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Formation of autonomous agent networks for manufacturing systems

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Designing flexible manufacturing systems that can cope well with the dynamic environment has been an important goal. The objective of this paper is to describe a modelling approach developed to design a manufacturing system as a society of autonomous agents—called autonomous agent network (AAN). Within the AAN, autonomous agents are loosely coupled. System's tasks are accomplished by the autonomous agents collaboratively through the communication and information exchange definitions—protocols. The approach in this paper consists of autonomous agent formation and protocol formation. Reducing the degree of uncertainty, reducing the impact of uncertainty, and keeping the desired level of productivity are the main motivations for forming autonomous agents for manufacturing. By using two basic communication acts, 'request' and 'tell', five basic protocols are formed. The five basic protocols can further form specific task-application protocols to define the complex communication among autonomous agents. The methodology is demonstrated with an industrial case study. In addition, the validation of the performance in communication, autonomy and flexibility of AANs are also explained in this paper.

1. Introduction

Integration has been an important issue in the stages of modelling and designing manufacturing systems, because an integrated manufacturing system may lead to better decision and operation performance. The first challenge of manufacturing system integration is that a manufacturing system is manifold; it is impossible to use a single perspective to study the whole manufacturing system. Hence, various viewpoints, e.g. organization, resources, information, function (Beeckman 1989), have been applied to study the basic integrating infrastructure of manufacturing systems. The second challenge is the problem-solving approach. Traditionally, the design of manufacturing system is through a 'divide-and-conquer' process, e.g. functional decomposition. However, such a process is usually applied well in the design of a single central system only. The application of the process to today's highly distributed and collaborative manufacturing systems becomes a challenge. As Davis (1980) points out, although the structure of the problem may suggest some initial division, most problems of interest cannot be trivially and independently decomposed. 'The sub-problems are often insoluble in isolation, and even if they were, it would be difficult to merge the independently developed solutions' (Davis 1980). This problem becomes more obvious when the activities involve people with different levels of skills, jargons, techniques, objectives or viewpoints to participate.

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The theory of distributed problem solving (DPS) provides a solution for the above dilemma, because DPS describes the interactions of groups of agents attempting to cooperate to solve problems (Decker 1987). Instead of decomposing the problems and merging the sub-solutions, DPS solves problems by the agents,† which cooperate with each other through communication protocols. Manufacturing systems also possess the nature of DPS, as most of the decision-makers are distributed in distance and time. However, when DPS is applied to manufacturing systems, the 'autonomous agents' and 'protocols' should first be known. This fundamental problem is addressed in this article. Through the rational formation of agents and protocols, manufacturing systems can be designed with autonomous agents. An agent in this article is defined as 'a programme (autonomous entity) that represents a group of parties'. Parties may include 'resources', e.g. humans, machines and computer systems. The role of agents is to cooperate with each other through protocols to perform specific tasks, and to achieve the manufacturing systems' goal. Nevertheless, a task is defined like an 'enterprise activity' (Beeckman 1989). A task is performed by the support of the parties.

Without such rational formation, there may be inadequate agents, or too many of them. In both cases, the manufacturing system will deteriorate instead of improving. The autonomous agents are loosely coupled and form an autonomous agent network (AAN) which can be applied as a model of a manufacturing system. According to Tsukada and Shin (1996), 'loosely coupled' means 'the agents are not necessarily cooperating closely on any particular task, but they may affect one another, and in particular, the action of one may hinder another from achieving its goal'.

The remainder of this paper is organized as follows. In section 2, three related research fields (DPS, organizational communication, and information integration and collaboration) are briefly reviewed to support the study of the new formation method. In section 3, a two-phase general method of forming agents is presented. In section 4, five basic information exchange protocols are proposed. Then, for the communication in manufacturing systems, task-application protocols are derived from the five basic protocols. In section 5, the autonomous agent network is validated qualitatively by comparing with the definition of autonomy and flexibility to explain the capability of AAN to cope with a dynamic environment. The final section presents concluding remarks and future research work.

2. Related work

2.1. *Distributed problem solving*

When problems in manufacturing systems become more complicated, people are unable to solve them individually. Usually, either a problem is decomposed into subproblems and different people are asked to solve the sub-problems, or served people are teamed together to solve the problem. However, as stated in the previous section, the sub-problems are insoluble in isolation, and it is difficult to merge the independently developed solution (Davis 1980). Therefore, the team approach is often applied to solve the complex problem.

DPS, instead of decomposing complex problems, attempts to cooperate distributed agents for the solution. Researchers (Randall and Smith 1983, Decker 1987, Moulin *et al.* 1991) agree that agents must be intelligent and possess memory

† The terms 'agents' and 'autonomous agents' are used interchangeably in this paper.

capabilities. Meanwhile, researchers usually assume that agents exist and are given, e.g. knowledge-base systems (Wong 1993, Polat *et al.* 1993), parts, machines, worktables and manipulators (Nagata and Hirai 1994), operators (Leplat 1991), decision makers (Rasmussen 1991), and personal assistants (Maes 1994). Unfortunately, agents do not naturally exist in the manufacturing systems. Because the term agent has been assigned different definitions, the applicability of agents is confused.

On the other hand, the protocol is another important element of DPS. Protocols provide the rules for agents on how to cooperate effectively together. Decker (1987), following Chang's (1985) approach, denotes that a protocol considers the following entities: (i) who speaks; (ii) to whom; (iii) when; (iv) with what duration and frequency; and (v) by what decision procedure. Wong (1993) also defines protocols as sequences with precisely defined steps to convene more complex intentions than single communication acts, where the communication act is the basic type of interaction between agents (e.g. request, assert, etc.). Another research direction concerns building protocols for use. For example, Randall and Smith (1983) develop a contract net environment.

2.2. *Organizational communication*

Organizational communication provides a general principle to explain the communication among agents. Weick (1990) defines an organization as an identifiable social entity pursuing multiple objectives through the coordinated activities and relations among members and objects. Such a social system is open-ended and dependent for survival on other individuals and sub-systems in the larger entity which in this case is society. From his study, three characteristics of an organization are concluded.

(1) Entities and organization.
(2) Objectives and coordinated activities.
(3) Adaptability and survivability of an organization.

Jablin (1990) summarizes five reasons for organizational group communication.

(1) Generate information.
(2) Process information.
(3) Share information necessary for the coordination of interdependent organizational tasks.
(4) Disseminate decisions.
(5) Reinforce a group's perspective/consensus.

These five reasons provide a good checklist for developing protocols. Jablin also points out that the most influential factors affecting interpersonal communication patterns and relationships among group members are the characteristics of the task on which they are working. One important finding in Jablin's research is that as task certainty increases, the group coordinates itself more through impersonal (rules, plans) than through personal communication modes. These findings from organizational communication form the background for discussing interacting behaviours among agents, particularly as they are applied to real manufacturing systems.