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TRAJECTORIES AND SIMULATION MODEL OF AGVs WITH TRAILERS

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Abstract. *Automated Guided Vehicle (AGV) systems have been frequently used as material handling equipment in manufacturing systems since the last two decades. Particularly, AGVs with trailers are, and will continue to be, the backbone of the material transport industry. In this paper, a study of the trajectories and simulation model of hypothetical systems, which include a FMS (Flexible Manufacturing Systems) environment, were developed. In addition, a simulation model has been developed to assist in this respect. The simulation model is based on a distributed scheduling algorithm which also implements an advanced planning mechanism in the form of a decentralized Job Shop system control.*

Keywords: *Flexible Manufacturing Systems, Automated Guided Vehicle, Trajectories Planning, Scheduling by Edge Reversal.*

1. INTRODUCTION

The evolution of robotics is influenced by the new demands of customers on the characteristics of products of service (quality, quantity and time). One of these evolutions or developments are the manipulators used by Flexible Manufacturing Systems (FMS), which have obvious advantages on acting in repetitive tasks (assembly, painting, etc.). However, such structures have limited movements within its surroundings, differently from mobile robots, that can accomplish movements along a factory, deviating obstacles, producing flexibility; a tireless search of the industries. With the development of navigation technologies for autonomous vehicles and the increase of the processing capacity of the new computers, application possibilities are enlarged. On the international level, the field of application of mobile robots is not restricted to the industry; it is significantly wider, also reaching the areas of logistics (distribution and storage), oceanographic and underwater exploration, planetary exploration, and military applications. Currently in the industry, and specifically in existing industrial projects of mobile robotics, the main target applications are in manufacturing (factories, cells and flexible manufacturing systems) and in the logistics of supply chain and storage and services. In the last years, there has been a lot of interest in the development of applied technologies in AGVs, from the automation of tasks involving transfer and loading of materials to simple inspection tasks. This involves controlling the movement of the vehicles, from an initial point to an end point, offering great improvement in the reduction of risks, time of transfer and energy consumption. In the manufacturing industry, common types of vehicles are AGVs with trailers (Tow/Tugger) that are developed for the transport, load and unload of materials between different stations to work within the FMS.

AGV systems are considered as one of the most appropriate modes for material handling support of contemporary flexibly automated production environments. In general, such a system consists of a set of cooperating driverless vehicles which transport goods and materials among the different workstations and storage sites of a production facility. Usually, AGVs follow a set of predetermined, physical or virtual guidepaths embedded into the facility layout, and are coordinated by a centralized or distributed computer-based control system. Some of the primary advantages attributed to these environments are increased routing flexibility, space utilization and safety, resulting in a reduced overall operational cost (Reveliotis, 2000). The research on the design and operation of AGV systems with trailers, especially, involve highly interdisciplinary technological areas such as electronics, mechanics, computational and control, synergistically integrated on projects and products or manufacturing processes, created the concept of “Mechatronics” (Lengerke *et al*., 2007).

A flexible manufacturing system, in which the use of automated guided vehicles (AGVs) is typical, is a growing trend in many industrial scenarios. This paper introduces a novel distributed algorithmic approach to the execution control of activities (work centre oriented) and, in an integrated way, transportation (AGV oriented) scheduling. The relationship between *jobs*, modeled as *processes*, and *work centers*, modeled as *resources*, defines an undirected graph *G* representing a target Job-shop system. Analogously, the transportation performed by AGVs, also modeled as processes, and their corresponding physical paths, modeled as resources, can also be seen as a dual Job-shop problem. The new approach is based on the Scheduling by Edge Reversal (SER) graph dynamics which, from an initial acyclic orientation over *G*'s edges, that can be defined via traditional and/or efficient heuristics, let jobs and AGVs to proceed in deadlock- and starvation-free fashion without the need of any central coordination.

2. AGV´S IN FLEXIBLE MANUFACTURING SYSTEMS

FMS planning is significantly different from traditional job-shops where there is human involved. An FMS is designed to manufacture a variety of items or products simultaneously and to provide alternative processing routes for individual products. The flexibility dimension can be characterized in no routing flexibility, flexible alternative machines, flexible alternative operation sequences and full routing flexibility. The planning component of paths on FMS consists of a mission planner, navigator and pilot. Guide-path design is an important problem in AGV system design and is one of the very first problems to be considered. The guide-path depends greatly on the allocation of shop-floor space, layout of storage zones and the arrangement of handling stations (Le-Anh and De Koster, 2006). In most cases, the shop-floor space is fixed and it imposes constraints on the guide-path design problem. The vehicle guide-path is usually represented such that aisle intersections, pick-up and delivery locations can be considered as nodes on a graph connected by a set of arcs. The arcs describe the paths that vehicles can follow when moving from node to node. Directed arcs between two nodes indicate the direction of the vehicle flow. Cost can be assigned to each arc representing the distance between the two end points of a segment or the time required by a vehicle to travel along the arc.

2.1 Potential Field Methods

During the past few years, potential field methods (PFM) for obstacle avoidance have gained increased popularity among researchers in the field of robots and mobile robots. One of the reasons for the popularity of this method is its simplicity and elegance. In this work, maps of cells already constructed and potential fields are used, for the purpose of planning for local paths. One of the goals is to study a navigation system for an AGV that allows using potential fields, to navigate along a collision-free path form an initial point to an end point, consequently, it is made a description of this method and presented the proposals of some authors (Figure 1).

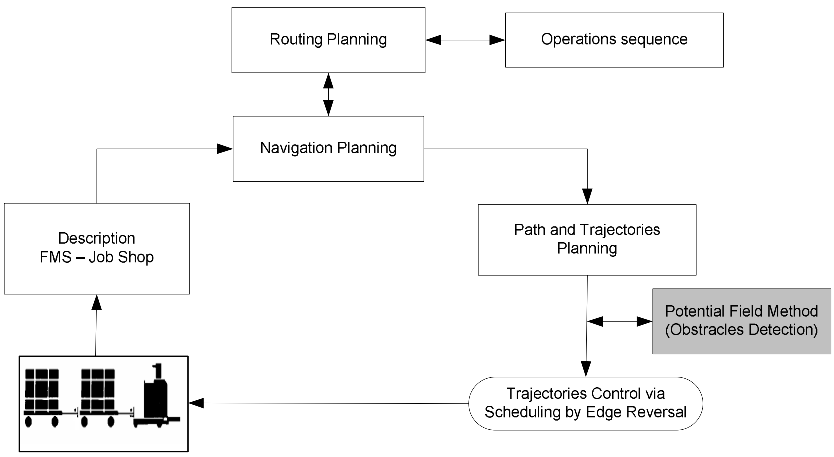

Figure 1. Schema of Potential field Method interaction on AGV with trailer

The PFM was brought to the computer world in 1978 by Khatib and Lemaitre and reused for the same authors, in other work later (Kathib, 1985). Used as a local method (Latombe, 1992) and having been, later, widely used in global strategies and dominantly approached for planning and control of mobile robots (Trajano *et al*., 2007). The underlying idea of the method is to fill the AGVs workspace with a virtual potential field in which the vehicle is attracted to its goal and is repulsed away from the obstacles (Figure 1).

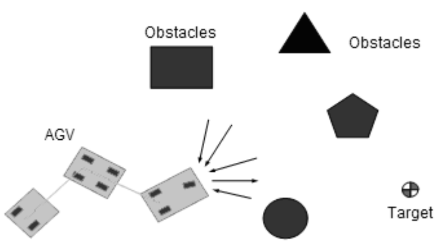

Figure 1. Influence of potential field on AGV with trailers

The intensity of the field does not depend on the velocity of the particles, as the field is radial; it is enough to know the distances among particles to get to define the potential function completely. In this method, is considered x as a position of a point that moves in a forces field. The target provides an attractive force and obstacles, repulsive forces. Although this method has been initially introduced to manipulators, its application to mobile robots is also possible. The PFM is named to the fact that the field (vector) of forces F(x) is derived form the field (scalar) potential $U(x)$, with:

$$F(x) = -\nabla\left[U(x)\right] \tag{1}$$

The AGV control is obtained subjecting it to the virtual potential field determined by:

$$U\left(\vec{x}\right) = U_{atr}\left(\vec{x}\right) + U_{rep}\left(\vec{x}\right) \tag{2}$$

Where $U(\vec{x})$ is the resultant potential, U_{atr} is the attractive potential (Figure 2) generated by target point (x_{obj}), U_{rep} is the repulsive potential (Figure 2) generated by the obstacles and $\vec{x} = (x, y)^T$ is the position vector of AGV. The actuate virtual force $F(x)$ in the AGV is defined by the command vector of the equation (3).

$$\vec{F}\left(\vec{x}\right) = \vec{F}_{atr}\left(\vec{x}\right) + \vec{F}_{rep}\left(\vec{x}\right) \tag{3}$$

Where F_{atr} is an attractive force that guides the control point of the vehicle to the target, and F_{rep} is a force which induces a virtual repulsion the surface of the obstacle produced by $U_{rep}(x)$.

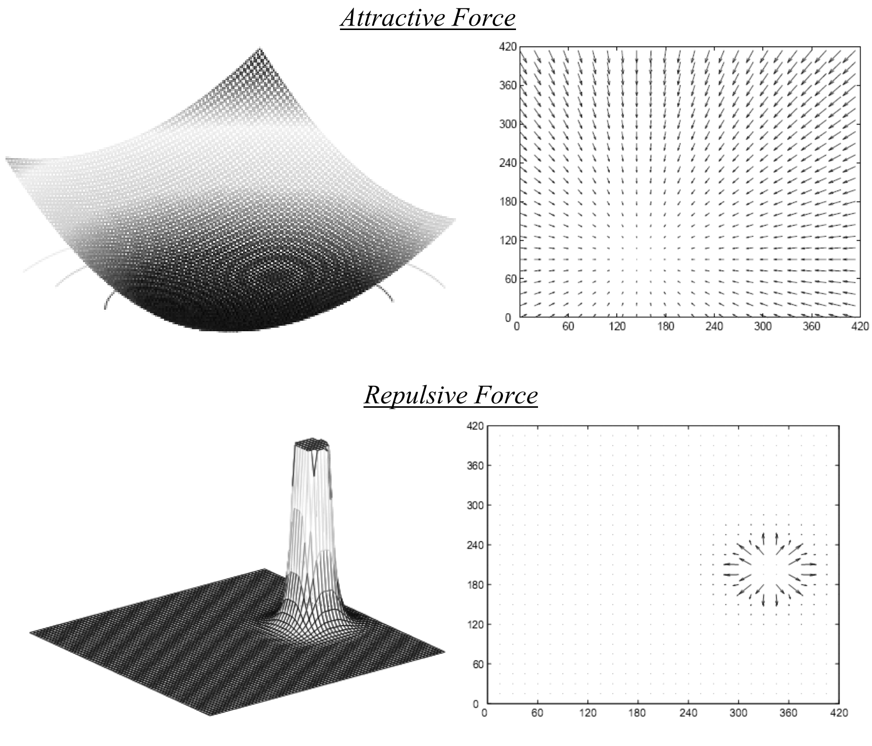

Figure 2. Attractive potential field generated by a target point and repulsive potential field generated by an obstacle and their induced forces (Kathib, 1985).

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The attractive component is performed using a quadratic relationship (parabolic function) not negative, whose first derived is continues and it possesses a single null value in $\vec{x} = \vec{x}_{obj}$ and that depends on the positions of AGV ($\vec{x}$) center, and of the target ($\vec{x}_{obj}$) defined for:

$$U_{atr}\left(\vec{x}\right) = \xi(\vec{x} - \vec{x}_{obj})^2 \big/ 2 \quad (4)$$

The ξ factor is positive scale of attractive potential field. The induced force by attractive potential field is certain from the equation (3) and results in:

$$\begin{aligned} &\vec{F}_{atr}\left(\vec{x}\right) = -\vec{\nabla} U_{atr}\left(\vec{x}\right) = \\ &-\xi\rho_{obj}\left(\vec{x}\right)\vec{\nabla}\rho_{obj}\left(\vec{x}\right) = -\xi\left(\vec{x} - \vec{x}_{obj}\right) \end{aligned} \quad (5)$$

The artificial potential field defined conduces to a stable system. However, to assure the asymptotic stability of the system a dissipative force proportional to the velocity $\dot{x}$ is added. Thus k_{dis} a gain of velocity, the forces that contribute to the movement and AGVs stability are of the form:

$$F^{*}_{atr}\left(x\right) = -\xi\rho_{obj} - k_{dis}\dot{x} \quad (6)$$

Where $\dot{x} = (\dot{x}, \dot{y})^T$ with $\dot{x} = v\cos(\phi)$ and $\dot{y} = v\text{sen}(\phi)$, is v a magnitude of linear velocity and ϕ the navigation direction of the AGV for a reference external. The calculation of the repulsive potential field generated by the obstacles, using a less distance to the obstacles $\rho(\vec{x})$ is given by equation (7), Where ρ_0 a positive constant that represents a distance limit of influenced of the repulsive potential field, η is the positive scale factor and $\rho(\vec{x})$ represent a less distance of indicated point for $\vec{q}$ and obstacles for $\rho(\vec{x}) = min \,||\, \vec{x} - \bar{x} \,||$ with $\bar{x}$ a pertinent point to the obstacles.

$$U_{rep}\left(\vec{x}\right) = \begin{cases} \dfrac{1}{2}\eta\left(\dfrac{1}{\rho\left(\vec{x}\right)} - \dfrac{1}{\rho_0}\right)^2, & se \quad \rho\left(\vec{x}\right) \le \rho_0 \\ 0, & se \quad \rho\left(\vec{x}\right) > \rho_0 \end{cases} \quad (7)$$

The choice ρ_0 depends on the maximum velocity and capacity of deceleration of AGV. The induced force by the repulsive potential field given by equation (7) is obtained considering the symmetric of the gradient of the repulsive potential field, thus applying the gradient:

$$\begin{aligned} &F_{rep}\left(\vec{x}\right) = -\vec{\nabla} U_{rep}\left(\vec{x}\right) \\ &F_{rep}\left(\vec{x}\right) = \begin{cases} \eta\left(\dfrac{1}{\rho\left(\vec{x}\right)} - \dfrac{1}{\rho_0}\right)\dfrac{1}{\rho^2\left(\vec{x}\right)}\vec{\nabla}\rho\left(\vec{x}\right), & se \quad \rho\left(\vec{x}\right) \le \rho_0 \\ 0, & se \quad \rho\left(\vec{x}\right) > \rho_0 \end{cases} \end{aligned} \quad (8)$$

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Where $\vec{\nabla}\rho(\vec{x})$ is the unit vector of the partial derivative of the distance between the AGV center and the obstacle, determining the direction that the force is applied. Considered the existence of n obstacles, the total repulsive force is given by the sum vector of repulsive forces $\vec{F}^{*}_{rep,k}(\vec{x})$, exerted by each of the obstacles and resultant force (Figure 3), given by:

$$\vec{F}^{*}_{rep}\left(\vec{x}\right)=\sum_{k=1}^{n}\vec{F}_{rep,k}\left(\vec{x}\right); \qquad (9)$$
$$F^{*}\left(x\right)=F^{*}_{atr}\left(x\right)+F^{*}_{rep}\left(x\right)$$

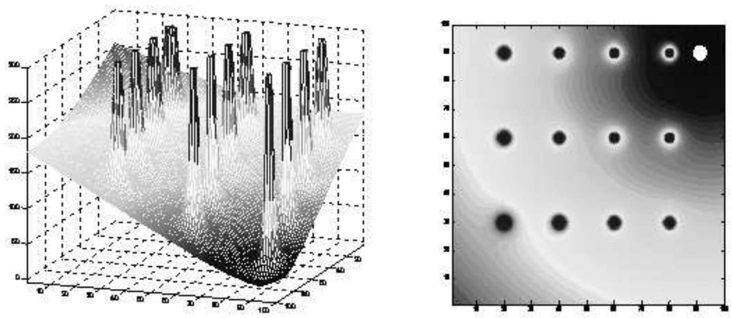

Figure 3. Resultant potential field and induced forces by field

The method of the potential field can be used for off-line global planning, when the environment of AGV is known a priori, as is the case of FMS, or in on-line local planning when the environment is unknown and the presence of obstacles will be detected by sensors of AGV. Under the influence of the virtual potential field, the AGV moves in the symmetrical direction of the gradient, of areas of highest potential for areas of lowest potential, where the gradient is null. However, the virtual potential field is a local method that does not attend to the restrictions nonholonomics of AGV and presents problems for possessing other minimal (local) where the gradient is null. Thus, AGV can be blocked in a local minimal. Solutions to this problem are proposed as the definition of potential to take one of a few local minimal (global method), to include techniques to escape the local minimal, apply random forces, cooperation or use the navigation functions (potential functions without local minimal). A solution was made by Chengqing *et al*., (2000), in a very interesting work that creates the concept of virtual obstacle to eliminate the greatest failure of the various potential functions tried already; the local minimal.

3. DISTRIBUTED CONTROL OF JOB-SHOP SYSTEMS VIA EDGE REVERSAL DYNAMICS

In order to implement a distributed scheduling algorithm for decentralized control of Job-shop systems employed throughout, we decided to use a scheduling scheme which ensures by construction a deadlock- and starvation- free system. The adopted approach is based on the algorithm presented in Gafni and Bertsekas (1981); Barbosa and Gafni (1989) and Barbosa (1996) to assure the mutual-exclusion on distributed asynchronous systems, namely Scheduling by Edge Reversal (SER). In this context, SER is a simple and powerful distributed algorithm, is originally conceived to support Distributed Systems under the heavy load condition, when processors are constantly demanding access to all resources that they use.

With the current interest in Flexible Manufacturing System (FMS), there is a growing need for scalable Job- shop solutions. This article presents a new approach to the distributed representation and control of Job-shop systems. The novel approach consists on mapping a Job-shop system into an undirected graph $G = (N, E)$, where $N = \{1, ..., n\}$ is the set of activities and E is defined as follows: if R_i is the set of resources used by activity i in order to operate, an edge $(i,j) \in E$ exists whenever $R_i \cap R_j \neq \emptyset$, that is, activities i and j share at least one atomic resource. Next, an initial acyclic orientation ω is defined over E (Figure 4).

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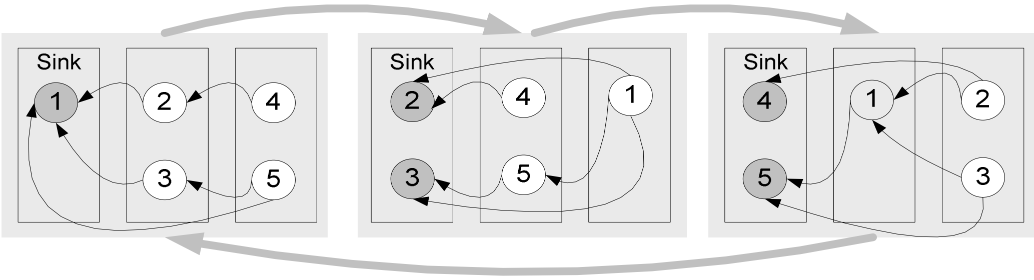


Figure 4. SER operation

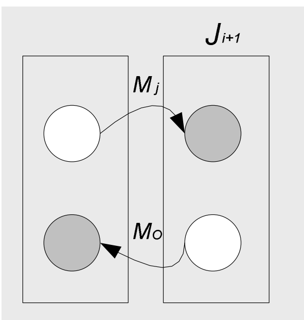
As shown in the following sections, this setup can be produced via well-known heuristic criteria, such as Earliest Due Date (EDD), Shortest Processing Time (SPT) and Priority (P) (Panwalkar and Iskander, 1977; Chan *et al*., 2003). The Scheduling by Edge Reversal (SER) dynamics is then applied over *G*, where activities having all of its edges oriented to themselves have the right to operate upon shared resources and then reverse all associated edges, becoming source nodes in a new acyclic orientation ω'. This ensures that neighboring activities in the system cannot operate simultaneously upon shared resources. In this context, SER acts as a decentralized control mechanism, ensuring mutual exclusion, coordinating all planned activities, no matter if they are concurrent or sequential. Besides, the proposed algorithm takes into consideration transport times, integrating transport and activity schedules, and also providing scalable solutions (Lengerke *et al*., 2008). In addition, it produces optimal minimum make-spam solutions comparable to traditional methods, while creating a deadlock and starvation-free system by construction.

3.1 SER on Job-shop Systems for Trajectories Planning of AGVs

AGV trajectories planning are an important problem in the transportation, distribution and logistic fields. Trajectories are the customary series of stops and collision during a trip (programming of a succession of procedures). Computing the firing sequence of transitions which will yield an optimal result and also avoid deadlocks which might be present is important to real-time control of the modeled system. If an FMS is modeled the trajectories planning of AGVs using SER, an optimal firing sequence is an optimal schedule for the system. Hence a method to find an optimal firing sequence of transitions is beneficial to both SER and FMS scheduling. FMS scheduling can be simulated with the traditional Job-shop system that differentiates the FMS is the involvement of humans. A perpetual deadlock can happen in FMS due to a number of works which are expected to move resources to each other. Therefore, a model that can handle such complex systems is necessary.

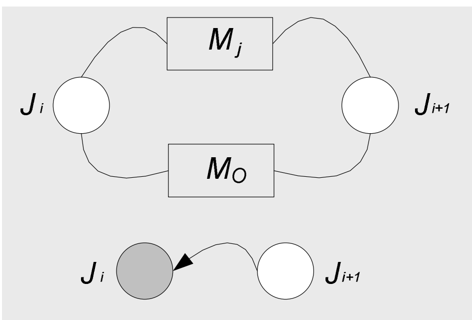
Definition: The problem of Job-shop systems can be developed from a scheduling distributed algorithm to control this category of decentralized systems. This is possible through a mapping of the Job-shop target in a graph $G = (N,E)$ where each element of *N* is one of the planned activities, with pre-established time, to be implemented in exclusive mode on a limited set of resources, which access restrictions defined the edges set *E*. It is also shown as an acyclic orientation is performed directly on *E* the basis of criteria such as traditional heuristic EDD, SPT and P. The dynamics of scheduling by edge reversal can then be applied to *G*, acting as a decentralized control mechanism of coordination of the implementation of various activities planned, whether concurrent or sequential. To implement SER in such systems, is a new concept provided a description of the form of sharing (AND, OR, XOR, negative, among others) to solve the problem of planning routes of the AGVs.

Binary Operators: For OR sharing, operates a single resource *M* (machine) in a process *J* (job). The resource is released (edge reversal) when finish the processing time (p_{ij}) in each of the operations of process (*O*) (Figure 5). For AND sharing is illustrate in Figure 6 and XOR sharing is illustrate in Figure 7.



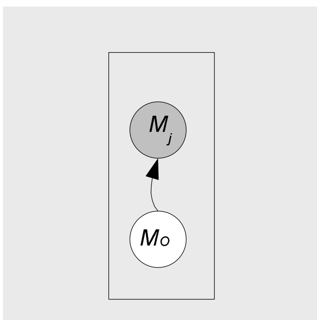
$$J_i = M_j + M_{j+1} + \ldots + M_O$$

Figure 5. OR Sharing



$$J_i = M_j M_{j+1} \ldots M_O$$

Figure 6. AND Sharing



$$J_i = M_j \oplus M_{j+1} \oplus \ldots \oplus M_O$$

Figure 7. XOR Sharing

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The scheduling by edge reversal can be also used in the creation of a mechanism for dynamic planning programming of trajectories, allowing traffic concurrent of AGVs by the various trajectories (P_i) that constitute the different trajectories of AGVs on layout in FMS. Each layout of FMS is presented in a schematic diagram in order to show the trajectories of vehicles. Each AGV needs some trajectories to complete its scheduled displacement; this displacement is related to a displacement time with relation velocity ($t_i = S_i / v_c$). The trajectories number is define as $P = S_1^1, S_1^2, ..., S_1^k, S_2^1, S_2^2, ..., S_2^p, ..., S_r^q$. In the example presented at Figure 8 trajectories for three AGVs with trailers were generated using *Universal Mechanism* (UM) software, where one or more collisions (shared resources) occur. If there is a conflict (collisions), classics rules for dispatching (such as EDD, SPT, and Priority) can be used.

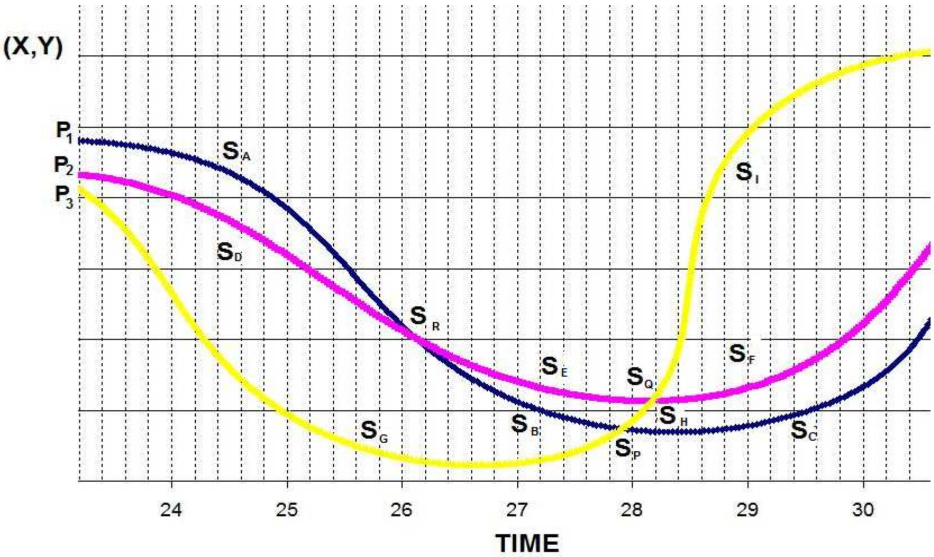

Figure 8. Trajectories generated with UM software for three AGVs with trailers

Table 1. Sample Trajectories Problem

AGV	Frame 1		Frame 2		Frame 3		Frame 4		Frame 5	
	Trajectory time	Trajectory number	Trajectory time	Trajectory number	Trajectory time	Trajectory number	Trajectory time	Trajectory number	Trajectory time	Trajectory number
P_1	27,7	S_A	4,2	S_R	14,3	S_B	1,9	S_P	23,9	S_C
P_2	27,2	S_D	4,2	S_R	16,8	S_E	2,6	S_Q	20,7	S_F
P_3	46,2	S_G	1,9	S_P	0,6	S_H	2,6	S_Q	20,7	S_I

Table 2. Construction of Schedule Job Shop for Example Table 1

Step *t*	A_t	e_k	S^*	***k***
1	O_{11} O_{21} O_{31}	0 0 0	D	O_{21}
2	O_{11} O_{22} O_{31}	0 27,2 0	A	O_{11}
3	O_{12} O_{22} O_{31}	27,7 27,2 0	G	O_{31}
4	O_{12} O_{22} O_{32}	27,7 27,2 46,2	R	O_{22}
5	O_{12} O_{23} O_{32}	31,4 31,4 46,2	R	O_{12}
6	O_{13} O_{23} O_{32}	35,6 31,4 46,2	E	O_{23}
7	O_{13} O_{24} O_{32}	35,6 48,2 46,2	B	O_{13}
8	O_{14} O_{24} O_{32}	49,9 48,2 46,2	P	O_{32}
9	O_{14} O_{24} O_{33}	49,9 48,2 49,9	Q	O_{24}
10	O_{14} O_{25} O_{33}	49,9 50,8 49,9	H	O_{33}
11	O_{14} O_{25} O_{34}	49,9 50,8 50,8	P	O_{14}
12	O_{15} O_{25} O_{34}	51,8 50,8 50,8	Q	O_{34}
13	O_{15} O_{25} O_{35}	51,8 50,8 53,4	F	O_{25}
14	O_{15} --- O_{35}	51,8 71,5 53,4	C	O_{15}
15	--- --- O_{33}	75,7 71,5 53,4	I	O_{35}
16	--- --- ---	**75,7** ----- 74,1	---	---

The three trajectories (P_1, P_2, P_3) are represented as an expression given by the Equation (10) of the XOR sharing and the dynamics of edge reversal for the system are summarized in Figure 9 and Figure 10.

$$
\begin{aligned}
P_1 &= S_A \oplus S_R \oplus S_B \oplus S_P \oplus S_C \\
P_2 &= S_D \oplus S_R \oplus S_E \oplus S_Q \oplus S_F \\
P_3 &= S_G \oplus S_P \oplus S_H \oplus S_Q \oplus S_I
\end{aligned}
\tag{10}
$$

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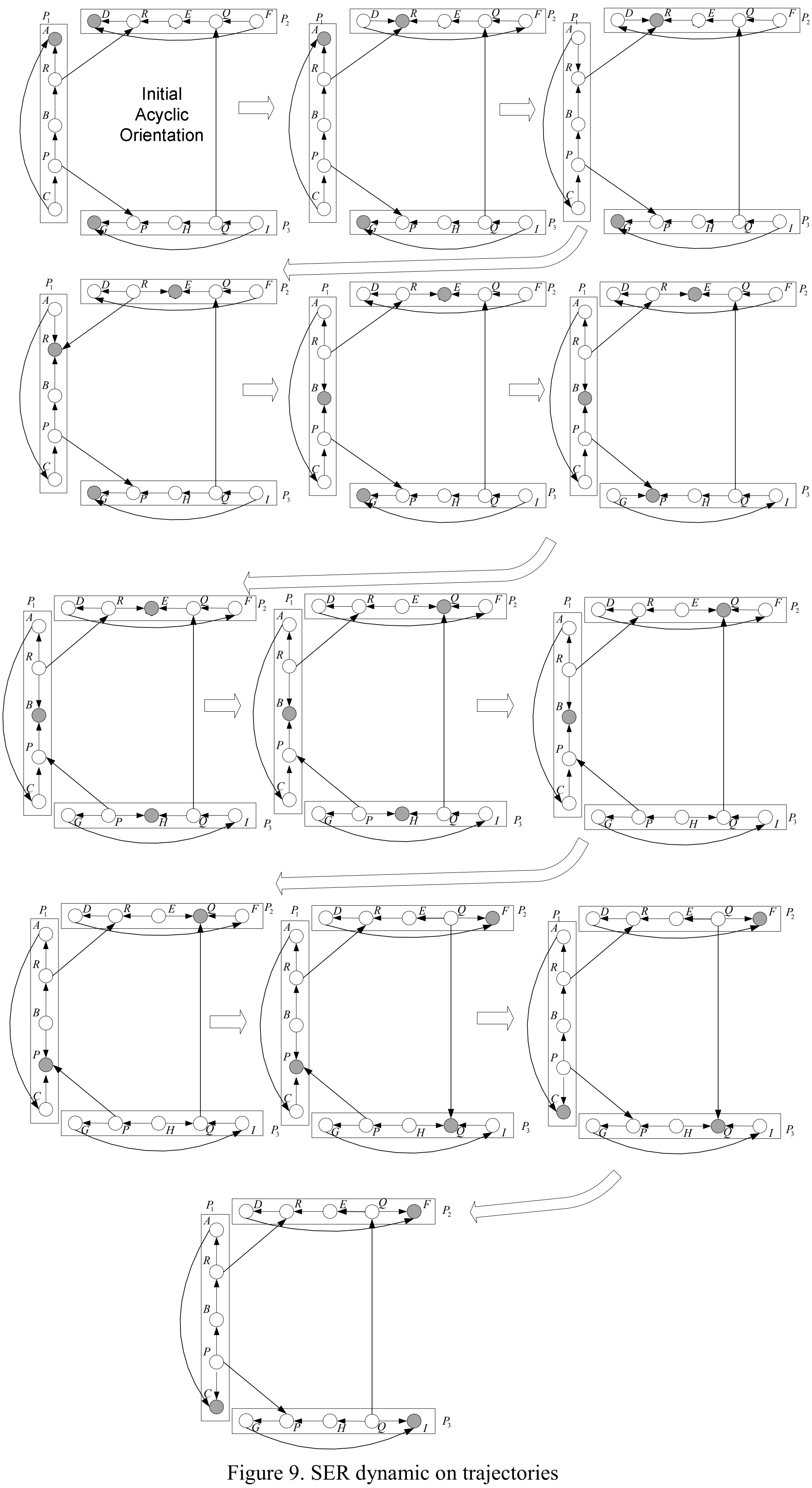

Figure 9. SER dynamic on trajectories

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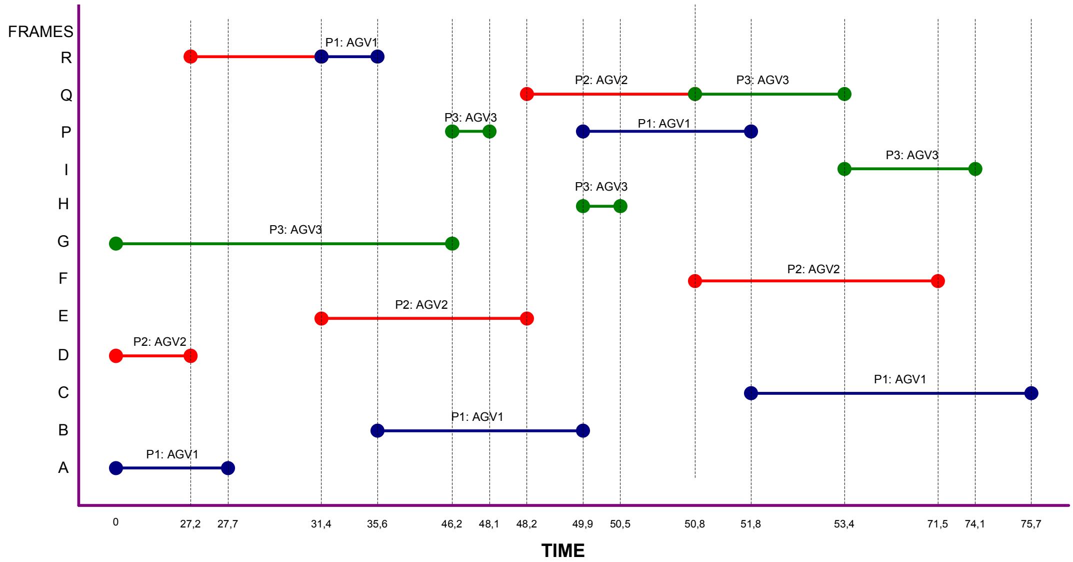

Figure 10. The generated schedule for trajectories

4. AGV SIMULATION MODEL

In this research, the performance of vehicles with trailers is studied mainly using the system based on computer simulation called *Universal Mechanism* (UM) developed in 1990 in the laboratory of computational mechanics of Bryansk State Technical University, Russia. The package was designed to automate the analysis of mechanical objects, which can be represented as systems of rigid bodies (or multibody systems), whose bodies are connected by means of kinematic elements (joints) and forces. A car, a locomotive, robots and excavators, various mechanisms and devices are examples of such systems. The simulation workflow on UM works as follows: (i) Real mechanical system or its prototype, (ii) preparing input data and conception of a model, (iii) describing kinematical model, (iv) describing dynamical model, (v) automatic generation of equations of motion; and (vi) analyzing model's dynamical performance. A automatically generates of motion equations, and then numerically solve these equations. Animation and online motion graphics and dynamic performances are available during the simulation (Yazikov *et al*., 2004). In purpose model, vehicles control velocity is realized by equation $T = C_1 * (W - W_d)$, where torque T is applied on back wheel, W is real linear velocity and W_d is desired linear velocity (figure 11). The direction system is given by a harmonic motion of headset in which the amplitude and frequency of movement can be changed allowing the simulation of trajectories different (Figure 12). The system has the following equation $M = ampl1 * \sin(OM * t)$, where $ampl1$ is the amplitude of the movement and OM is the frequency. The contact between the surface and the tire is given by a contact force which can modify some parameters such as static and dynamic friction, and the rigidity coefficient. The values utilized for this simulation are: static friction (0.9), dynamic friction (0.85) and rigidity coefficient (900000 N/m). The trailer is connected to the AGV through a rotational joint in the Z axis and also he has the headset is passive. The AGV model characteristics based on industrial models for simulation are (Amerden, 2009): for the AGV mass is 1280 kg and the trailer mass is 545 kg.

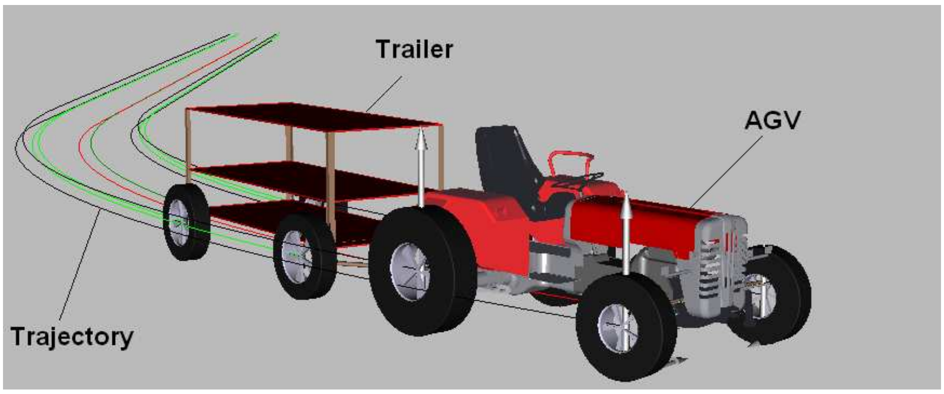

Figure 11. UM simulation software for AGV with 1-trailer trajectories

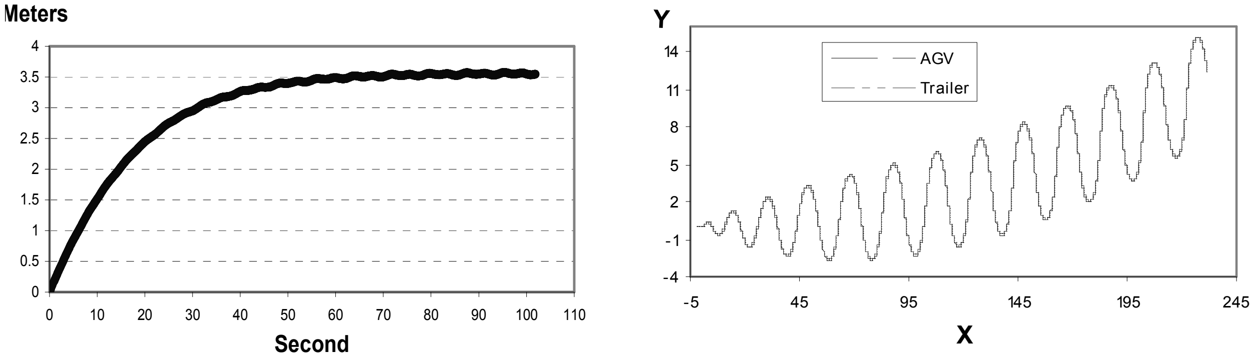

Figure 12. Velocity and trajectories for AGV with 1-trailer

5. CONCLUSIONS

The present work opens up a path to the study of AGVs with trailers in the areas of planning and obstacles detection in AGVs. This involves the identification and planning of trajectories, in order to support the development of new optimization techniques to minimize the cost function of the behavior of automated vehicles. This article presented an implementation of a distributed scheduling algorithm for decentralized Job-shop systems that can be used for FMS control and scheduling.This novel approach allows the decentralization of the trajectories control and enables the distributed control to deal with any modification of the due time, caused by its asynchronous nature. The next step is the use of this algorithm in two real conditions: (i) AGV traffic control in automated container terminal and automated large scale freight transport systems and (ii) computational grid scheduling and grid data movement.

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