AGV Navigation in Flexible Manufacturing Systems using Formation Control

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Abstract: A formation control strategy is proposed for the navigation of non-holonomic (2,0) automated guided vehicles (AGVs) in flexible manufacturing systems (FMS). Each AGV is equipped with a formation control, which is based on artificial vector fields to guarantee convergence to each of the location goals. Repulsive vector fields are employed to define the navigation layout and to avoid collisions with other AGVs. The AGV navigates by reaching each of the location goals without the need of route planning. The formation control was implemented as part of an architecture and successfully tested in a virtual reality FMS with 4 AGVs.

Keywords: AGV navigation, formation control.

1. INTRODUCTION

Flexible manufacturing systems (FMS) are commonly employed in different industries as suitable alternatives to respond to the highly demanding markets (e.g. Desai et al. (2001); Cao et al. (1997)). The transportation of raw materials and finished products can be carried out by different devices such as manipulator robots, conveyor belts or automated guided vehicles (AGV). Employing AGVs for these tasks implies many other operational challenges such as collision-avoidance, on-line rescheduling, battery recharging, low-level manufacturing conflict resolution, etc. Therefore, the operational complexity of AGV-navigation in FMS imposes an interdisciplinary approach for constructing hierarchical control strategies. This paper proposes a navigation strategy of AGVs operating on a delimitated area of the factory-floor using formation control.

From a control-theoretical point of view, the most common approach to the navigation control of the AGVs is to design a control law enabling each AGV to follow a pre-specified trajectory within the FMS environment (e.g. Arai et al. (2002); Balch and Arkin (1998)). However, the resulting controllers are difficult to implement and maintain because any change in the product manufacturing rules of the FMS may lead to re-computing the pre-specified trajectories. Collision-avoiding is also difficult to achieve resulting into unacceptable hazards. Decentralized control strategies proposed for multi-agent robot systems (MARS) have shown to provide an interesting alternative for the coordination of groups of mobile robots using incomplete information and accomplishing a common task (e.g. Chen, and Wang (2005); Leonard and Fiorelli (2001)). One classical problem of the theory of MARS is formation control, in which a set of mobile robots—each one subject to partial knowledge of the system—is desired to reach a particular pattern, avoiding possible collisions.

The paper considers non-holonomic wheeled mobile robots of the type (2,0), as defined in Gholipour and Yazdapanah (2003). The production of a particular good is assigned to an AGV as a sequence of locations goals. Each location goal corresponds to a formation defined with respect to a fixed virtual leader as proposed by Zhang and Hu (2007). This allows, simultaneously, to reach absolute desired positions (instead of relative ones) and to specify a safety area which the AGVs must not trespass during the FMS operation. Collisions are avoided by defining suitable repulsive vector fields. The dynamic model of the AGV considered together with the formation control are discussed in section 2. In order to test the performance of the proposed control, a virtual-reality FMS was built with four AGVs as shown in section 3. Each AGV is equipped with a modular-hierarchical control architecture built "ad-hoc" to test the ability of the controller to reach desired formations whilst navigating on the FMS floor without colliding with other AGVs. Section 4 shows the results of simulations tests under three situations: convergence in finite time of the AGV to a sequence of desired location goals, collision-avoiding for achieving fixed formations with other AGVs and collision-avoiding while navigating freely to achieve a desired position on the FMS-floor. Including the formation control law as part of an architecture seems to be promissory. The simplicity of the mathematical expressions makes it easy to implement and to maintain. Finally, section 5 discusses
2. AGV KINEMATIC MODEL AND FORMATION CONTROL

Attractive potential functions are employed to declare location goals. The negative gradient of these functions are used as control inputs for the AGVs. While this simple strategy allows to ensure convergence to the desired locations, possible collisions can not be ruled out. In order to discard the event of a collision, the control law is modified using an artificial unstable focus-type vector field centered at the position of every other AGV. The same type of unstable behavior is forced with respect to a virtual leader (Zhang and Hu (2007)). The virtual leader does not exist physically. However, it allows to ensure two key features of the closed-loop system: Firstly, absolute positions are reached, as the position of the virtual leader is referred to an inertial coordinate frame. Secondly, by scaling appropriately a repulsive vector field centered at the virtual leader location, a safety area can be ensured.

Denote by \( N = \{R_1, ..., R_5\} \), the set of the non-holonomic (2,0) AGVs moving on the factory-floor. AGV \( R_5 \) is considered as the virtual leader and the rest are follower AGVs. The kinematic model of each \( R_i \), as shown in Fig. 1, is described by

\[
\begin{bmatrix}
    \dot{x}_i \\
    \dot{y}_i \\
    \dot{\theta}_i
\end{bmatrix} = R_i(\theta_i) \begin{bmatrix}
    v_i \\
    w_i
\end{bmatrix},
\]

where \( v_i \) is the linear velocity of the midpoint of the wheels axis and \( w_i \) is its angular velocity. In the rest of the paper, the formation strategy is related to the coordinates \( \alpha_i = (p_i, q_i) \) shown in Fig. 1 which are given by

\[
\alpha_i = \begin{bmatrix}
    p_i \\
    q_i
\end{bmatrix} = \begin{bmatrix}
    x_i + l \cos(\theta_i) \\
    y_i + l \sin(\theta_i)
\end{bmatrix}, i = 1, ..., n
\]

The goal of each AGV \( R_i, i = 1, ..., 4 \) is to be steered to a relative position \( c_{5i} \) with respect to the virtual leader avoiding collisions, i.e. it is necessary to design a control law \( u_i(t) = g_i(N_i(t)) \) for every robot \( R_i \), such that \( \lim_{t \to \infty}(\alpha_i - \alpha^*_i) = 0, i = 1, ..., n \) and \( \|\alpha_i(t) - \alpha_j(t)\| > d, \forall t \geq 0, i \neq j \) where \( d \) is the diameter of a circle centered in the coordinate \( \alpha_i \) that circumscribes each AGV.

![Fig. 1. Kinematic model of unicycles](image_url)

![Fig. 2. Formation Control Strategy using a virtual leader](image_url)
vector fields, we define a control law given by

\[
\gamma_i = \|\alpha_i - \alpha_5\|^2, \quad i = 1, ..., 4
\]

\[
\gamma_5 = \|\alpha_5 - m\|^2
\]

The functions \(\gamma_i\) are positive definite and reach their global minimum \((\gamma_i = 0)\) when \(\alpha_i - \alpha_5 = c_{5i}, \quad i = 1, ..., 4\) and \(\alpha_5 = m\). A control law based on the negative gradient of functions \(\gamma_i\) steering every agent to the minimum of these potential function but collisions can occur. For avoiding this, we propose repulsive vector fields (between pair of agents) given by

\[
\beta_{ij} = \delta_{ij} V_{ij}\left[\frac{(p_i - p_j) - (q_i - q_j)}{(p_i - p_j) + (q_i - q_j)}, \quad j \neq i\right]
\]

where

\[
\delta_{ij} = \begin{cases} 
1, & \text{if } \|\alpha_i - \alpha_j\|^2 \leq d^2 \\
0, & \text{if } \|\alpha_i - \alpha_j\|^2 > d^2
\end{cases}
\]

\[
V_{ij} = \left(\frac{1}{\|\alpha_i - \alpha_j\|^2} - \frac{1}{d^2}\right)^2
\]

and for the safety area an square repulsive area given by

\[
g = (p_i - p_5)^4 + (q_i - q_5)^4
\]

\[
V_{55} = \left(\frac{1}{g} - \frac{1}{\frac{d}{5}}\right)^2
\]

The repulsive vector field is a clockwise unstable focus centered at the position of the another AGV. This vector field is scaled by a function \(V\). This function tends monotonously to infinity when the distance between agents tends to zero and \(V = 0\) in the limit of the minimum allowed distance. Thus, the repulsive forces appear only in a danger of collision. For \(V_{55}\), the repulsive field takes an almost-square shape of side length \(l\) defining the non-trespassing zone in the FSM layout. Using the previous vector fields, we define a control law given by

\[
\begin{bmatrix} v_i \\ w_i \end{bmatrix} = A^{-1}(\theta_i) \left[-\frac{1}{2} k \frac{\partial \gamma_i}{\partial \alpha_i} + \eta \sum_{j \neq i} \beta_{ji}\right], \quad i = 1, ..., 3
\]

where \(k, \eta \in \mathbb{R}\) and \(k, \eta > 0\). The dynamics of the coordinates \(\alpha_i\) for the closed-loop system (3)-(12) is given by

\[
\dot{\alpha}_i = -\frac{1}{2} k \frac{\partial \gamma_i}{\partial \alpha_i} + \eta \sum_{j \neq i} \beta_{ij}, \quad i = 1, ..., 5
\]

The control law (12) steers the coordinates \(\alpha_i\) to a desired position. However, the angles \(\theta_i\) remain uncontrolled. These angles do not converge to any specific value. Thus, the control law is to be considered as a formation control without orientation.

3. THE VIRTUAL FMS

A diagram of the FMS considered in this paper is depicted in Fig. 3. Four AGVs are initially located in the parking-battery-recharging area. The two large boxes represent the feedstock and the finished goods warehouses.

![Diagram of the FMS considered in this paper](image)

Fig. 3. The FMS Virtual Environment

The small boxes represent the working stations, where the AGVs deliver and, after a while, pick up a particular material to follow up the manufacturing process. The behavior specifications of the AGVs are as follows:

1. Each AGV must pick up first feedstock from the feedstock-warehouse.
2. Each AGV must carry the material through a specified sequence of working stations. This sequence is given by a production planner not considered in this paper.
3. Each AGV must deliver the processed product to the finished-product-warehouse.
4. Two or more AGVs must not occupy simultaneously the same position.
5. The non-trespassing zone— is delimited by a square area identified as a "Safety area" in Fig. 3—which the AGVs must not invade.

The formation control is implemented as part of a hierarchical control architecture operating each AGV of the FMS (Molina (2009)) as shown in Fig. 4.

The strategic and tactical level tasks are carried out separately from the operation of the AGV whilst the operational aspects are resolved on-line by navigation control module of each AGV. For the sake of testing the formation control, a simple scheduling strategy was established in which each product to be manufactured is assigned to an AGV. An upper coordination module at the tactical level deals with construction of the part production rules (i.e. production recipes) that are assigned to the AGV (Sanchez et al. (2009)). Production rules are locally translated by the recipe interpreter block of the navigation module into a sequence of location goals that must be executed by the physical device layer (not
4. SIMULATION RESULTS

The formation control module was tested in the virtual FMS described previously for the following cases: i) navigation of one AGV and convergence on finite time; ii) collision-avoiding of 2 AGVs while navigating; iii) navigation of multiple AGV to achieve a fixed formation. Location subgoals were defined outside each warehouse and workstation in order to resolve situations of two or more AGVs requesting access to these resources when is being used by another AGV. Each subgoal represents a queuing position that an AGV can occupy in a fixed formation. Fig. 5 shows the queuing position for each FSM resource.

For the first case, a production recipe dictates collecting first feedstock and then visiting in sequence each of the four workstations, delivery of the finished product to the warehouse and return to the parking area. The navigation trajectories deployed on a x-y axis are depicted in Fig. 6. Convergence times on each axis are shown in Fig. 7. Note that the AGV speed diminishes when approximating the inflexion points of the upper line.

Collision-avoiding maneuvering of two AGVs can be observed in trajectories shown in Figs. 8 and 9. A collision situation is created by assigning to AGV1 location sequence \((p_1, p_2, p_3, p_4, p_5, p_6)\) and to AGV2 location sequence \((p_6, p_5, p_4, p_3)\). Collision is averted near working station 4 by the action of unstable repulsive fields of both AGVs.
proved to be a useful tool for rapid prototyping and testing of the proposed ideas in which an agent-based approach will be incorporated.

REFERENCES