PERFORMANCE OF TWO REAL TIME CONTROL STRATEGIES FOR AGV SYSTEMS: A CASE STUDY

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Abstract

Real time control of material handling devices is essential to guarantee efficiency and flexibility of automated manufacturing systems. This paper presents a performance based comparison of two control policies previously presented by one of the authors to avoid deadlock and collisions in zone controlled Automated Guided Vehicle Systems (AGVSS). Coloured Timed Petri Nets are used to model the dynamics of AGVSS and implement the control strategies stemming from the knowledge of the system state. Several simulations of an AGVS with varying fleet size show the effectiveness of one of the considered control strategies compared to the alternative policy.

1 Introduction

Efficient and effective real time control has basic importance to manage Automated Guided Vehicle Systems (AGVSS). AGVSS are flexible material handling devices suitable to improve the performance of Automated Manufacturing Systems (AMSS) [9]: the controller assigns route and velocity to vehicles and avoids collisions and deadlocks during the AGV's missions.

This paper makes use of a standard technique for vehicle management of AGVSS, i.e., zone control. More precisely, the guide-paths are separated into disjoint zones and deadlocks can occur when a set of AGVs competes for a set of zones detained by vehicles of the same set. In particular, to cope with deadlock in zone-controlled AGVSS, Fanti [1, 2, 3] proposed some deadlock avoidance policies based on digraph analysis. Such algorithms avoid not only deadlock states but also some peculiar conditions, known as “restricted deadlock” [4]. When a restricted deadlock occurs, the system is not in deadlock condition but some vehicles permanently remain in circular wait, partly because some of them are blocked and partly since the controller prevents them from moving. Following the approach in [1], the AGVS controller structure is composed of two levels: the path scheduler and the real time controller. The path scheduler is a higher control level selecting the paths to assign to the vehicles. On the other hand, the real-time controller has two functions: i) it validates the path proposed to a vehicle (path validation) so that each mission is completed without deadlock and restricted deadlock; ii) it validates the next zone in the path to prevent deadlocks and collisions, by enabling or inhibiting the AGV zone acquisition (zone validation).

This paper focuses on the specification of the real time controller. The AGVS structure and dynamics are described by a resource oriented Coloured Timed Petri Net (CTPN): tokens are vehicles and the path that each AGV has to complete provides the token colour. Moreover, associating a time concept to the Coloured Petri Net allows the investigation of the system performance. Indeed, we propose a performance based comparison of two control policies managing traffic in AGVSS previously presented by one of the authors. In particular, the paper considers the most flexible procedure to avoid deadlock and restricted deadlocks in AGVS based on digraphs presented in [1]. An alternative approach presented in [3] bases decisions on the results of a simulation run of the CTPN model, forecasting the AGVSS behaviour. In order to compare the two approaches, an AGVS is adopted as a case study. Simulation evidences in the MATLAB-Stateflow environment [8] show that the policy introduced in [3] exhibits better performance indices than the control strategy presented in [1].

The paper is organised as follows. Section 2 describes the AGVS layout and the CTPN model. Section 3 recalls previous results on deadlock avoidance in AGVSS. In addition, Section 4 recalls the considered control policies and Section 5 describes the controller synthesis. Finally, Section 6 presents several simulation results for the case study and Section 7 draws the conclusions.

2 The AGVS model

2.1 The AGVS description

The case study adopted in this paper is an AGVS with a layout involving unidirectional and bi-directional guide-paths. The AGVS is divided into several disjoint zones and each zone can represent a workstation, an intersection of paths or a straight lane (see figure 1). Moreover, the AGVS includes a docking station where idle vehicles are parked. The set of zones of the AGVS is denoted by Z={zi, i=1,…,NZ}, where zi for i=2,…, NZ represents a zone and z1 denotes the docking station. In addition, V={vj: j=1,…, NV} is the set of vehicles available in the system. Since each zone can accommodate only one vehicle at a time, zones zi for i=2,…, NZ have unit capacity. On the contrary, the docking station can accommodate all the vehicles and is modelled by zone z1 with capacity equal to NV. The AGVS shown by figure 1 connects six workstations (denoted in the figure by z2, z3, z4, z5 and z6) and the
docking station $z_1$. Four additional zones denote the intersections of the paths with parts of lanes ($z_2, z_3, z_4$ and $z_5$). The paths $z_1$-$z_2$, $z_1$-$z_3$, $z_2$-$z_4$ and $z_5$-$z_2$ are bidirectional and the others are unidirectional. We describe the route $r(v)$ assigned to the vehicle $v \in V$ by the zones sequence $r(v)=(z_i, \ldots, z_j)$ that ends to the docking station. In the sequel, $r(v)$ denotes the residual route that $v \in V$ has to visit to complete its travel starting from a certain system configuration: obviously, it is a subsequence of $r(v)$.

Figure 1. A zone-control AGVS.

2.2 The coloured timed Petri net model

This section recalls a modular method to build the coloured Petri net modelling the system layout and dynamics [2, 3]. We assume that the reader is familiar with Coloured Timed Petri Nets (CTPN) (see [6] for details).

A CTPN is an 8-tuple $\text{CTPN} = (P, T, \text{Co}, \text{Inh}, \mathbf{C}^+, \mathbf{C}^-, \mathbf{M}_0, \mathbf{\Omega})$ where $P$ is a set of places, $T$ is a set of transitions, $\text{Co}$ is a colour function defined from $P \times T$ to a set of finite and not empty sets of colours [6]. $\text{Co}$ maps each place $p \in P$ to a set of possible token colours $\text{Co}(p)$ and each transition $t \in T$ to a set of occurrence colours $\text{Co}(t)$.

In our model, a place $z_i \in P$ denotes the zone $z_i \in Z$ and a token in $z_i$ represents a vehicle that is in zone $z_i$. The transition set $T$ models the guide-paths between consecutive zones. Moreover, the set of arcs $(P \times T) \cup (T \times P)$ is defined as follows: if $z_i$ and $z_m$ are two consecutive zones in the AGVS, then transition $t_{im}$ belongs to $T$ and it is such that $t_{im} \in z_m$ and $t_{im} \in z_i$. To admit just one vehicle in each zone other than the docking station, there is an inhibitor arc between each pair $z_i \in P$ with $i \neq 1$ and transition $t_{im} \in T$, i.e., $\text{Inh}(z_i, t_{im})$. More precisely, the inhibitor arc between a place $z_i \in P$ and a transition $t_{im} \in T$ implies that transition $t_{im}$ can be enabled if $z_i$ does not contain any token. Since $z_1$ can accommodate $N_V$ tokens, there are no inhibitor arcs between $z_1$ and each $t_{i1} \in T$.

Having described the skeleton of the CTPN, it is necessary to model the AGVS behaviour and the travels of vehicles. Hence, each AGV $v \in V$ is modelled by a coloured token and its token colour is $<r(v)>$, where $r(v)$ is the residual path that the vehicle has to follow to reach the docking station. A marking $M$ is a mapping defined over $P$ so that $M(z_i)$ is a set of elements of $\text{Co}(z_i)$, also with repeated elements, i.e., a multi-set [6] corresponding to token colours in the place $z_i$. The state of the AGVS is represented by the marking of the CTPN, i.e., if $M(z_i)=<r(v)>$, then vehicle $v$ is in zone $z_i$ and its colour $<r(v)>$ represents the sequence of zones that $v$ has to visit starting from the current marking. Consequently, the colour domain of place $z_i \in P$ is: $\text{Co}(z_i)=<r(v)>$ where $r(v)$ is a possible sequence of zones and $z_i$ is the first zone of $r(v)$.

Moreover, $\text{Co}$ associates with each transition $t_{im}$ a set of possible occurrence colours: $\text{Co}(t_{im})=\text{Co}(r_{in})$ such that $r_{in}$ is a possible sequence of zones and $z_i$ and $z_m$ are respectively the first and the second element of $r_{in}$. Hence, the CTPN is represented by the $|P| \times |T|$ pre- and post-incidence matrices $\mathbf{C}^+$ and $\mathbf{C}^-$, respectively defined as follows:

1. if there exists an arc from $z_i$ to $t_{im}$ then $\text{Co}(z_i)=\text{Co}(r_{in})$, where $\text{Co}(r_{in})$ stands for "the function makes no transformation in the elements", otherwise $\text{Co}(z_i)=\emptyset$.
2. if there exists an arc from $t_{im}$ to $z_m$ then $\text{Co}(z_m)=\text{Co}(r_{in})$, otherwise $\text{Co}(z_m)=\emptyset$. More precisely, $\text{Co}(r_{in})$ is the residual sequence of zones obtained from $<r(v)>$ disregarding the first element $z_i$.

The set $\mathbf{\Omega}$ is defined by $\mathbf{\Omega}=(\text{Co}(x), x \in P \cup T)$. Moreover, considering that at the initial marking $M_0$ a route $r(v)$ is assigned to each $v \in V$, $M_0$ is defined as follows: if $z_i \in P$ is the first zone of a route $r(v)$ for some $v \in V$, then $M_0(z_i)=<r(v)>$ else $M_0(z_i)=\emptyset$.

2.3 The AGVS dynamics

Now, to investigate the performance of the system it is convenient to extend the CPN with the time concept [6]. To do this we introduce a global clock, i.e., the clock values $t \in \mathbb{R}^+$ represent the model continuous time, where $\mathbb{R}^+$ is the set of non negative real numbers. Moreover, the temporisation of the Petri net is achieved by attaching a delay to the output arc of each transition, i.e., there is a delay after which the token becomes available. Here, the time delay $\delta(z_{im}, t_{im}) \in \mathbb{R}^+$ is the time necessary for each AGV to move from zone $z_i$ to zone $z_m$. Moreover, we allow each token to have a time stamp $s(r(v))$ attached to it, in addition to the token colour $<r(v)>$. As soon as a token with colour $<r(v)>=(z_i, z_{im}, \ldots, z_j)$ is in zone $z_i$, its stamp is reset to zero and the token will be available after $\delta(z_{im})$ time units. Hence, transition $t_{im}$ is said to be ready for execution when the stamp $s(r(v))$ satisfies condition $s(r(v)) \geq \delta(z_{im})$.

Moreover, transition $t_{im}$ is enabled at marking $M$ with respect to the colour $<r(v)> \in \text{Co}(t_{im})$ if two conditions are simultaneously verified:

\begin{align*}
C1) & \quad M(z_{im})=\emptyset \text{ if } m=1, \\
C2) & \quad M(z_i) \subseteq \text{Co}(z_{im})(<r(v)>), \text{ with } M(z_i)=<r(v)> \text{ and } r(v)=(z_i, z_{im}, \ldots, z_j).
\end{align*}

In general, the firing of a transition $t$ with respect to colour $c \in \text{Co}(t)$ leads to a new marking $M'$, denoted by $M[t(c)]=M'$. A sequence $M[t(c_1)]=M[t(c_2)]=M_0=\ldots=M_n$, where $c_1||c_2||\ldots||c_n$ is a firing sequence: in this case we say that $M'$ is reachable from $M$. Symbol $R(M)$ denotes the set of reachable markings from $M$. 
Example 1. Now, let us consider the AGVS described in subsection 2.1, with $N_V=5$ and the following routes assigned to the AGVs: $r(v_1)=(z_7, z_2, z_3, z_8, z_7, z_1)$, $r(v_3)=(z_7, z_2, z_3, z_8, z_7, z_1)$. We remark that $v_1$ is a vehicle waiting for destination in the docking station.

Each time delay is depending on the current CTPN marking. Each vertex in Figure 2. The CTPN at marking $M_0$ for the case study ($N_V=5$).

A digraph is considered as follows: $M_0(z_7)=$< $(z_7, z_2, z_3, z_8, z_7, z_1)$>, $M_0(z_3)=$< $(z_7, z_2, z_3, z_8, z_7, z_1)$>. The proposed deadlock avoidance strategies [4, 1]. The proposed two policies for the AGVS only if $e_{im}$ is assigned to a vehicle $v_i$. Moreover, let the capacity of a cycle $C_2(M)$ be the subset of second level cycles from $M_0$ (second level cycle) and let $|P|$ be the number of distinct resources involved in all the cycles corresponding to the vertices of $v_2$. Finally, let $C_2(M)$ be the minimum capacity of the second level cycles from $M_0$ (second level deadlock). Considering that $n_V(M)$ indicates the number of vehicles performing transport operations in the current marking (not including the vehicles waiting in the docking station) the following proposition is proven in [1]:

Proposition 2: A marking $M$ can be a second level deadlock state for the AGVS only if $\Gamma(M)$ is not empty and $n_V(M) \geq C_2(M)$.

Now, a deadlock avoidance policy must prevent not only deadlock, but also unsafe states that are not deadlock but can incur a deadly embrace in the next future. To define an efficient deadlock avoidance strategy, a state named second level deadlock is characterized by the definition of a second digraph $D_2(M)=(N, E_2(M))$ called residual path digraph [1]. A digraph $D_2(M)$ is built taking into account the residual path that each vehicle in the system has to complete at the current marking $M$. Hence, $e_{im} \in E_2(M)$ iff $z_m$ immediately follows $z_i$ in $r(v_i)$, for some $v_i \in V$. Now, a second level deadlock can occur only if the cycles of $D_2(M)$ enjoy a particular property that can be exhibited using a further digraph, $D_2(M)=(N(M), E_2(M))$, named second level digraph and obtained from $D_2(M)$ as follows. Denoting by $\gamma_1, \gamma_2, \ldots, \gamma_M$ the complete set of the cycles of $D_2(M)$ not including $z_i$, we associate a vertex $\gamma_k \in N(M)$ to each cycle $\gamma_k$ of $D_2(M)$. Moreover, an edge $e_{im}$ is in $E_2(M)$ if the following two conditions hold: a) $\gamma_i$ and $\gamma_k$ have only one vertex in common (say $t_0$); b) there exists a residual path $r(v)$ for some $v \in V$ requiring zones $z_k$, $z_m$ in strict order of succession and $e_{im}$ is an edge of cycle $\gamma_m$ while $e_{im}$ is an edge of cycle $\gamma_k$.

Now, let $\gamma_2$ be a cycle from $D_2(M)$ (second level cycle) and let $\Gamma(M)$ be the subset of second level cycles enjoying the following property: $\gamma_2 \in \Gamma(M)$ iff the cycles associated with the vertices of $\gamma_2$ are all disjoined but for one vertex, common to all of them. Moreover, let the capacity of a cycle $\gamma$ (denoted by $C_2(\gamma)$) be defined as the number of resources involved in such a cycle. Analogously, let us define the capacity of a second level cycle $C_2(\gamma)$ as the number of distinct resources involved in all the cycles corresponding to the vertices of $\gamma_2$. Finally, let $C_2(M)$ be the minimum capacity of the second level cycles from $\Gamma(M)$ ($C_2(M)=\infty$ if $\Gamma(M)$ is empty). Considering that $n_V(M)$ indicates the number of vehicles performing transport operations in the current marking (not including the vehicles waiting in the docking station) the following proposition is proven in [1]:

Proposition 2: A marking $M$ can be a second level deadlock state for the AGVS only if $\Gamma(M)$ is not empty and $n_V(M) \geq C_2(M)$. We remind that a digraph containing $N$ nodes is completely characterized by its $(N \times N)$ adjacency matrix [5]. Modelling the AGVS by the CTPN, it is possible to obtain the $(I \times P)$ adjacency matrices $A_T(M)$ and $A_g(M)$ of digraphs $D_T(M)$ and $D_g(M)$ respectively, by means of the incidence matrix of the CTPN at marking $M$.

3 Previous results about deadlock conditions

Here, we recall the main definitions and results necessary to explain the deadlock avoidance strategies [4, 1]. The proposed techniques use digraphs to characterize deadlock: all the current interactions between vehicles and zones are described by means of a digraph $D_\text{CTPN}(M)=(N, E_\text{CTPN}(M))$ named Transition digraph and depending on the current CTPN marking. Each vertex in $N$ corresponds to a zone $z_i$, so that the same symbol is used for vertices and zones, i.e., $N=Z$. The vertex set is fixed, but the edge set changes at each event occurrence and is defined as follows: $e_{im} \in E_\text{CTPN}(M)$ iff there exists at marking $M$ a vehicle $v_i \in V$ occupying $z_i$ and requiring $z_m$ as the next zone. The following is proven in [1]:

Proposition 1. The AGVS is in deadlock condition in the current marking $M$ iff there exists a cycle in the transition digraph that does not contain zone $z_i$.
share the same algorithm checking for zone validation and differ for the path validation algorithm.

### 4.1 Control policy 1

In terms of Petri nets modelling, a transition \( t_m \in T \) is said to be controlled if its firing is determined by a CP when \( t_m \) is enabled according to conditions C1 and C2. Therefore, a CP is a mapping associating with each event \( \sigma \in \Sigma_1 \cup \Sigma_2 \) and with each marking M a control action that enables and inhibits event \( \sigma \), i.e., distinguishing between 1-type and 2-type events:

\[ f_1(\sigma; M) = \begin{cases} 1 & \text{if } M^* \text{ is reachable from } M \text{ under } f_1 \text{ and priority rule } \pi, \\ 0 & \text{otherwise.} \end{cases} \]

\[ f_1(\sigma; M) = \begin{cases} 1 & \text{if } M^* \text{ is reachable from } M \text{ under } f_1 \text{ and priority rule } \pi, \\ 0 & \text{otherwise.} \end{cases} \]

\( f_2(\sigma; M) = \begin{cases} 1 & \text{if the digraph } D(M') \text{ and described by } A_2(M') \text{ exhibits a cycle that does not include } z_i, \\ 0 & \text{otherwise.} \end{cases} \]

It is proven in [3] that an AGVS under CP2 is deadlock and restricted deadlock free. Moreover, the check performed by \( f_2 \) works in polynomial time.

### 5 Synthesis of the controller

This section describes the activities of the real time controller: the Zone Validation and the Path Validation Algorithms (ZVA, PVA) that implement CP1 and CP2. While the ZVA is the same for CP1 and CP2, these differ for the PVA.

#### 5.1 Zone validation

Let us suppose that the CTPN is at marking M and that transition \( t_m \) is colour enabled, i.e., \( M(z_k)=<0> \) and \( M^*(z)$

\[ A1 \text{ If } M^*(z)=<0> \text{ then the zone is validated and } M \text{ is not validated. Go to step A5.} \]

\[ A2 \text{ If } M^*(z)=<0> \text{ then the controller determines the new marking: } M^*(z)=<0>; M'(z)=<z_{z_m}, \ldots, z_i>; M'(z)=M(z) \text{ for each } z \in P \text{ with } z \neq z_{z_m} \text{ and } z \neq z_i. \]

\[ A3 \text{ Build } A_1(M). \]

\[ A4 \text{ A depth-first search algorithm [7] is applied to } A_1(M): \text{ if the search finds a cycle not including } z_i \text{ then } f_2(\sigma_2; M)=0 \text{ and go to step A5, else } f_2(\sigma_2; M)=1 \text{ and go to step A6.} \]

\[ A5 \text{ The zone is not validated, the behaviour of the AGVS continues with the CTPN at marking } M. \text{ STOP.} \]

\[ A6 \text{ The zone is validated and } t_m \text{ fires, the behaviour of the AGVS continues with the CTPN at marking } M'. \text{ STOP.} \]

#### 5.2 Path validation

Path validation consists in enabling or inhibiting 1-type events to avoid deadlocks and restricted deadlocks as a new path is assigned to some vehicle. Let \( r \) be the path that the scheduler proposes for vehicle v and let \( M \) be the current marking of the CTPN at time \( \tau \). Under CP1, the controller executes the following PVA.

\[ PV A1 \]

\[ B1 \text{ Update the marking of the CTPN as follows: } M'(z_k)=<r(v)> \text{ where } z_k \text{ is the first resource of } r(v) \text{ and } M'(z)=M(z) \text{ for each } z \in P \text{ with } z \neq z_k. \]

\[ B2 \text{ A depth-first search algorithm is applied to } A_1(M'): \text{ if the search finds a cycle not including } z_i \text{ then } f_2(\sigma_2; M)=0 \text{ and go to step B4, else } f_2(\sigma_2; M)=1 \text{ and go to step B5.} \]

\[ B3 \text{ Build the path digraph and the second level digraph. If } \Gamma^*(M') \text{ is not empty and } n_V(M') \in \Sigma_2 \text{, then } f_2(\sigma_2; M)=0 \text{ and go to step B4, else go to step B5.} \]

\[ B4 \text{ The path } r(v) \text{ is not validated and the evolution of the CTPN} \]

\[ B5 \text{ The zone is validated and the behaviour of the AGVS continues with the CTPN at marking } M'. \text{ STOP.} \]
A set of 300 routes resulting in three replications of a set of 100 routes is considered in six experiments for both control systems (e.g., the AGVS dynamics) with the execution of MATLAB computation routines (e.g., the ZVA and PVA algorithms), while keeping track of time by way of a software clock. More precisely, here the Petri net places are represented by a finite state automaton, with sub-states modelling the zone shift of the AGV currently under investigation. As already mentioned, the main difference in the implementation of the two CPs is in the PVA definition. In particular, in the AGVS controlled by CP1 a “PVA1” block tests the presence of a particular cycle in the second level digraph originating from the new marking. Instead, in the system controlled by CP2 a “PVA2” block performs a simulation of the AGVS in order to check the task marking reaching under the ZVA control and supposing that no 1-type event occurs.

6.3 Simulation results
The AGVS throughput is depicted in figure 3 for CP1 and CP2, respectively, when using different AGV fleet sizes. Figure 3 shows that the AGVS throughput is maximized under CP1 when five vehicles are available, whereas the highest number of accomplished transportation tasks is obtained under CP2 with six vehicles. Moreover, Figure 3 shows that the transportation system under both PVA strategies is not efficient for a modest AGV fleet size, since the number of vehicles is small compared with the AMS size as well as with the number of tasks to be completed. All the same, under both real time control strategies the AGVS is inefficient for a large AGV fleet size: traffic becomes congested and vehicles are often blocked in order to avoid deadlock and collisions. The average percentage time of loaded and booked travel under both CPs is reported in figure 4. Under both techniques the index decreases with the increase in AGV fleet size: this is expected, because of the corresponding traffic congestion. Figure 5 depicts the average percentage blocked time of vehicles. For both techniques the performance index increases with the fleet size, since the number of vehicles is small compared with the AMS size as well as with the number of tasks to be completed.
size. Indeed, the probability that a vehicle is blocked while executing a transportation task increases when the system is overcrowded. The average empty and available time is reported in figure 6. Such an index is only partly dependant on the adopted control policy: in fact, it is influenced by the selected dispatch policy and by the transport request rate, i.e., by the path scheduler design. Finally, the AGVS utilization index is reported in figure 7. Here, the average percentage time a vehicle is either booked travelling toward a loading station, or loaded and blocked, or else carrying a piece towards its destination is reported. This index is high for both CPs: most of the time vehicles are busy out of the docking station. We observe that CP2 outperforms CP1 in all the performance indices reported in figures 3-7. In fact, the path validation algorithm based on the task marking reaching tends to reject a lower number of tasks with respect to the algorithm based on cycles detection in the digraphs associated to the AGVS.

7. Conclusions

This paper presents a performance based comparison of two control policies (CPs) previously presented by one of the authors for zone controlled Automated Guided Vehicle Systems (AGVSs). The two CPs share the same algorithm checking for zone validation (ZVA) and differ for the path validation algorithm (PVA). A case study is considered. The AGVS structure and dynamics are described by a resource oriented Coloured Timed Petri Net (CTPN), allowing the investigation of the system performance. We compare the two CPs on the basis of appropriate performance indices in the MATLAB-Stateflow environment. Simulation evidence show the effectiveness of one of the considered control strategies compared to the alternative policy.

References


