response, a control method was developed in [9] for enhancing the failure control management of a special case of AGVs, an underground transportation system. In the research, both loaded and unloaded AGVs were considered. More recently, the reliability of AGVs was modelled as a cost function to optimise the time and cost of the operation of AGVs [10]. All of these studies have shown that the reliability and efficiency of AGV systems can be achieved at the same time. However, to the best knowledge of the authors, the availability of AGVs and its influence on the efficiency and performance of the system has never been discussed before. This motivates the research studied in this paper.

The availability of a system can be guaranteed via conducting appropriate maintenance, in which either major or minor repairs or even replacement of defective components would take place. At present, preventive, corrective and predictive maintenance are primary maintenance strategies that are popularly adopted in engineering practice. Usually, preventive maintenance is conducted periodically despite the actual health condition of the AGVs. In contrast to the former, corrective maintenance is conducted only when a failure is present in the AGV. Predictive maintenance monitors the state of components/subsystems in order to determine the optimal maintenance time. These maintenance strategies, their merits and constraints, as well as their influences on system availability have been investigated in other industries [11, 12]. For example, different maintenance policies for manufacturing production lines were simulated in [13] and the maintenance cost and the availability of an aircraft system were optimized in [14]. Given the lack of research on the impact of maintenance activities on the availability of AGV systems, in this research, two different maintenance strategies, namely preventive and corrective maintenance, for multi-AGV systems are considered. Their different contributions to the system efficiency and availability are investigated. The predictive maintenance is not considered in this research because (1) it has not been a proven technology in the application of AGVs due to the difficulty of obtaining reliable remaining life prediction of the AGV components under the constantly varying conditions they operate in; (2) neglecting predictive maintenance behaviour simplifies the simulation model thus making the methodology described here easier to follow. However using the approaches outlined in this work predictive maintenance could be built into the model. Once an AGV has failed in the system, it should be recycled as soon as possible to prevent further deadlock and conflict. When modelling the multi-AGV system, the automatic recycling of a failed AGV, i.e. the use of an additional AGV to collect the failed AGV and transport it to the appropriate site, and its travelling path in the system, are considered in order to reduce the human's intervention in the operation of the system. A specific area for storing the failed AGV and the maintenance plan are considered when modelling the multi-AGV system. In this way, the influences of the location of the maintenance site and maintenance plan of the failed AGV on the system efficiency can be investigated through modelling the system using coloured Petri nets (CPNs). Such comprehensive research paves the way to achieve more successful layout design, operation and maintenance of multi-AGV systems. To the best of the authors' knowledge, CPNs have never been applied to the study of the reliability, operation, mission and maintenance of AGVs and AGV systems. Hence the aim of the work presented in this paper is to demonstrate the advantages of applying this modelling technique to this area. Also, the technique has been adapted in this work and a novel approach is adopted using five different types of nets which interact to provide the overall system availability. Adopting this approach makes the method very versatile and it can be easily modified if the requirements or missions change.

The remaining part of this paper is organised as follows. The CPN modelling methods are discussed first in Section 2; the configuration of the AGV system & mission of interest are described in Section 3; All CPN based models for describing the multi-AGV systems, recycle and maintenance behaviours are established and simulated respectively in Sections 4 and 5; the simulation calculations and result discussions are performed in Section 6; and the paper is finally completed with a few key research conclusions in Section 7.

2. Methodology for modelling recycling and maintenance processes

Due to its efficient and cost effective nature, modelling has been identified as an important approach to improve the design, operation and maintenance of an AGV system. However, any model developed would need to be dynamic and highly adaptive. Since Petri nets (PNs) provide an intuitive graphical representation of a system, and allow flexible description of any event caused by the modification of design, operation and maintenance of a system, they are adopted to model the problem considered in the paper.

The concept of a PN was developed by Petri [15], and it is defined as a direct bipartite graph that consists of four types of symbols: circles, rectangles, arrows and tokens, as shown in Fig. 1. Circles represent the places, which are conditions or states such as mission failure, phase failure, or component failure; rectangles represent the transitions, more abstractly actions or events which cause the change of condition or state. It should be mentioned that if the time for completing the transition is zero, the rectangle is filled in, otherwise it is hollow; arrows represent arcs which are connections between places and transitions. Arcs with a slash on and a number, n, next to the slash represent a combination of n single arcs and the arc is said to have a weight n. No slash always means that the weight is one; and small filled in circles represent tokens which carry the information in the PNs. The tokens move via transitions as long as the enabling condition is satisfied, which gives the dynamic properties of the PN. For example in Fig. 1, there are two and three tokens (represented by small filled in circles) in each of the two input places to the transition. The input places have arcs with weights 1 and 3, respectively. The transition is said to be enabled since the number of tokens contained in every input place is equal to or greater than the corresponding arc weights. As the transition is enabled after the time associated with the transition, t, the number of tokens equivalent to the arc weights are taken out of the input places and the number of tokens equivalent to the output arc weight are transferred to the output place. In this example one token appears in the output place as shown in Fig. 1.

The marking of a net at any particular time gives the state of the system being modelled at that time. Due to the strengths of the PN approach in describing systems the technique has been widely applied to modelling a variety of systems. For example, a hybrid PN modelling method coupled with parameter trend which prescribes thresholds and allowable margins of fault places, and fault tree analysis has been applied to model the maintenance policy of heating and cooling systems in [16] and functional product availability and support cost were predicted by using fault tree, Petri net and discrete event simulation techniques in combination in [17]. The maintenance of an offshore wind turbine was modelled by using PNs in [18] where, three types of different maintenance strategies, namely periodic, conditional and

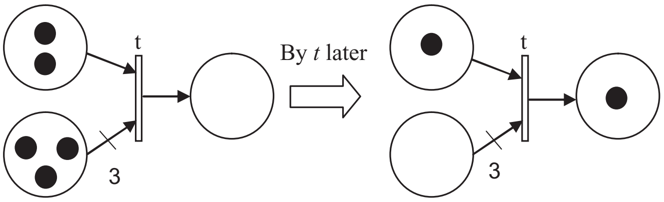

Fig. 1. Petri net model with transitions.