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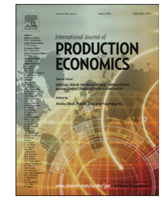

Routing and dispatching of multiple mobile agents in integrated enterprises ☆

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A B S T R A C T

Agent-based technology provides a natural way to design and implement enterprise collaboration. We model the integrated manufacturing enterprise as a directed graph and reduce the problem of enhancing the efficiency of mobile agents to the problem of finding resource-constrained extremal paths in the graph. We suggest a general two-stage solution method combining routing and dispatching, which extends an earlier computational scheme in the literature for the constrained path problems. The new method essentially improves on several earlier algorithms and provides a new approach for constructing a fully polynomial-time approximation scheme (FPTAS) for the multi-agent constrained path problem.

1. Introduction

Global competition and rapidly changing customer requirements necessitate dramatic changes in the production styles and configurations of manufacturing organizations. The traditional centralized approach limits the flexibility, expandability, and reconfigurability of manufacturing systems. Emerging information and communication technologies are powerful technologies that have stimulated the creation and development of various forms of enterprise collaboration. Agent technology is a comparatively new paradigm that provides a natural way to address such problems, and to design and implement efficient distributed intelligent manufacturing systems.

In the context of collaborative intelligent manufacturing, we define an agent as a human or software system that communicates and cooperates with other human or software systems to solve a complex problem that is beyond the capability of each individual system and such a system is capable of autonomous actions, without the direct intervention of human beings or other agents. This definition is compatible with the definitions given by Pan and Tenenbaum (1991), Jennings and Wooldridge (1998), and Shen et al. (1997, 2001, 2006). An autonomous agent-based manufacturing system is a system that is able to function without the direct intervention of human beings or other agents in some environments, and that has control over its own actions and internal states. It is a loosely coupled network of manufacturing enterprises integrated with the suppliers, customers, and partners along complex supply chains that work together to solve problems that are beyond their individual capabilities.

Introducing the notion of mobile agents, White (1994) describes a computational environment known as “Telescript”, in which running programs are able to transport themselves from host to host in a computer network. Tsichritzis (1985) suggests the notion of mobile computation by describing a hypothetical computing environment in which all the objects could be mobile. Mobile agent-based technologies have been used in intelligent manufacturing for more than two decades. The latest achievements in multi-agent systems have brought new possibilities for integrated manufacturing enterprise management (see, e.g., Shen, 2002; Shen et al., 2000, 2006; Chabrol et al., 2006; Agnetis et al., 2007; Gallay and Hongler, 2009; Chiong and Dhakal, 2009).

Among numerous possible functions carried out by mobile agents in integrated manufacturing enterprises (IMEs), we study in this paper the routing and dispatching of mobile agents used for information retrieval in the operations of IMEs. This domain is a major potential application area for mobile agents. In this application, information is spread over several nodes, which are commonly geographically separated. The motivation for agent mobility is not the information technology itself but rather the benefits that mobile agents bring to operating distributed

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systems. Mobile agents migrate to the nodes where the data are located to perform their retrieval tasks there instead of transmitting data across the network. Consequently, the mobile agent can utilize the bandwidth of the network much more efficiently than when simply accessing the distributed database using a direct connection from a remote area.

The hosts provide information and also activities, services, and inter-agent communication. All the services and information are available at different sites and in different forms, levels of accuracy, and degrees of reliability. Hence, a mobile agent routing problem arises in which limited computational resources are available at many possible sites. A given benefit function determines how much benefit (e.g., information from sites, retrieval data etc.) each site contributes to an agent's mission. Since information is available at many different sites that yield different degrees of benefit, the mobile agent should find a best possible itinerary to visit the sites under resource constraints. The manager agent assigns the starting and finishing points of travel to each agent, together with an area of possible locations. The area is given by a map that is presented as a graph in which each subsystem is depicted as a node, possible links are depicted as arcs, and expected benefits (amount of information) are assigned to each arc in the graph. The problem of enhancing the efficiency of multiple mobile agents then reduces to a non-standard problem of finding resource-constrained extremal paths in a graph for each agent. The main theme (working programme) of our study is to validate the proposed model and algorithm. Specifically, we seek to show that a combination of the routing and assignment problems may render a more realistic model of mobile agent planning in IMEs than a series of the routing problems only, and that the advanced approximation algorithms may outperform the laborious exact algorithms in practice.

The remainder of the paper is organized as follows: In the next section we provide a brief overview of the related works. In Section 3 we give the problem formulation and a network configuration of the multi-agent based retrieval system. In Section 4 we develop an exact pseudo-polynomial dynamic programming solution algorithm for the problem. In Section 5 we propose efficient approximation algorithms for solving the scheduling and dispatching problems. In Section 6 we present the results of computational experiments conducted to test the performance of the proposed algorithms. In Section 7 we summarize the main findings and suggest some topics for future research.

2. Related work

Various researchers (Qi et al., 2001; Dasgupta, 2003; Sultanik, 2004; Zhang et al., 2004; Wu et al., 2004; Baek and Yeom, 2006, to mention a few) have been working on improving the information-retrieval efficiency of mobile agent based distributed systems. Mobile agent scheduling and routing is a planning approach that helps enhance the performance of the mobile agents in carrying out their tasks in a distributed agent application (Moizumi and Cybenko, 2001; Baek, 2006). In the aforementioned literature, the agent routing problem is regarded as an ordinary scheduling problem, like the travelling salesman problem (TSP). Brewington et al. (1999) formulated the so-called travelling agent problem (TAP), which is analogous to TSP, whereby one seeks to decide the sequence of nodes to visit in order to minimize the total execution time until the desired information is found. TAP is more flexible and dynamic than TSP in several respects. First, clones of agents are allowed to perform their tasks. Besides, several agents are allowed to perform the same task and visit the sites more than once. In addition, there are multiple agents whereby the assignment of tasks to agents is to be determined and the number of agents is to be minimized. It is obvious that if the agent's task is to visit all the nodes once and only once, then the agent scheduling problem reduces to the classical TSP. Since TSP is an NP-hard problem, TAP is NP-hard, too. Moizumi and Cybenko (2001) explored how agents can efficiently spend their time travelling throughout the network to complete sets of tasks; they applied dynamic programming to find an approximate solution to the problem under study in polynomial time. Baek (2006) presented another mobile routing model and solved the problem of minimizing both the number of agents and the total execution time under the condition that the turnaround time is minimized.

Our study may be considered as complementary to the works of Baek (2006), Rech et al. (2005), and Camponogara and Shima (2010). Specifically, we develop a graph-theoretic model for computing the agent's itinerary under resource constraints, which enables the design of exact dynamic programming and fast approximation solution algorithms.

3. Problem formulation

3.1. ISE's infrastructure and network configuration

To model mobile agents working in an integrated manufacturing enterprise environment, we exploit the concept of a mobile intelligent agent (a migent in short), introduced by Elalouf et al. (2011a). It is a mobile agent supporting intelligent manufacturing management and its multiple functions, which include enterprise integration, enterprise collaboration, manufacturing process planning, scheduling and control, materials handling, and inventory management. A virtual integrated enterprise can be represented as an oriented graph in which the nodes represent mutually dependent components that jointly form an organization committed to providing a product or service (Shen et al., 1997, 2001, 2006). Thus, from the customer's perspective, as far as the product/service is concerned, these interacting components, for all practical and operational purposes, are virtually acting as a single enterprise. Each component is supplied with or can generate, when needed, a transmittable programme that serves as a mobile agent. A detailed discussion of the applications of agent technology in virtual integrated enterprises can be found in the cited literature.

In integrated manufacturing enterprises, migents can be used in different ways:

- They can integrate order processing, product design, engineering analysis, process planning, production planning and scheduling, simulation, and execution.
- They enhance communication and cooperation among departments within an enterprise and among enterprises.
- They can represent different manufacturing resources (e.g., machines, robots, tools, fixtures, AGVs, and human operators) or aggregations of resources (e.g., robotic cells and production lines).
- They can be deployed to represent negotiation partners, either physical plants or virtual players, such as master plants, virtual partners, or dynamic consortia, to facilitate enterprise collaboration.

Consider, as an illustration, the agent-based manufacturing enterprise infrastructure suggested by Shen et al. (1997) and presented in Fig. 1. Its objective is to integrate the manufacturing enterprise's activities such as design, planning, scheduling, simulation, and execution with those of its suppliers, customers, and