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 FSM 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 delimited 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 Yazdanpanah (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 FSM 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 FSM-floor. Including the formation control law as part of the AGV-control hierarchy seems to be promissory. The simplicity of the mathematical expressions makes it easy to implement and to maintain. Finally, section 5 discusses

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some limitations of the current approach and future work heading towards the design of a complete architecture for controlling AGV operations in FMS.

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 nos 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

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\theta}_i \end{bmatrix} = R_i(\theta_i) \begin{bmatrix} v_i \\ w_i \end{bmatrix}, R_i(\theta_i) = \begin{bmatrix} \cos\theta_i & 0 \\ \sin\theta_i & 0 \\ 0 & 1 \end{bmatrix}, \quad i = 1, ..., n \tag{1}$$

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

$$\alpha_i = \begin{bmatrix} p_i \\ q_i \end{bmatrix} = \begin{bmatrix} x_i + \ell\cos(\theta_i) \\ y_i + \ell\sin(\theta_i) \end{bmatrix}, i = 1, ..., n \tag{2}$$

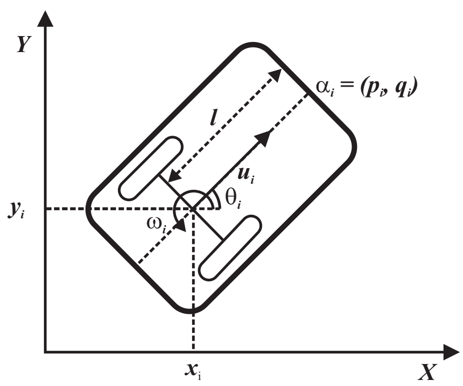

Fig. 1. Kinematic model of unicycles

The point α_i can be the center of mass of the AGV or the place where a sensor or actuator is located. The idea of controlling coordinates α_i instead of the center of the wheels axis is frequently found in the mobile robot literature in order to avoid singularities in the control law (e.g. Desai et al. (2001)). The dynamics of (2) are given by

$$\dot{\alpha}_i = A_i(\theta_i) \begin{bmatrix} v_i \\ w_i \end{bmatrix}, A_i(\theta_i) = \begin{bmatrix} \cos\theta_i & -\ell\sin\theta_i \\ \sin\theta_i & \ell\cos\theta_i \end{bmatrix}, \quad i = 1, ..., n \tag{3}$$

The so-called decoupling matrix $A(\theta_i)$ of each AGV is non-singular. Then, it is possible to design a control strategy for positioning α_i at a desired location using the control law

$$\begin{bmatrix} v_i \\ w_i \end{bmatrix} = A^{-1}(\theta_i)\dot{\alpha}_{id}, i = 1, ..., n \tag{4}$$

where $\dot{\alpha}_{id}$ is the desired dynamics of coordinates α_i.

To design a formation strategy, we define N_i the subset of positions of the AGV which are detectable for R_i. In this paper, the subsets N_i are defined by

$$N_i = \{z_5\}, \quad i = 1, ..., 4 \tag{5}$$
$$N_5 = \emptyset$$

Let $c_{ji} = [h_{ji}, v_{ji}]^T$ denote a vector which represents the desired position of R_i with respect to R_j in a particular formation. Thus, we define $\alpha_i^* = f(N_i)$, $i = 1, ..., n$ as the desired relative position of every R_i in the formation given by

$$\alpha_i^* = \alpha_5 + c_{5i}, \quad i = 1, ..., 4 \tag{6}$$
$$\alpha_5^* = m \tag{7}$$

where $m \in \Re^2$ is an specific position in the FMS of the *virtual leader* AGV. The positions α_i^*, as shown below, can be the positions of workstations in the FMS. The formation strategy using R_5 as virtual leader is shown in Fig. 2. This formation can be considered as a star formation centered in the virtual leader.

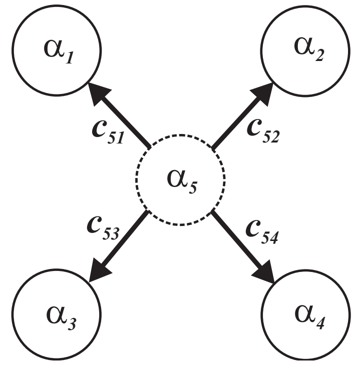

Fig. 2. Formation Control Strategy using a virtual leader

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 α_i that circumscribes each AGV.

In order to guarantee the convergence to the desired formation, local potential functions are defined by

$$\gamma_i = \|\alpha_i - \alpha_5\|^2, i = 1, ..., 4 \qquad (8)$$
$$\gamma_5 = \|\alpha_5 - m\|^2$$

The functions γ_i are positive definite and reach their global minimum ($\gamma_i = 0$) when $\alpha_i - \alpha_5 = c_{5i}$, $i = 1, ..., 4$ and $\alpha_5 = m$. A control law based on the negative gradient of functions γ_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

$$\beta_{ij} = \delta_{ij} V_{ij} \begin{bmatrix} (p_i - p_j) - (q_i - q_j) \\ (p_i - p_j) + (q_i - q_j) \end{bmatrix}, j \neq i \qquad (9)$$

where

$$\delta_{ij} = \begin{cases} 1, & \text{if} \quad \|\alpha_i - \alpha_j\|^2 \leq d^2 \\ 0, & \text{if} \quad \|\alpha_i - \alpha_j\|^2 > d^2 \end{cases} \qquad (10)$$
$$V_{ij} = \left(\frac{1}{\|\alpha_i - \alpha_j\|^2} - \frac{1}{d^2} \right)^2$$

and for the safety area an square repulsive area given by

$$(11)$$
$$g = (p_i - p_5)^4 + (q_i - q_5)^4$$
$$V_{i5} = \left(\frac{1}{g} - \frac{1}{l^2} \right)^2$$

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_{i5}, 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

$$\begin{bmatrix} v_i \\ w_i \end{bmatrix} = A^{-1}(\theta_i) \left(-\frac{1}{2} k \frac{\partial \gamma_i}{\partial \alpha_i} + \eta \sum_{j \neq i} \beta_{ij} \right), i = 1, ...5 \qquad (12)$$

where $k, \eta \in \Re$ and $k, \eta > 0$. The dynamics of the coordinates α_i for the closed-loop system (3)-(12) is given by

$$\dot{\alpha}_i = -\frac{1}{2} k \frac{\partial \gamma_i}{\partial \alpha_i} + \eta \sum_{j \neq i} \beta_{ij}, i = 1, ...5 \qquad (13)$$

The control law (12) steers the coordinates α_i to a desired position. However, the angles θ_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.

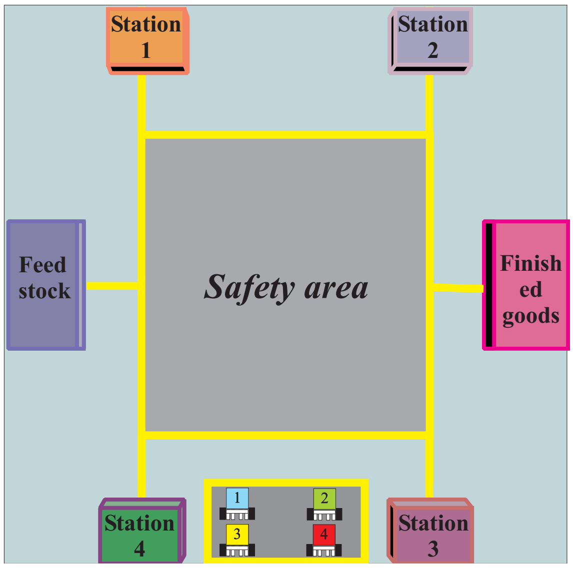

Fig. 3. The FSM Virtual Environment

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 FSM (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

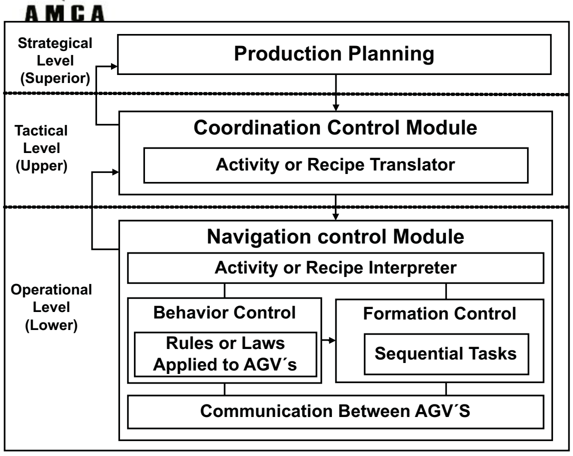

Fig. 4. Hybrid control architecture including the formation control module as part of the navigation control module

shown in the figure). The formation control block is employed within the navigation control module to drive the navigation on the FSM floor. Molina (2009) deals also with on-blocking conditions and other operational issues (such as battery-recharging, failure mode operation, etc.) resolved by the behavior control block.

Magallon (2008) implemented the control architecture in Matlab-Simulink and the FMS previously described was deployed in a virtual environment as shown in Fig. 3. The *virtual leader* was placed at the centre of the layout with quadratic repulsive fields to create the navigation area.

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 queueing position that an AGV can occupy in a fixed formation. Fig. 5 shows the queueing 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 designated location goals represented by 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.

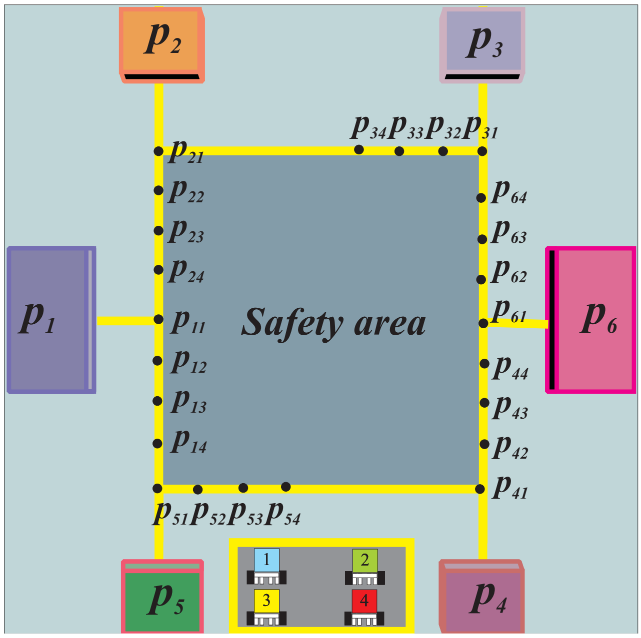

Fig. 5. Implementation of subgoal locations

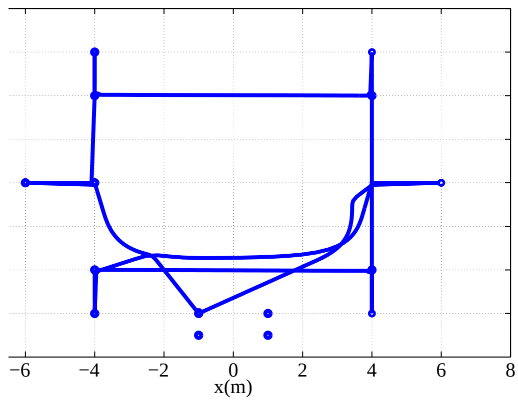

Fig. 6. Navigation of one AGV visiting both warehouses and all working stations in sequence to fulfill a production recipe. Navigation trajectories

Trajectories achieving a desired formation (e.g. queuing at a feedstock-warehouse inlet) without colliding are presented in Fig. 10. Queue positions were assigned arbitrarily to each AGV. In this case, the AGV identification number corresponds to its position in the queue. All AGV initiated from the parking area simultaneously. AGV1 reached its location goal p_{11} with minor disturbances. AGV3 gave way to AGV2 that initiated its trajectory from a further location than AGV3. With a higher priority, AGV2 reached its location goal followed by AGV3.

5. CONCLUSIONS AND FUTURE WORK

The proposed formation control law seems to be a simpler alternative for the navigation of AGVs compared to other approaches based on calculating trajectories. Other important low-level functional issues remain to be explored such as emergency procedures, fault-recovery, collision avoidance of non-identified objects or the dynamic construction of orderly formations to resolve AGV queueing outside the processing facilities. The virtual-reality environment has

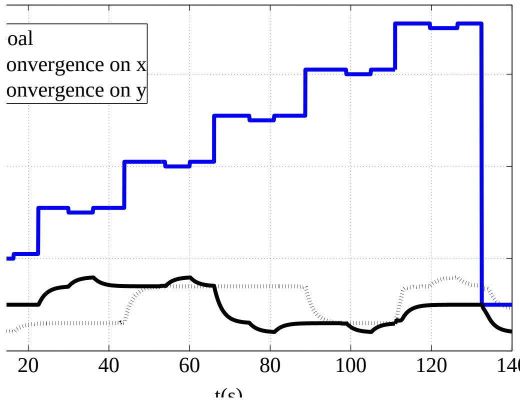

Fig. 7. Navigation of one AGV visiting both warehouses and all working stations in sequence to fulfill a production recipe. Convergence to location goals in finite time

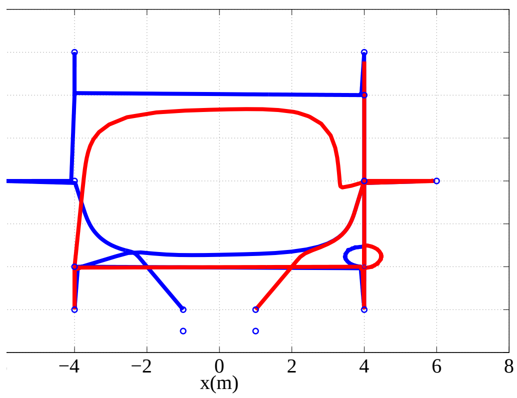

Fig. 8. Collision avoiding during navigation. Trajectory paths

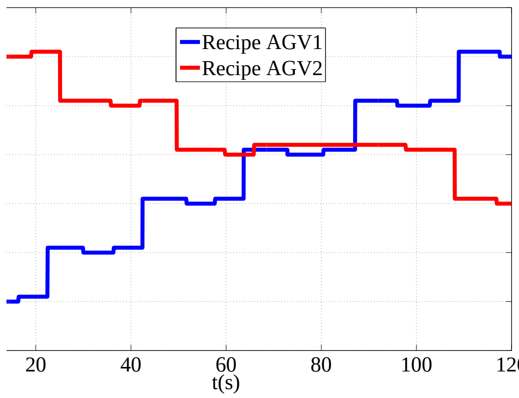

Fig. 9. Collision avoiding during navigation. Convergence to location goals in finite time

proved to be a useful tool for rapid prototyping and testing of the proposed ideas in which an agent-based approach will be incorporated.

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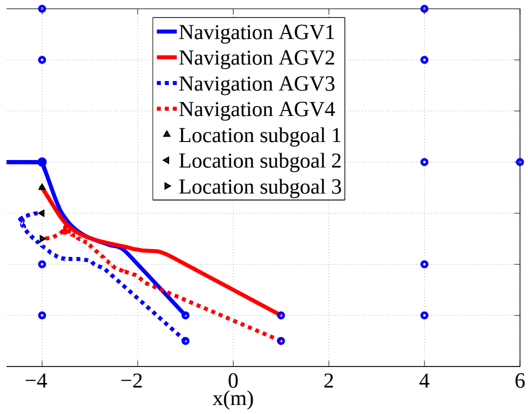

Fig. 10. Navigation of 4 AGVs to achieve a desired fixed formation

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