Computers in Industry 60 (2009) 204–216

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

# A stigmergic approach for dynamic routing of active products in FMS

Yves Sallez *, Thierry Berger, Damien Trentesaux

*LAMIH, CNRS, University of Valenciennes and Hainaut-Cambrésis, Le mont Houy, F-59313 Valenciennes cedex 09, France*

ARTICLE INFO

*Article history:*
Available online 22 January 2009

*Keywords:*
Stigmergy
Dynamic routing
Active product
Manufacturing control
Flexible manufacturing system

ABSTRACT

This paper illustrates the capacity of a stigmergic routing control model to automatically find efficient routing paths for active products in flexible manufacturing systems (FMSs) undergoing perturbations. The proposed model is based upon a functional architecture with two levels: a virtual level in which virtual active products (VAPs) evolve stochastically in accelerated time, and a physical level in which physical active products (PAPs) evolve deterministically in real-time. The physical active products follow the best paths that have been detected on the virtual level, with a virtual level exploration being triggered when a perturbation is diagnosed in the transportation system. The data used for the simulation on the virtual level is then updated to reflect the real state of the transportation system. The model's adaptive capabilities are illustrated with several simulation scenarios using NetLogo software, and an on-going real implementation is presented.

## 1. Introduction

This paper is relevant to the context of distributed dynamic control of production processes in flexible manufacturing systems (FMSs). In this context, a stigmergic routing control model, capable of automatically finding efficient routing paths for active products in flexible manufacturing systems undergoing perturbations, is proposed.

Most of the research in the FMS domain focuses on the distributed control of Dynamic Allocation Processes (DAP) (e.g., dynamic scheduling). Little attention has been paid to the distributed control of Dynamic Routing Processes for products (DRP), (e.g., transportation times are assumed constant, paths unique and conveying capacity unlimited) [1–10]. In addition, products are usually considered to be passive entities: they never communicate, decide or act during the routing process. However, recent technological advances (e.g., RFID, smart cards, embedded systems) have led to research on "active products", in which products are able to act based on the real state of the system (e.g., resources, production and transportation systems). These "active" capabilities may be embedded in the product itself or may operate from a distance [11].

Given these realities, we have begun to work on the distributed control of DRP using the notions of "active product" and stigmergy to provide efficient, real-time, adaptive product routing. These notions make our model more realistic, able to take such aspects as limited system capacity and system reliability into account.

This paper is structured as follows: Section 2 gives a short presentation of the state-of-the-art in the domain of stigmergy applied to manufacturing control. Section 3 presents the assumptions on which our model is based, as well as the notations and variables that are used in subsequent sections. Section 4 describes the model, and Sections 5 and 6, respectively, introduce the developed simulator and report the results obtained. Section 7 provides a short synthesis and Section 8 describes the ongoing implementation. Section 9 offers our conclusions and perspectives for future research.

## 2. Stigmergy: concepts and the state-of-the-art in manufacturing control

FMS routing is a difficult problem because its nature is stochastic and time-variable. Our objective in this study was to build an efficient routing system that is capable of finding the best routing solutions in real-time and of adapting to new traffic situations and changes in the conveying network's connectivity (e.g., jamming, failures or slowdowns on the network arc, topological modifications). Some insect societies that use stigmergy – for example, ant colonies – exhibit these desirable properties. However, the customary optimization algorithms (i.e., path-finding) can hardly support such dynamics. For a more detailed discussion of the advantages of stigmergy compared to other optimization approaches (e.g., simulated annealing, tabu search, iterated local search, evolutionary computation), see reference [14]. Once we had built our system, we sought to integrate it into a more general distributed control system. This integration was facilitated by the naturally distributed nature of stigmergic control.

---

* Corresponding author. Tel.: +33 327511463; fax: +33 327511310.
*E-mail address:* yves.sallez@univ-valenciennes.fr (Y. Sallez).

0166-3615/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.compind.2008.12.002

### 2.1. *Concept of stigmergy*

The term "stigmergy" describes the mechanism used during ant foraging activities [12]. Ants find food and carry it back to the nest, simultaneously laying down a pheromone trail. Other ants, detecting the pheromones, follow the trail back to the food source. As more ants bring food to the nest, they each reinforce the chemical trail on the path they follow. Since pheromones tend to evaporate over time, the more attractive trails accumulate more pheromones and thus have an advantage over the other trails. Over time, due to the natural reinforcement of the ants, only the shortest trail remains.

### 2.2. *Use of stigmergy in manufacturing control systems*

The first experiments related to the industrial use of stigmergy were conducted in the early 1980s by Deneubourg et al. [13], who simulated "ant-like robots". Dorigo's work [14,15] gave rise to a new field of research known as Ant Colony Optimization (ACO), which has been used successfully to solve optimization problems (e.g., Travelling Salesman Problems, Network Routing for telecommunications and the Internet). Several researchers – Parunak [16], Brückner [17], Peeters [18] and Hadeli [19] – have also applied the stigmergy concept to specific situations in manufacturing control systems.

### 2.3. *Use of stigmergy for dynamic routing*

Several successful routing algorithms inspired by ant colony behavior have been proposed [14]. In a time-variable context, the most appropriate is AntNet [15], which is an ACO approach applied to adaptive learning for routing tables in communications networks. In AntNet, routing information is gathered through a stigmergic learning process using routing packets. These packets are lightweight agents that are generated concurrently, but independently, by the network nodes, and given the task to sample the paths to an assigned destination. An ant going from a source node *ns* to a destination node *nd* collects information about the quality of the path that it follows (e.g., end-to-end delay). Its path is then backtracked from *nd* to *ns* to update the routing information at the intermediate nodes.

### 2.4. *Parallel between stigmergic approach and reinforcement learning methods*

The routing problem can be seen as a stochastic, distributed and time-variable reinforcement learning problem [20]. Dorigo and Stützle [14] have drawn some parallels between AntNet and classic reinforcement learning approaches, such as Markov decision processes, Monte Carlo systems or temporal difference TD($\lambda$) methods. Like Monte Carlo methods, TD($\lambda$) methods use the bootstrapping paradigm and can learn directly from raw experience without recourse to a model of the environmental dynamics [21]. In the bootstrapping paradigm, nodes estimate the cost of a path by combining the cost estimates made by neighboring nodes and the cost of travelling to those neighboring nodes. A bootstrapping mechanism is used in the distributed Bellman-Ford or Q-routing algorithms. As Dorigo and Stützle have explained [14], the main difference between AntNet and the TD($\lambda$) methods is that AntNet requires no information backchaining from one state (i.e., the triplet–current node, destination node and next hop node) to its predecessors. Each state is rewarded only on the basis of the ant's trip time information strictly relevant to it.

### 2.5. *Specificity of our approach*

Our approach to the routing problem was inspired by AntNet. However, certain adaptations were needed to adapt AntNet for use in a FMS context. In AntNet, mobile agents (routing packets) are used to update the routing tables in real-time and to distribute information about the network's traffic load. In an FMS context, this would be unrealistic since using real shuttles to explore the network would be highly prejudicial in terms of time efficiency.

In response to this problem, we propose a functional two-level – physical and virtual – architecture for the distributed control of DRP. The following section describes the assumptions on which our model is based and presents our modelling approach.

## 3. Assumptions and the proposed modelling approach

### 3.1. *Assumptions*

Our proposed architecture is based upon four assumptions concerning four different system aspects:

(1) The *topology* of the transportation system is assumed to be associated to a strongly connected, directed graph, in which nodes can be both resources and disjunction points, and arcs are the parts of the system that require no decisions during the routing process since the product can only move in one direction towards the next node. Routing times are assumed to be non-negligible compared to production times.

(2) The *global systemic architecture* of the production control system, in this paper, pertains to the distributed DRP and DAP control systems. This architecture is assumed hierarchic (Fig. 1), meaning that allocation is optimized prior to routing. Inputs to the distributed DRP control system are assumed to be the set of pairs (*ns*, *nd*), where *ns* is the resource source node

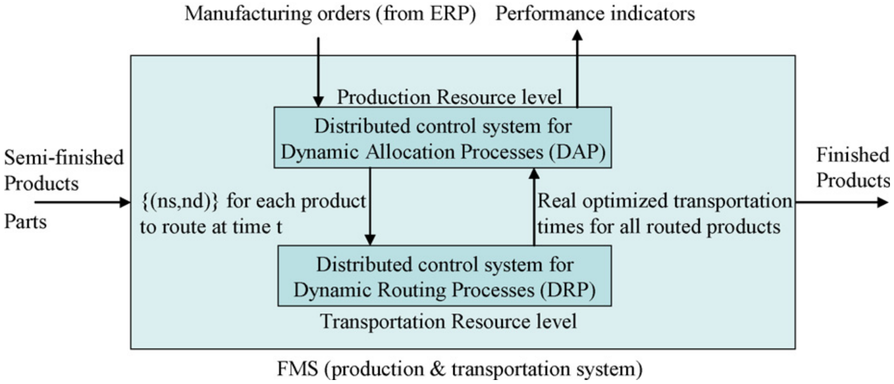

**Fig. 1.** Global systemic architecture of the production control system.