Motion Coordination of AGV’s in FMS using Petri Nets

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Abstract: This paper proposes a modeling strategy for automated Flexible Manufacturing Systems (FMS) that incorporates automated guided vehicles (AGV’s) as material handling systems. Using the industrial standard ISA-95, the task-based coordination of equipment and storages is constructed considering process restrictions, logical precedence conditions, shared resources and the assignment of the robots to move work pieces individually or in subgroups. The Petri Net model calls in the low level to formation, marching and collision avoidance control laws, for omnidirectional robots. The hybrid architecture is implemented and validated for the case of a FMS and four mobile robots.

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1. INTRODUCTION

Nowadays, the FMS involves new technologies of automation in order to coordinate the assembly of different and concurrent products (Groover (2008)). The Petri Net (PN) formalism has served to represent the asynchronous firing of actions, blocking, concurrency and other dynamic behaviours frequently appeared in large FMS (Li (2014)).

The Material-Handling System (MHS) is a set of resources for the carrying of workpieces between storages and workstations. The installation of AGV’s, emulating the coordinated work achieved by a group of workers, proposes a more flexible MHS, substituting some traditional fixed and non-reconfigurable transport setup, like conveyor belts or manipulators mounted in rails. The collective behaviour of groups AGV’S presents some advantages like redundancy and fault tolerance when a robot is broken and the loading of large objects by subgroups of robots in specific formation patterns (Krontiris (2013)). An industrial AGV’s setup is the Kiva system (Wurman (2008) and D’Andrea (2012)) where shelves are charged and moved by small autonomous robots, sharing information about inventories and work orders (Enright (2011)).

The motion coordination of AGV’s in a FMS must enable formation control, group path following or marching and inter-robot collision avoidance (Ailon (2012)). At same time, this coordination must obey process specifications, fault tolerance strategies and the routes assignment (Chen (2014)). In the context of mobile robotics control, the motion coordination of multiple robots, mainly omnidirectional and unicycle-type robots, has been studied using behavior-based control laws (Bravo (2011)), swarms stability (Fidan (2013)), bio-inspired navigation (Savkin (2013)), virtual structures (Chang (2011)), leader-followers schemes (Zhao (2010)) and artificial potential functions (Kowdiki (2012)).

Although the possibilities to implement the previous control laws in the context of FMS, the most of the previous works do not clarify how these low-level control strategies can be connected to a coordination layer of MHS within a production system. Moreover, the coordination layer must be designed according to industrial standards as ISA-95 (Instrument Society of America (1999)). However, commonly the discrete-event community studies only the high-level behavior of FMS excluding the analysis of the motion of the AGV’s, for instance (Gradišar (2012)) and (Sanchez (2010)). Few works like (Hernandez-Martinez (2011)), propose some hybrid architectures of formation control and a planning level, in this case neural networks, for dispersion tasks. A supervisory control for Finite State Automata using AGV’s is obtained briefly in (Sanchez (2009)) for an FMS, which presents the drawback of the state explosion for a real case. Hybrid architectures of PN and multi-agent systems have been addressed for communication in computer systems (Celaya (2009)).

This paper proposes a procedure to class of FMS using PN according to the task-based coordination proposed by the ISA-95 standard. The PN model represents the concurrency of tasks obeying the logic of precedence between tasks, the limitation of storages and the availability of the robots. The transportation tasks selects the adequate AGV’s to move the pieces implementing three basic continuous control laws to achieve formations, marching and collision avoidance of groups of robots. The approach was preliminarily presented in Hernandez-Martinez (2014) using a different case of study. Numerical simulations show the hybrid control performance. The approach links the two control levels clarifying the implementation of hybrid control in the engineering practice.
Denote by $A_1\{RM_{ij}, PM_i, n_{ij}\}$ the AGV’s transportation tasks a raw material from $RM_{ij}$ to $PM_i$ using $n_{ij} \leq r$ AGV’s and denote by $A_2\{PM_i, IS_{ij}, m_{ij}\}$ the transportation from $PM_i$ to $IS_{ij}$ using $m_{ij} \leq r$ AGV’s. Note that $m_{ij} \leq n_{ij}$ due to the decrease of the dimension and weight of the machining action. If $n_{ij}, m_{ij} > 1$, implies that the robots achieve a formation control and path following that will be detailed in the next section.

Each Assembly Station $AS_{p}, p = 1, ..., m$ realize $S_{i1}, ..., S_{ir_p}$ assembly programs. Let $U(S_{pq}) \subseteq \{IS_{i1}, ..., IS_{nk\alpha}\}$ be the set of Intermediated Storages that contains the subparts needed to complete the assembly program $S_{pq}$ and $K(S_{pq}, IS_{ij}) \in \mathbb{Z}^{+}$, $\forall IS_{ij} \in U(S_{pq})$ the quantity of subparts of $IS_{ij}$ to achieve the assembly program $S_{pq}$. Then, we define $A_3\{IS_{ij}, AS_p, m_{ij}\}$ as the task related to the transportation of a part from $IS_{ij}$ to $AS_p$. Note that the previous task must be repeated $K(S_{pq}, IS_{ij})$ times but not necessarily by the same robots. Finally, when the assembly program $S_{pq}$ has finished, the AGV’s do the $A_4\{AS_p, FP_{pq}, t_{pq}\}$ tasks to move the final product from $AS_p$ to the Final Product Storages $FP_{pq}$ (with capacity $C(FP_{pq})$ and manually unloaded), using now $t_{pq} \leq r$ robots. Fig. 1 summarizes the notation of the tasks of $PM, AS$ and the routes of the AGV’s in the system. Note that some arrows are related to the number of pieces $K(S_{pq}, IS_{ij})$ moved by the robots.

Based on the task decomposition proposed in the ISA-95 standard, Fig. 2 shows the tasks of the FMS with a clear separation of the MHS (the AGV’s and storages) and the process workstations (machines and assembly stations). The ISA-95 establishes that all the product sequences are reduced to the correct ordering (product recipe) of these tasks supervised by a computer system, avoiding the reprogramming of routines in the local controllers of the FMS elements when a new product is required.

Fig. 3 shows the normal process flow between tasks (rectangles) and storages (circles). The wide arrow denotes the AGV’s tasks; the continuous or dotted arrows are direct or inverse precedences between a pair of tasks, respectively. The direct logical precedences, for example $A_1 - M_{ij}$ and $M_{ij} - A_2$, establishes that only when the precedent task ends,
the subsequent task can be enabled. On the other hand, a
inverse precedence occurs when the finish of a posterior task
enables again the start of an initial task, in a normal
functional flow of the FMS. For example, when the AGV’s
finish the task A2, they can transport again raw materials
to the machine PM1, it becomes in an “inverse” logical
precedence conditions (dotted line) between A2 – A1. The
second section of the Fig. 3 shows the tasks A3 repeated
K(Spq, ISij) times to gather the subparts to make the assembly
Spq and move the products to the storage FPpq through a task
As. Note an inverse precedence of A4 – A3 which ensures that
the AGV’s reload the assembly station only when the previous
product has been stored in FPpq. Next section describes the equipment models and the relationships given
in Fig. 3 translated to PN.

Fig. 3. Logical precedence conditions of a FMS

4. PN MODELS OF THE FMS

According to (Cassandras (2008)) a PN with finite capacity is
a weighted and bipartite graph given by a 5-tuple PN = (P, T,
F, W, M0), where P = {p1, p2, ..., pm} and
T = {t1, t2, ..., tn} are the disjoint sets of nodes called places
and transitions, respectively. F ⊆ (P × T) ∪ (T × P) is the set
of arcs, connecting places to transitions and vice versa.
W:F → Z+ is the function that assigns the weights to each arc
and M(pj): P → Z+, represents a m-entry vector with the
number of tokens residing inside each pj ∈ P which has a
finite capacity cj of tokens, i.e. M(pj) ≤ cj. Let M0 as the
initial marking.

A transition ti ∈ T is said to be enabled in a PN with finite
capacity iff Mk(pi) ≥ w(pi, ti), ∀pj|w(pj, ti) ∈ F, with
j=1,...,m and i=1,...,n, with the restriction w(ti, pj) +
Mk(pj) ≤ cj, ∀pj ∈ P. If ti is firing in the k-th firing in some
firing sequence, then the next marking state is defined by
Mk+1(pi) = Mk(pi) − w(pi, ti) + w(ti, pj). The set of all
possible markings reachable from M0 construct the reachability tree.

4.1 Tasks of AGV’s, Machines and Assembly stations

The tasks of AGV’s, machines and assembly stations are
given in Figure 4. The prefixes “s” and “f” denotes the start
and final of tasks, respectively. In the tasks A1(X,Y,w)
i = 1, ..., A, w is the quantity of robots needed to perform the
task, according to the table 4a. The number of AGV’s is the
tokens of the place labelled as AGV. When a task finished,
the w tokens are returned to the AGV place (available robots
again). In the most simple criteria, the selection of the AGV’s
for a task depends on the smallest distance of the robots with
respect to the point where the robots pick up the piece.
Similar to AGV’s, the machining and assembly tasks are
represented in Figures 4b and 4c, respectively. Note that the
places PM1 and ASp contain one token only, forcing that
every machine or assembly station can make one process
tasks at the same time.

4.2 Storages

The storages in the FMS are shown in Fig. 5 and classified in
three types: a) Manual load-Automatic unload (RMij), b)
Automatic load-Automatic unload (ISij) and c) Automatic
load-Manual unload (FPpq). The load of the storage RMij
requires a manual input transition INij that put tokens in the
RMij place, which are extracted by the start of a task Ta ∈ A1.
The storage ISij is loaded by the end of a task Ta ∈ A2 and
unloaded by the starts of tasks Ta1 ... Ta3. Finally, the end
of a task Ta ∈ A4 load to FPpq and it is unloaded by a manual
transition OUTpq that take tokens of the place FPpq.

4.3 Logical precedence conditions between tasks

Fig. 6a shows a simple PN translation of a D-direct between
two tasks where the boxes are tasks (left-side = start and
right-side=end). Note that the initial marking is equal to zero
and the final of the task Ta enables the start of Tb. Figure 6b
shows the case of an inverse precedence, where the
continuous line has been changed to a dotted line. Now, the
occurrences of the end of the subsequent Tb enable the start
of Ta. Note that the tokens in the place of the D-inverse is
different to zero, because it is necessary to enable the begin
of the task Ta in a first-time of the functional flow.

The logical precedence conditions (direct and inverse) are
extended to the conjunction of multiple tasks that enables the
start of multiple posterior tasks in Figure 6c and 6d,
respectively. It appears, for example in the case of the gathering of transportation of subparts that enables the
starting of an assembly task. Note that K(Ta1, ISij) is a weight
to each output arc denoting the number of subparts in
ISij needed to start the task Spq. In the inverse case, each
place contains initially K(Ta1, ISij) tokens representing the
amount of necessary subparts for ISij for each assembly
Spq, the input arcs to the places D also have the weight K(Ta1, ISij).

![Fig. 4. Models of AGV, Machines and Assembly stations](image-url)
Fig. 7. Diagram of precedence restrictions of the example

4.4 Example of PN modelling of FMS

Note that the substitution of the blocks of Fig. 3 by the simple PN models described before construct a complete PN of the FMS with the possible concurrence of tasks. For example, let be \( r = 4 \) AGV’s, 1 PM \((PM_1)\) with 2 machine programs and 2 AS \((AS_1, AS_2)\), with one assembly program each one, with \(U(S_{11}) = \{IS_{11}, IS_{12}\}\), \(U(S_{21}) = \{IS_{11}, IS_{12}\}\) in the quantities of subparts given by \(K(S_{11}, IS_{11}) = 3\), \(K(S_{11}, IS_{12}) = 1\), \(K(S_{21}, IS_{11}) = 1\), \(K(S_{21}, IS_{12}) = 2\). The precedence diagram and its translation to PN is given in the figures 7 and 8, respectively.

Fig 8. Complete PN model of the example

5. COORDINATION OF THE AGV’S

In the previous section, the task of transportation alludes to the quantity of AGV’s possible points to load or unload work pieces. In this subsection, the low level control laws for the AGV’s are described briefly. More complete information and formal proofs are found in our previous work in (Hernandez-Martinez (2011)).

Let \( N = \{R_1, \ldots, R_n\} \) be a subset of omnidirectional robots moving in the plane. Note that \( n \leq r \), where \( r \) is the total of AGV’s in the FMS. The kinematic model of each agent or robot \( R_i \), as shown in Figure 10, is described by

\[
\dot{z}_i = f_i \in \mathbb{R}^2, \quad i = 1, \ldots, n
\]

(1)

The dynamics of different non-holonomic mobile robots, like unicycle-type robots or car-like robots, can be reduced to the equation (1) using and appropriated control output and applying an input-output linearization as (Hernandez-Martinez (2011)). The main objective of the motion coordination control laws is to design the functions \( f_i \) to achieve 1) formation 2) convergence to a point and 3) marching behavior, avoiding the inter-robot collisions.

5.1 Leader-based Formation control with collision avoidance

Let \( N_i \subseteq \{z_1, \ldots, z_n\} \), \( N_i \neq \emptyset \), \( i = 1, \ldots, n \) denote the subset of positions of the robots which are detectable for \( R_i \), select arbitrarily \( R_n \) as the leader robot, then define

\[
z^*_i = \frac{1}{n_i} \sum_{j \in N_i} (z + c_{ij}), \quad i = 1, \ldots, n - 1
\]

(2)

\[
z^*_n = \frac{1}{n_n + 1} \left( \sum_{j \in N_n} (z_j + c_{jn}) + \tau \right)
\]

as the combination of the desired positions of \( \alpha_i \) with respect to the positions of all elements of \( N_i \), where \( n_i \) is the cardinality of \( N_i \) and the vectors \( c_{ij} = [h_{ij}, v_{ij}]^T \) are the desired position of \( \alpha_j \) respect to \( \alpha_i \) in a particular formation. In the case of the leader, \( z^*_n \) includes \( \tau \in \mathbb{R}^2 \) that denotes a
reference point (position of some storages or workstations) known by the n-th robot only. According to Sanchez (2010), a formation control law with inter-robot collision avoidance is given by

\[ f_i = -\frac{1}{2}k \left( \frac{\partial v_i}{\partial z_i} \right) - \frac{1}{2} \eta \left( \frac{\partial v_i}{\partial z_i} \right) \]  

where \( k, \eta > 0, \) \( \gamma_i = \|z_i - z_j\|^2 \) is and attractive potential function and \( \gamma_i = \sum_{t \in M_i} \left( \frac{1}{\|z_i - z_j\|^2} - \frac{1}{d^2} \right) i = 1, ..., n \) with \( M_i = \{ z_j \mid \|z_i - z_j\| \leq d \}, i = 1, ..., n \), is a repulsive potential function to avoid inter-robot collisions, where \( d \) is the diameter of a circle centered in the coordinate \( z_i \) that circumscribes each robot. The control law (3) describes an artificial vector field where the robots are attracted to their desired position and eventually avoid the inter-robot collisions.

5.2 Convergence to a point in the plane

When a robot \( R_i \) requires only the convergence to a static point \( \beta_i \in \mathbb{R}^2 \), (for example, its home base position), a modification of the control law (3) is reduced to

\[ f_i = -\frac{1}{2}k \left( \frac{\partial p_i}{\partial z_i} \right) - \frac{1}{2} \eta \left( \frac{\partial v_i}{\partial z_i} \right) \]  

where \( p_i = \|z_i - \beta_i\|^2 \).

5.3 Marching control

(Hernandez-Martinez (2010)) proposes the next marching control strategy where the leader follows a desired marching path \( m(t) \), and the follower robots maintain a rigid formation respect to the leader.

\[ f_i = -\frac{1}{2}k \left( \frac{\partial v_i}{\partial z_i} \right) - \frac{1}{2} \eta \left( \frac{\partial v_i}{\partial z_i} \right) + m(t), i = 1, ..., n \]  

\[ f_n = m(t) - k_m(z_n - m(t)) \]

where \( k_m > 0 \) is a gain parameter. Note that the derivative of the marching path must be communicated to all the followers to ensure that the formation errors converge to zero (Hernandez-Martinez (2011)).

5.4 Example of a transportation tasks

To illustrate the use of the control laws (3)-(5), suppose that the robots must realize a transportation task \( A_1(RM_{12}, PM_1, 3) \), i.e. three robots work together to move a piece from the raw material storage \( RM_{12} \) placed in the workspace coordinate \([-60,30]\) to the process machine \( PM_1 \) located in the coordinate \([0,70]\). Assume that \( N_1 = \{z_1\}, N_2 = \{z_2\}, N_3 = \{z_3\} \), i.e. the robots are communicated in a cyclic pursuit configuration (Hernández-Martínez (2011)), and they require to achieve a line-shape formation pattern given by \( c_{11} = [0,5,5], c_{21} = [0,5,5], c_{13} = [0,-11] \). Fig. 9 shows a numerical simulation of the three robots doing the task \( A_1(RM_{12}, PM_1, 3) \) with \( k = 0.2, k_m = 100, \eta = 1 \times 10^7, d = 5 \) and \( \varepsilon = 1 \). The initial positions (home base) of the four robots are \( \beta_1 = (-10.5,0), \beta_2 = (-3.5,0), \beta_3 = (3.5,0) \) and \( \beta_4 = (10.5,0) \).

For \( 0 \leq t < 250 \), three robots are selected (by minimal distance) from home to the position of \( RM_{12} \) using the formation control law with collision avoidance (3). For \( 250 \leq t \leq 500 \), the formed robots uses the marching control law (5), where the marching path is given by the parametric equations for straight line that begins in the position of \( RM_{12} \) and ends in the position of \( PM_1 \). Finally, for \( 500 < t \leq 750 \), the robots has finished the transportation of the work piece and they use the control law (4) breaking formation and returning to their home positions, avoiding again the inter-robot collisions. Fig. 9 shows the posture and orientation of the robots in some time instants.

6. CONCLUSIONS

This work presents a methodology for the discrete-event modelling of FMS based on the task decomposition proposed by the industrial standard ISA-95 and its translation to generic PN models. Thus, the coordination of the AGV’s in the approach is decomposed in two levels. In the high-level, the PN model enables the transportation tasks considering the availability of the robots and the restrictions of the process. When it occurs, the AGV’s are selected according to the shortest distance to the initial point of the task. On the other hand, every task in the low-level control implements the continuous control laws for the robots to achieve the desired motion behaviour. Therefore, the task assignment and the convergence to the formation, tracking and collision avoidance are solved in the hybrid architecture at same time. The approach is a systematic method that closes the concepts of Discrete-event systems in an industrial manufacturing context and clarifies the application of continuous motion control laws of AGV’s in real FMS. The added value is the scalability of the methodology, which is ready to be easily programmed in industrial supervisory software. In further research, additional behaviours, as fault diagnostics, stochastic time of tasks, delays, etc., will be incorporated to complete the Petri model.
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